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PETROGRAPHIC AND ENGINEERING PROPERTIES OF FINE-GRAINED ROCKS OF CENTRAL ALBERTA

by

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CONTENTS

Illustrations

Tables

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ABSTRACT

The central Alberta Plains are underlain by a gently westward-dipping succession of nonmarine detrital strata of Late Cretaceous and Paleocene ages, which merges to the west with folded and faulted Cretaceous beds of the Rocky Mountain Foothills. Bedrock slumping is especially common along river valleys and man-made slopes in the eastern Plains, decreasing to the west towards the Foothills margin. This change in bedrock "strength" across the strike of the strata corresponds to an apparent regional increase in a westerly direction of the relative intensity of diagenetic effects, described in terms of compression, recrystallization, cementation, and chemical alteration.

The finer-grained rocks of central Alberta are mainly siltstones and silty claystones containing montmorillonite as the dominant clay material. The strata exhibit extreme variability in texture and microstructures: most are laminated to some degree, but few are fissile or exhibit marked grain orientation. Wet-dry cycle tests, an approximate measure of bond strength and hence the effects of diagenesis, show that the fine-grained strata in the eastern part of the area (Upper Cretaceous) are mainly "compaction" rocks, whereas those in the western Plains and adjacent Foothills (Paleocene and Cretaceous, respectively) are mainly "cementation" rocks. This distinction is supported by bulk density determinations of outcrop and corehole samples, which increase in value from east to west, although this trend is masked to some extent by local variations in mineral composition, especially montmorillonite content.

Most of the fine-grained rocks from the central Alberta Plains are characterized by properties intermediate between those of true "soil" and true "rock", i.e. they are "soft rocks." Drained direct shear tests on corehole samples from the Plains area show that three strength parameters (ϕ'_P, C'_P, ϕ'_R) exhibit high correlations with clay and montmorillonite contents, bulk density, wet-dry cycle ratings, and distance from the Foothills margin. The fourth parameter (C'_R) shows low or nonexistant correlations with other rock properties. Multiple regression analyses of the data indicate that the major casual factors associated with strength parameters are: ϕ'_P - clay content; C'_P - density, distance; ϕ'_R - clay content.

INTRODUCTION

The veneer of glacial deposits that covers the central Alberta Plains is underlain by a thick succession of relatively soft, gently dipping sedimentary strata of Late Cretaceous and Early Tertiary ages. These strata are of similar composition and origin and, although "rocks" in a geologic sense, are characterized in many places by massive slumping where exposed along the valleys of postglacial streams and rivers (Hardy *et al.*, 1962; Rennie, 1966; Hayley, 1968).

The instability of natural slopes developed in near-surface bedrock formations of central Alberta is well known to engineers and geologists alike, and a number of case histories documenting slumping phenomena in the eastern portion of this area have been reported (Painter, 1965; Pennell, 1969). From these and other observations, it is apparent that the bedrock formations of central Alberta exhibit properties which suggest that they are neither true "rocks" nor "soils" in an engineering sense, but lie in a transition zone between these two types of materials. Thus, their behavior in engineering situations is difficult to predict on the basis of conventional theories and models or by using conventional testing techniques, and it is uncertain in many cases whether the principles of soil or rock mechanics should be used in the analyses of such situations.

The questions then arise: what are the geotechnical properties of sedimentary materials in this transition zone between "soil" and "rock", and what are the relationships between these properties and the geologic attributes of such materials? It has been observed, for example, that the propensity for slope failure, i.e. slumping, along bedrock river valleys in central Alberta appears to decrease in a westerly direction, towards the margin of the Rocky Mountain Foothills, in accordance with an apparent increase in induration or rock "hardness" in that direction. However, the gross lithology and inferred depositional origin of the near-surface bedrock remain similar over this distance, and it may be postulated that post-depositional (diagenetic) processes have affected the mass physical properties of these materials. Thus, it would be beneficial to determine those geological factors or variables that are associated with the processes involved in the transformation of soil to true rock, and to relate these variables to the potential behavior of the soft transitional materials in various engineering situations.

Scope of the Investigation

The investigation is essentially a pilot study of the engineering and geologic properties of the fine-grained (i.e. silty or clayey) Cretaceous-Tertiary strata of central Alberta. The program was set up with the following objectives in mind:

(1) to describe the basic attributes of these materials: namely, composition, texture, structure, and derived mass properties such as density, plasticity, and shear strength;

(2) to determine the interrelationships among these properties;

(3) to assess the effects of diagenesis on the properties of these materials: for example, to assess the effects of compression, cementation and like phenomena on peak and residual strength.

To this end a series of outcrop and corehole samples was collected from near-surface bedrock formations of the central Alberta Plains, adjacent to a line extending from within the Rocky Mountain Foothills on the west to the Plains region northeast of the City of Edmonton (Fig. 1). Thus, samples of siltstone and claystone were collected from across the strike of the strata in a direction that appears to coincide with a gradational change in the intensity of diagenetic effects, as exemplified by the change from hard, fractured rocks of the Foothills to the soft, tectonically undisturbed materials of the east-central Plains.

The samples were subjected to a variety of tests and analytical procedures. Examination of thin sections provided information on the composition, texture, and, in particular, the microstructure of the samples. Compositional and textural data also were obtained from grain-size analyses, X-ray diffraction patterns, and conventional "wet" chemical analyses. Standard soil mechanics tests were used to evaluate properties such as bulk density, water content, and plasticity. Wet-dry cycle tests were employed to evaluate further inherent soft rock properties, e.g. bond strength. Effective peak and residual strength parameters were determined from drained direct shear tests.

All of these techniques or tests are well known to geologists or engineers but are seldom used in conjunction with one another on the same group of materials. The combination of data from such procedures should provide a clearer insight into the properties of complex materials such as the bedrock deposits of central Alberta.

Acknowledgments

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Lesueur slide area in northeast Edmonton. To the many others who provided assistance, the writer extends his thanks.

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THEORETICAL BACKGROUND

Definition of Terms

Much of the research in soil mechanics has concentrated on the foundation engineer's chief problem soil – clay, which Terzaghi (1936) divided into *stiff* and *soft* clay on the basis of a liquidity index of less than 0.5 for stiff clay. Boulder clays, lacustrine clays which are overconsolidated by dessication, and heavily overconsolidated clays of Tertiary and older ages are all grouped as stiff clays (Morgenstern, 1967). On the other hand, the distinction between a soil (stiff clay) and a sedimentary rock (shale) is arbitrary in that there exist all gradations between the two materials. Terzaghi and Peck (1967) state:

> "The materials that consititute the earth's crust are rather arbitrarily divided by the civil engineer into the two categories, *soil* and *rock*. Soil is a natural aggregate of mineral grains that can be separated by such gentle mechanical means as agitation in water. Rock, on the other hand, is a natural aggregate of minerals connected by strong and permanent cohesive forces. Since the terms "strong" and "permanent" are subject to different interpretations, the boundary between soil and rock is necessarily an arbitrary one. As a matter of fact there are many natural aggregates of mineral particles that are difficult to classify either as soil or as rock."

From the point of view of simplicity, these definitions may be acceptable, but they do not give operational criteria for distinguishing between the two materials. For example, many compaction shales (Philbrick, 1950) cannot be classified as soil by this definition, although their behavior is often like that of highly overconsolidated clays (Hardy *et al.*, 1962). Therefore, although Terzaghi and Peck's concepts can be used to differentiate between true "soil" and true "rock" – i.e. for the end members of the system – materials with intermediate properties are left nameless. It is proposed here to call these transitional materials "soft rock" for want of a better term: this name implies that they are indeed sedimentary rocks from a geologist's viewpoint, although differing significantly from those indurated materials called "rock" by the civil engineer.

In addition to the problems involved in distinguishing between soil and rock there is no generally acceptable scheme for classification of fine-grained sedimentary materials such as argillite, shale, mudstone, claystone, etc. To clarify the terminology, the following definitions are employed throughout the text:

> *shale:* a highly indurated, readily fissile rock composed of predominantly silt- and clay-size particles;

> *clay-shale:* an indurated, readily fissile soft rock, which under certain circumstances can revert to a clay of medium to high plasticity, thereby assuming the physical characteristics of a highly overconsolidated clay;

claystone: a rock or soft rock (dependent upon the degree of induration) which is composed of predominantly clay-size particles;

siltstone: a rock or soft rock (dependent upon the degree of induration) which is composed of predominantly silt-size particles.

Soil-Rock Transformation

The transformation of a sedimentary deposit from the state of a freshly deposited loose soil mass to that of a true rock involves a number of physical and chemical processes that can be grouped together under the general term "diagenesis" (Pettijohn, 1957). This transformation is illustrated schematically in figure 2. However, in nature it is not necessary for the process to be carried to completion, i.e. a rock in the engineering sense of the term may not be formed. Natural conditions may be such that neither the required physical nor chemical processes are conducive to complete transformation. Also, changes in the natural environment may reverse the direction of diagenetic processes, and the mass may revert to the soil phase. Such a reversal may be caused by a reduction of overburden pressure due to the erosion of overlying material with resulting rebound. Hence, geologic age is not necessarily a measure of the degree of induration of sedimentary deposits. Indeed, soft rocks can be found in formations as old as Cambrian (Mead, 1936).

At any one point in geologic time materials can be found at any stage indicated on the transformation diagram (Fig. 2), and at this stage the material may be subjected to any one of the following sets of processes:

(1) the diagenetic transformation;

(2) the rebound transformation;

(3) a combination of (1) and (2): for example, rebound of the sedimentary mass with concomitant chemical alteration.

As a consequence, an engineer or geologist who is concerned with materials in the transition zone between "soil" and "rock' may ask:

(1) At what point in the system does a material cease behaving like a soil and begin behaving like a rock?

(2) At what point in the system are diagenetic processes no longer reversible, i.e. at what point will rock-like material lose its capacity to revert to soil-like material when conditions permit?

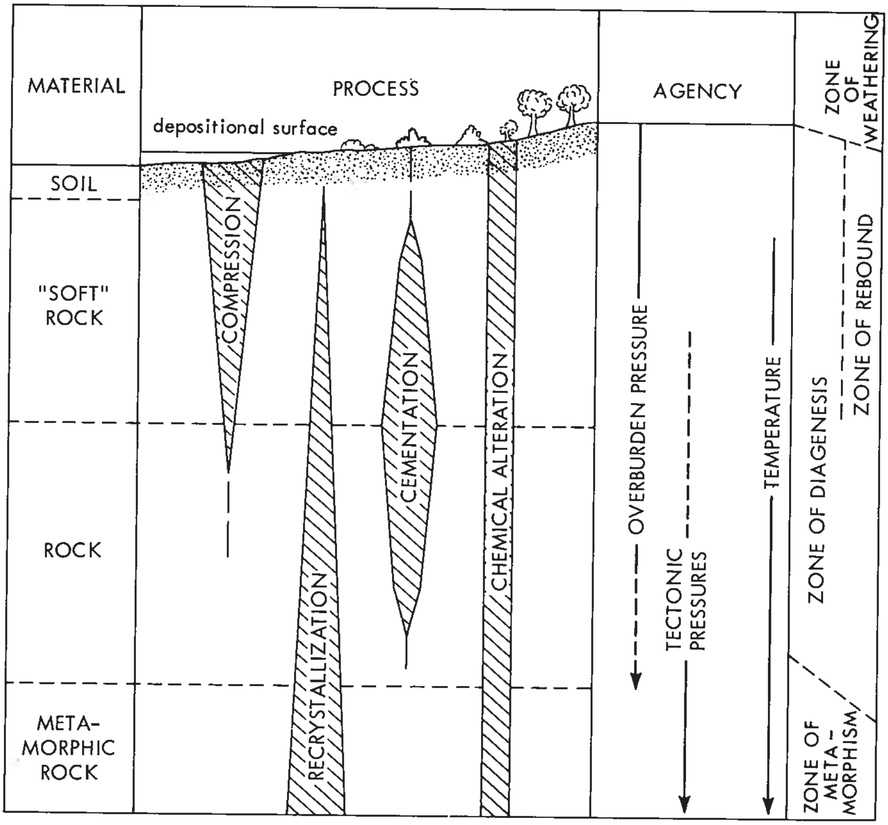


FIGURE 2. Schematic representation of diagenetic processes involved in soil-rock transformation.

(3) What criteria can be used to categorize the various stages of diagenesis between soil and rock?

Diagenesis

The complex processes which convert a newly deposited sediment into a rock are collectively referred to as diagenesis. This phenomenon is almost synonymous with the term lithification (Pettijohn, 1957) but excludes those processes which occur at elevated temperatures and pressures, i.e. metamorphic processes.

The exact nature of diagenesis is not clearly understood, although the major processes which are associated with this phenomena are outlined in figure 2. They are: *compression* (or compaction as understood by geologists); *cementation; recrystallization;* and *chemical alteration.*

Compression

Compression is a physical process that results in a reduction of the bulk volume of the sediment. The degree of compression that a fine-grained sediment acquires is largely dependent upon: (a) gravitational pressure, (b) particle size, (c) clay mineral constituents and their absorbed cations, and (d) type and concentration of electrolyte (Mead, 1964). The degree of compression in clastic sediments as observed in deep boreholes in the Gulf Coast led Hedberg (1936) to recognize four stages of compression which grade into one another:

(1) *mechanical rearrangement stage:* involves gravitational rearrangement of particles and expulsion of free water that results in a decrease in porosity from an initial value of approximately 70 to 90 per cent to a value corresponding to the liquid limit.

(2) *dewatering stage:* extends the compression process to the point where the clay particles begin to come into contact with each other. Free water is expelled from large cavities and adsorbed water is either expelled or redistributed, i.e. most adsorbed water is removed at grain-to-grain contacts.

(3) *mechanical deformation stage:* porosities are about 30 to 35 per cent and the clay particles are close to a stable arrangement with respect to gravity, most adsorbed water at points of contact having been removed. Further compression involves bending and crushing of particles with some additional expulsion of adsorbed water. Previous to this stage, water supplied most of the binding force of the system, but with the contact of clay particles, chemical readjustment and recrystallization add to the rigidity of the system.

(4) *recrystallization:* mechanical deformation decreases as most components are in positions of permanent stability, and chemical alteration and recrystallization are dominant factors. Newly formed minerals fill the pores and further decrease porosity. Beyond this point, metamorphic processes associated with higher temperatures and pressures alter shales to slate.

Cementation

Cementation is the process associated with the deposition of minerals (quartz, carbonates, clay minerals, iron oxides) in the voids of a sediment. Cementation may occur simultaneously with deposition or after deposition and burial over a wide range of pressures and temperatures. Cementation tends to increase rigidity, strength, and density. Where rocks are exposed to weathering phenomena, the reverse process – decementation – may occur, depending upon the composition of the cementing agents and the intensity of the weathering processes.

Recrystallization

Recrystallization implies changes in sediment texture and structure without the addition of foreign mineral matter. Recrystallization may simply involve the development of larger crystals of existing constituents (e.g. development of coarse-grained rock salt from a fine-grained deposit), or the elements in the original minerals may regroup to form new compounds. The result is generally a stronger, denser material.

Chemical Alteration

These are the processes by which the mineral assemblages of a sedimentary deposit are altered to meet equilibrium conditions during or after deposition. They usually involve the formation of new minerals by reaction between the solid constituents and pore fluids. Alteration of clay minerals is especially common, e.g. montmorillonite subject to potassium-bearing waters may alter to illite, and unstable volcanic glass may alter to montmorillonite. A sediment may change color when the ferric ion of iron compounds changes to the ferrous ion in a reducing environment.

The type of chemical alteration and its duration depend on the natural constituents of the deposit and the physico-chemical conditions under which the reactions take place.

Stress History and Recoverable Strain Energy

In many cases the degree of induration of rock or “soft rock” materials can be attributed in part to the high overburden pressures under which the deposit was originally compressed. This situation is to be expected in nonfolded areas like the Alberta Plains, where the strata are nearly flat-lying and essentially undisturbed by the effects of horizontal compressive (tectonic) forces and associated high temperatures and chemical activities. Such compressive forces well may have exerted an influence on the Plains strata, but from a large-scale structural point of view, the beds are undisturbed.

A counterbalance to the effects of compressive forces is found in areas where the deposits have been unloaded subsequently by erosion of overburden by normal agencies of erosion or by the melting back of the ice sheet in glaciated areas. In such cases the removal of overburden pressures has resulted in the rebound of large areas underlain by sedimentary rocks. The loading and unloading conditions to which soft rocks have been subjected are responsible for the *in situ* stress condition found in formations composed of these materials.

The overburden pressures which prevail in a sedimentary deposit during its geologic history exert work to compress the deposit until a state of equilibrium is reached. It has been noted in the field and in the laboratory that part of the compression and hence part of the work or energy expended is of a recoverable nature. These concepts were clarified and expanded by Bjerrum in the Third Terzaghi Lecture (1967).

Most compressible deposits contain many flexible, plate-like particles – e.g. clay minerals or micas – which are distorted during loading. Upon removal of load these particles may attempt to regain their original configuration; thus, a release of energy and an increase in volume may occur. This energy is recoverable strain energy. The actual amount of volume increase or rebound is controlled by interparticle bonds which may prevent distorted particles from regaining their original shapes. Bjerrum (1967) referred to all bond types, such as those formed by recrystallization and cementation, collectively as diagenetic bonds. Hence, the magnitude of the load during compression and rebound, the composition of the deposit, and the strength of the interparticle bonds will influence the magnitude of the intrinsic stresses.

During compression of a deposit, the effective horizontal stresses increase with the effective vertical stresses in accordance with the shear resistance of the mass. When rebound takes place, expansion will attempt to occur in the direction perpendicular to the plane of load removal. But, surface erosion brings about greater changes in vertical stresses than in horizontal stresses; consequently, large horizontal stresses are retained in overconsolidated clays. However, if the deposit is bonded, the horizontal stress is reduced by retention within the material of a greater amount of energy. Destruction of the bonds by weathering processes can allow expansion in the vertical direction and an increase in horizontal stresses.

Thus, in some clay deposits the strain is simultaneously recovered with a change of stress, whereas in others strain does not take place until the diagenetically-formed bonds are destroyed by weathering. Ultimately, lateral expansion of a slope due to breakdown of bonds by weathering may be sufficient to propagate the development of a failure surface. Bjerrum (1967) has classified overconsolidated clays and clay-shales based on the strength of the bonds and the effect of weathering on them. His classification system provides an indication of the potential danger inherent in these materials with respect to slope stability, although considerable scope still exists for developing a quantitative index for bond strength.

Shear Strength

Collin (1846) realized that the slopes of excavations in stiff clays and shales lost strength with time and ultimately weathered back to slopes comparable to nearby natural slopes which were considered stable with respect to a much longer time scale. He attributed the loss of strength to progessive softening of the materials. The concepts of progressive softening and its effects on shear strength were expanded by Terzaghi (1936), Skempton (1948), and Cassel (1948), who postulated that fissured materials are susceptible to the infiltration of water which may soften the material adjacent to a fissure and decrease the strength of the mass. However, as progressive softening is a time-dependent feature, a cut may remain stable for long periods of time. Skempton (1948) presented a plot of drop in strength *versus* time in years which illustrates that the average strength along the failure plane of slopes in London Clay decreases to that of the soft clay in the fissures. He stated that the final strength along a slip surface is composed of the strength through both unsoftened and softened clay. These concepts are still considered in explanations of slope instability in highly overconsolidated fissured clays and clay-shales.

Shear strength in the field may be evaluated on the assumption that the overall factor of safety is unity at the time of failure. Thus, if the slip geometry and environmental conditions of failure are known, the average shear strength along a failure surface may be calculated. The mathematical manipulations involved in the solution of the mechanics of the problem are now readily handled by sophisticated methods, e.g. Morgenstern and Price (1965). A field analysis, therefore, provides an indication of the true average shear strength which exists on the slip surface at the time of failure.

In the laboratory the shear strength of stiff clay and sedimentary rock is evaluated chiefly by the means of the triaxial test, the direct shear test, and the unconfined compression test. The success of these testing procedures depends on the ability of the test to duplicate the conditions of failure in the field and on the utilization of an undisturbed or intact sample which is representative of the mass under consideration. Unfortunately, intact samples which are not necessarily representative of the fissured mass in the field are often used in testing. A strength test on such a sample provides a value of the peak strength of the material. However, the failure plane of a sliding surface in the field passes through both intact and fissured materials, so that some reduced value of strength should be applied in stability analysis.

The reduced strength concept was clarified by Skempton (1964) when he emphasized the significance of residual strength. Figure 3a illustrates the shear strength characteristics of an overconsolidated clay or soft rock in a drained test. With deformation, the material builds up a resistance until a peak value (τ_p) is reached; with continued displacement the strength decreases until a minimum value (residual strength $= \tau_R$) is reached. If a series of similar tests under different normal loads is made, the peak and residual strength values can be plotted *versus* normal effective pressure to form two Mohr envelopes (Fig. 3b). The residual strength of a material may represent the shear resistance that develops along fissures or at points in a mass which have been strained beyond peak resistance, as in a progressive failure situation.

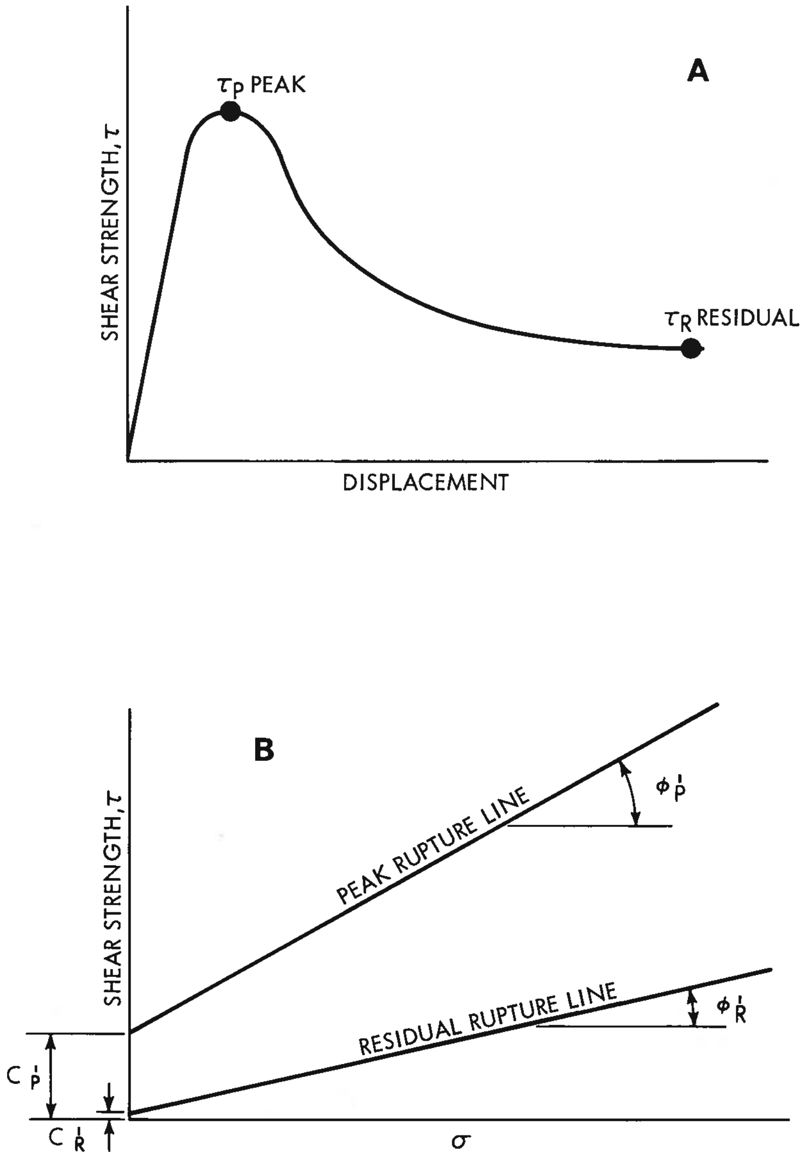


FIGURE 3. Effective shear strength characteristics of overconsolidated clay or soft rock.

Slope Stability

In the Fourth Rankin Lecture, Skempton (1964) applied residual strength concepts to a number of recorded slope failures in fissured materials and introduced the term "residual factor." The residual factor, R, is the proportion of the total slip surface in the material along which the strength has fallen to the residual value and may vary in magnitude from 1 to 0. The stability of slopes in Alberta "clay-shales" has been explained in terms of residual strength with R values near 1 (Sinclair *et al.*, 1966). Bjerrum (1967) also has applied the concepts of residual strength and recoverable strain energy to explain slope instability of intact materials in terms of progressive failure.

In summary, analysis of a soft rock slope requires an appreciation of (a) the concepts of peak and residual shearing resistance, (b) the residual factor, (c) the special engineering-geological properties of soft rocks, namely recoverable strain energy and the influence of diagenetic bonds.

GEOLOGY OF THE STUDY AREA

Selection and Location of Study Area

The study area lies in central Alberta between 53° 00′ and 54° 00′ north latitude and between 111° 00′ and 117° 30′ west longitude (Fig. 1). It comprises an area of about 16,000 square miles, the largest part of which lies within the Plains region, and a smaller portion in the southwest within the Rocky Mountains and Foothills.

The reasons for selecting this area are, firstly, accessibility: most of the sampling sites are on or adjacent to major highways and the remainder can be reached by municipal roads. Secondly, the geologic setting of the region is such that a relatively thick but lithologically homogeneous succession of strata can be sampled in an east-to-west direction, approximately across the strike of the rocks. This is the direction in which the apparent degree of induration increases, reaching a maximum in the folded and fractured rocks of the Rocky Mountains and Foothills. Thirdly, the shallow bedrock formations of this region, especially in the east, present serious problems of slope stability, to which basic data on the geotechnical properties of the rocks may contribute a better understanding.

Geologic Setting

The central Alberta Plains is an area of generally low relief underlain at shallow depths by a succession of predominantly nonmarine lenticular sandstone, shale, and coal beds of Late Cretaceous and Early Tertiary (Paleocene) ages. These rocks, which exhibit varying degrees of compression and cementation, form the "bedrock" of the region, being overlain in most areas by unconsolidated glacial and alluvial deposits of Pleistocene and Recent ages.

The bedrock structure of the Plains is that of a simple homocline, with the strata dipping gently westward at a few feet per mile (Fig. 1). Thus, successively younger strata outcrop at the bedrock surface in a westerly direction, to the point where they abut against the margin of the Rocky Mountain Foothills. Within the Foothills, strata ranging in age from Paleozoic to Tertiary are folded and faulted into a series of northwesterly-trending thrust sheets arranged in such a way that successively older strata are exposed in a westerly direction.

The eastern portion of this area is one of generally low relief, with a gradual rise in regional elevation from east to west. Topography is more irregular in the western part of the area, where concordant, flat-topped hilly areas and isolated ridges gradually rise in places to more than one thousand feet above the surrounding level of the Plains (e.g. Shiningbank Ridge). These areas, composed mainly of bedrock, constitute the remnants of a dissected plateau, merging to the west with the more pronounced valley and ridge topography of the folded Foothills region.

The land surface was modified to some extent by widespread glaciation during Late Pleistocene time, with the superimposition of local depositional and erosional topographic features upon the preglacial bedrock surface. Local relief also is provided by the valleys of two major river systems, the Athabasca and North Saskatchewan, which drain the western and eastern parts of the area, respectively. These rivers and such major tributaries as the McLeod and the Pembina Rivers are entrenched in narrow, steep-sided valleys 200 to 300 feet below the general land surface in places, although elsewhere, where they follow or cut across wide preglacial stream valleys, the local relief is much less.

Stratigraphy and Lithology

The shallow bedrock formations of the study area constitute a succession of lenticular detrital strata of predominantly nonmarine origin. The beds, which range in age from Late Cretaceous to Early Tertiary, are divisible into several rock units indicated on figure 1.

Belly River Formation ("Pale beds")

Beds assigned to the upper part of the Belly River Formation ("Pale beds") are the oldest of the bedrock formations exposed in that part of the Alberta Plains covered by the study area. They underlie the eastern part of the region, cropping out along the North Saskatchewan River and its tributaries downstream from Edmonton.

The unit is composed of complexly interbedded pale grey, bentonitic sandstone, laminated siltstone, and medium to dark grey, carbonaceous claystone. Thin beds of dark brown-weathering sideritic ironstone and coal also are present. The beds, deposited in a coastal plain or deltaic environment, closely resemble the highly bentonitic rocks of the overlying Edmonton Formation in the field, although they appear to be sandier in overall aspect.

Bearpaw Formation

The Bearpaw Formation underlies a large area in southern and east-central Alberta, where it consists primarily of dark grey marine shale, glauconitic sandstone, and thin bentonite beds. It thins to the north and west by interfingering with deltaic sediments in the lower and middle parts of the Edmonton Formation, so that in east-central Alberta the Bearpaw is present only as a thin shale unit 10 to 25 feet thick separating the "Pale beds" from the overlying Edmonton Formation (Allan, 1917). In the western part of the study area, the unit looses its lithologic identity entirely, and stratigraphers commonly do not distinguish between the Belly River and Edmonton Formation in this region (Fig. 1).

Edmonton Formation

The Edmonton Formation of latest Cretaceous age crops out over a large area in east-central Alberta. In the study area it forms the near-surface bedrock for a distance of about 70 miles perpendicular to the strike of the beds, extending parallel to Highway 16 from about 30 miles east of Edmonton to the Pembina River at Entwistle (Fig. 1). The eastern or lower boundary of the formation is defined by the contact with the underlying Bearpaw Shale; the western or upper boundary is marked by the contact with the overlying Paskapoo Formation. The formation is about 1500 feet thick near its western outcrop margin, thickening in the subsurface to the west towards the edge of the Foothills.

The Edmonton Formation consists mainly of soft-weathering, fine-grained clastic sediments deposited in fresh- to brackish-water environments. The predominant lithologies are pale-weathering, fine-grained, bentonitic sandstone and siltstone interbedded with and grading vertically and laterally into grey to brown, bentonitic, silty claystone. Coal and bentonite beds of variable thickness are present throughout the formation, together with thin dark brown-weathering beds of sideritic sandstone and claystone. The beds are lenticular and difficult to trace even locally owing to the lateral gradation of one lithology into another over short distances.

Detailed classification of the rock types of the Edmonton Formation in the field is made difficult by the gradational nature of lithologic contacts and by the finely laminated nature of the siltstones and claystones. The sandstones are generally soft, grey- to white-weathering, fine-grained, clayey rocks. Some hard sideritic or calcareous-cemented bands stand out as flattened or spherical nodules that are more resistant to erosion than the more common bentonitic sandstones. The clay-shales and siltstones constitute a gradational series of rock types difficult to categorize in the field. Many so-called "shales," for example, contain a high proportion of silt-size quartz, feldspars, and other granular detritus, grading at one end of the scale into siltstone and at the other into bentonite. Also, most such rocks do not exhibit fissility and thus are claystones rather than "shales." An exception is found in silty or "shaly" rocks that contain noticeable amounts of comminuted carbonaceous material along certain bedding planes: with addition of organic detritus these beds grade into impure coal.

Paskapoo Formation

The western part of the study area, between the Pembina River on Highway 16 and the eastern edge of the Foothills, is underlain by a thick succession of gently-dipping sandstones and shales, similar in gross lithology to the beds of the underlying Edmonton Formation. These strata, considered Early Tertiary (Paleocene) in age, are mapped as Paskapoo Formation in the eastern part of this region and as "Saunders Group" to the west (Map 1002A, Geol. Surv. Canada, 1951), although for practical purposes there is no obvious distinction between the two units.

The Paskapoo Formation consists of relatively soft-weathering, lenticular beds of sandstone, siltstone, and claystone of nonmarine origin. Thin coal beds are present and lenses of quartzite pebbles are found as the Foothills are approached.

The sandstones are fine- to medium-grained units ranging in thickness from a few inches to 100 feet. Such beds are relatively soft but appear less bentonitic or clayey than the sandstones of the underlying Edmonton Formation, although hard calcareous lenses are commonly present. The siltstone and claystone beds are thinner than the associated "massive" sandstones, consisting of medium to dark grey or greenish-grey rocks with thin sandy interbeds. Carbonaceous shales are present, grading in places into thin impure coal beds. The less silty claystones are soft, blocky fracturing rocks with little inherent fissility.

The similarity of gross lithologies throughout the succession, the lenticular nature of the beds, and the lack of outcrops make subdivision and correlation of the post-Edmonton succession of the western Plains difficult.

Historical Geology

Late Cretaceous-Tertiary bedrock formations of central Alberta form the upper part of a thick succession of clastic rocks ranging in age from Jurassic to Paleocene, which was deposited in a subsiding basin flanking highlands situated to the south and west of the present Rocky Mountains. These highlands, the site of erosion rather than deposition throughout most of the period under consideration, provided the detritus (including much volcanic material) which accumulated in the basin to the east, the amounts and composition varying from time to time, depending on such factors as the composition of the source rocks, the rate of uplift, topography, and climate. Thus, each gross lithologic unit or "formation" in the basin records an episode in a series of tectonic uplifts in the source region and concomitant downwarps in the marginal basin spread over a period of more than 100 million years (Alberta Soc. Petroleum Geol., 1964).

Figure 4 shows a series of schematic cross sections across the Alberta basin and hypothetical source area which record the major episodes of deposition and erosion from late Cretaceous to Recent times (G. B. Mellon, pers. comm.). Although the vertical scale is greatly exaggerated, and the position and extent of the source area and the degree to which the western part of the basin has been foreshortened are uncertain, the scheme holds true in principle.

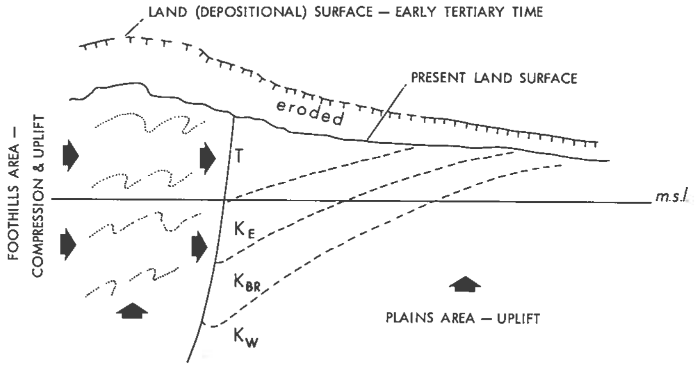
The first section shows the relationships among the subsiding basin, the highland source area to the west, and the inferred mean sea level at the time the lower part of the Edmonton Formation was being deposited. Detritus from the source area was transported by eastward-flowing streams to the basin over a depositional surface which sloped gently to the south and east. Sediments deposited in the western portion of the basin, above sea level at that time, consisted of complexly interbedded, lenticular bodies of sand, silt, clay, and organic matter now mapped by geologists as the "Edmonton Formation." The eastern portion of the basin was covered by a shallow sea in which fine-grained silty clays of the Bearpaw Formation accumulated. With the passing of time, eustatic changes in sea level combined with a steady influx of sediment from the west caused migration of the shoreline to the south and east. Thus, towards the end of Cretaceous (Edmonton) time, all of central and most of southern Alberta were the locus of continental (nonmarine) deposition, a situation that prevailed through the deposition of the overlying Tertiary (Paskapoo) beds.

The net result of these processes was to create a wedge-shaped blanket of lenticular, complexly interbedded, clastic and organic deposits, that, owing to the greater rate of subsidence (and hence, deposition) in the west, thickens in that direction. Except for the marine Bearpaw deposits, the various rock units were deposited by a series of aggrading streams flowing eastward across a gently sloping subaerial plain. Periodically, parts of the relatively flat depositional surface were sufficiently low and the supply of detritus sufficiently restricted to permit the accumulation of masses of organic matter, subsequently transformed into coal beds now associated with the Edmonton and Paskapoo Formations.

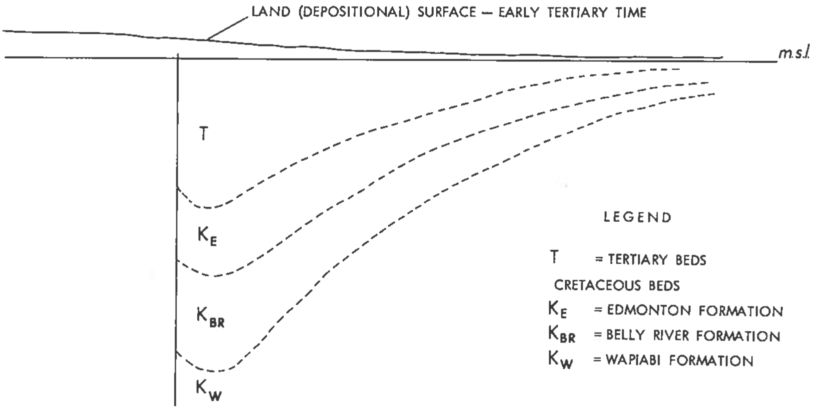
Towards the end of early Tertiary (Paleocene) time, events took place which transformed the Alberta basin from an area of subsidence and deposition into an area of uplift and erosion, processes which are still continuing. Figure 4 (stage 2) shows the schematic configuration of the source area and basin just prior to mountain-building movements that brought about this transformation at the end of Paleocene time.

These mountain-building movements ("Laramide Orogeny") are associated usually with compression and uplift of the western part of the basin, where the highly folded and faulted strata of the Rocky Mountains and Foothills are now situated. The duration of this process is uncertain, but its inception appears to have coincided with regional uplift of the eastern part of the basin as well as the folded western part, and the beginning of the long period of erosion that has persisted to the present day. For example, Rutherford (1928) estimates that approximately 2000 feet of strata have been removed from the study area during Tertiary time, if it is assumed that there has been no appreciable denudation of remnant plateaus such as Shiningbank Ridge. Consequently, as indicated in figure 4 (stage 3), the outcrop margins of various formational units have been stripped back in a westerly direction, with the younger Tertiary beds being preserved only in the western Plains and adjacent Foothills.

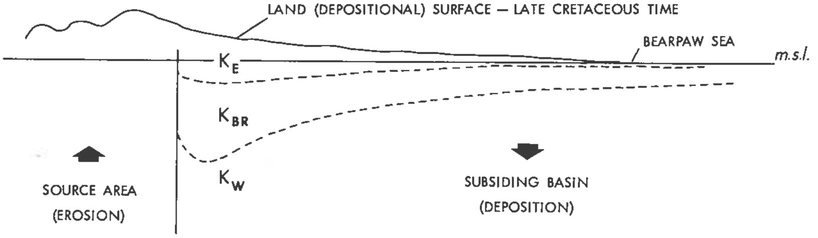
The prolonged period of erosion that took place in Tertiary time is largely responsible for the broad topographic outlines of the Alberta Plains as observed today. Locally, however, the late Tertiary landscape has been modified by Pleistocene glaciation, which has left a veneer of surficial deposits from a few inches



STAGE III - UPLIFT & EROSION



STAGE II - EQUILIBRIUM



STAGE I - DEPOSITIONAL

FIGURE 4. Schematic cross sections showing the Late Cretaceous-Tertiary history of central Alberta.

to several hundred feet thick over most of the region. The net effect of glaciation on topography is variable. In places, *hummocky* moraine deposits have enhanced the local relief by two or three hundred feet, or glacial meltwaters have cut steep-sided stream trenches into underlying bedrock. Elsewhere, preglacial valleys and other local depressions have been filled in by glacial deposits, resulting in a reduction in local relief.

Subsequent to the retreat of Pleistocene glaciers about ten thousand years ago, renewed erosion by larger streams and rivers has in places cut steep-sided valleys through glacial deposits and bedrock to depths of 200 to 300 feet below the general Plains level. Thus, Pleistocene glaciation can be considered as a relatively minor interruption of the processes of uplift and erosion of the Alberta Plains that have continued since early Tertiary time.

SAMPLING AND ANALYTICAL PROCEDURES

Description of Sampling Sites

A total of 74 samples were collected for analyses from 11 outcrop and 8 subsurface localities (Fig. 1), the descriptions of which are summarized in table 1. The sampling sites are arranged in an east-west direction, oblique to the northwesterly-trending strike of the strata, having been chosen with a view to accessibility and to obtaining representative material from major lithologic units of the Plains and Foothills regions.

All but one of the outcrop sites (Shiningbank Ridge) sampled during the summer of 1967 were selected at localities readily accessible to major highways or forestry trunk roads. The majority are along postglacial river or stream valleys, but some material from highway and railway cuts is included.

Profiles of some of the sampled outcrop localities are illustrated in figure 5. These and adjacent slopes are in the order of 45 degrees and appear to be stable at heights up to 250 feet. East of the City of Edmonton, outcrops are scarce and confined mainly to the valley of the North Saskatchewan River and the mouths of tributary creeks. They are seldom more than 50 feet high and most are partly covered by talus and vegetation.

In outcrop, sandstones, siltstones, and claystones are seldom separated from one another by sharp boundaries but rather grade into one another, seemingly without regulated order, by a gradual change in lithology. However, there are some cases where strata are separated by a discrete change in lithology, e.g. a calcareous sandstone bed resting directly on a well-defined claystone.

The siltstones and claystones are present as highly-fissured masses, with segments varying in shape from blocks to small slabs and in dimension from a fraction of an inch to nearly a foot. These segments, which have been derived mainly by weathering phenomena, are acted upon by the forces of erosion to develop extensive talus slopes of fragmented rock, particularly in the western portion of the study area. In east-central Alberta the fissured rock has reverted to a clayey or silty soil mass which mantles the slope and forms the talus.

Only the finer-grained clayey and silty beds were sampled; the thicker, more homogeneous sandstone beds present special problems of analysis and were excluded from the study. The sampling of outcrops involved removing the outermost one to two feet of highly fissured material and selecting representative pieces of claystone, siltstone, and bentonite from different beds, as distinguished by color, grain size, and degree of induration. Those samples which were to be thin-sectioned were treated with extreme care and were marked to indicate the direction of bedding. All samples were sealed in plastic bags to prevent moisture loss.

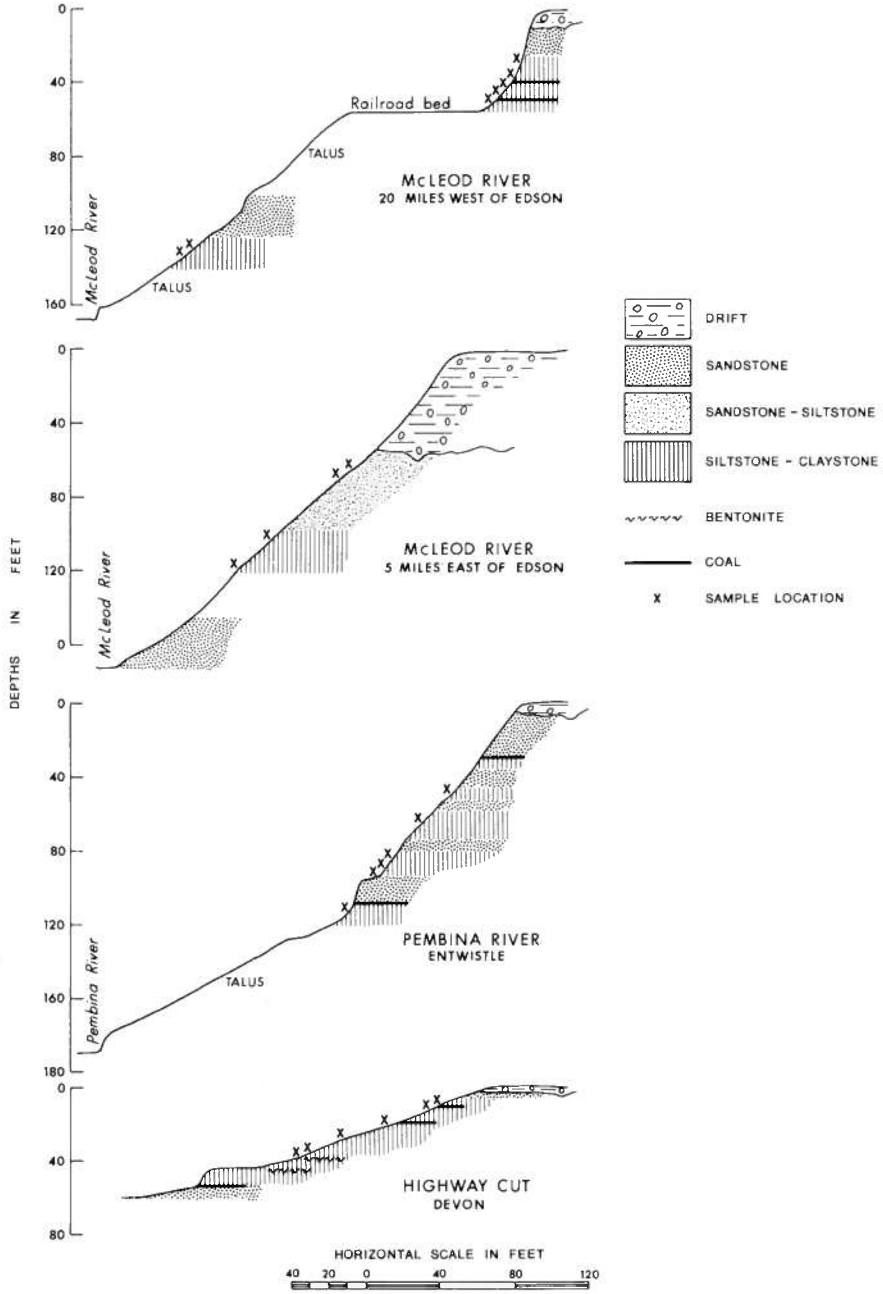


FIGURE 5. Cross sections of typical bedrock outcrops in central Alberta.

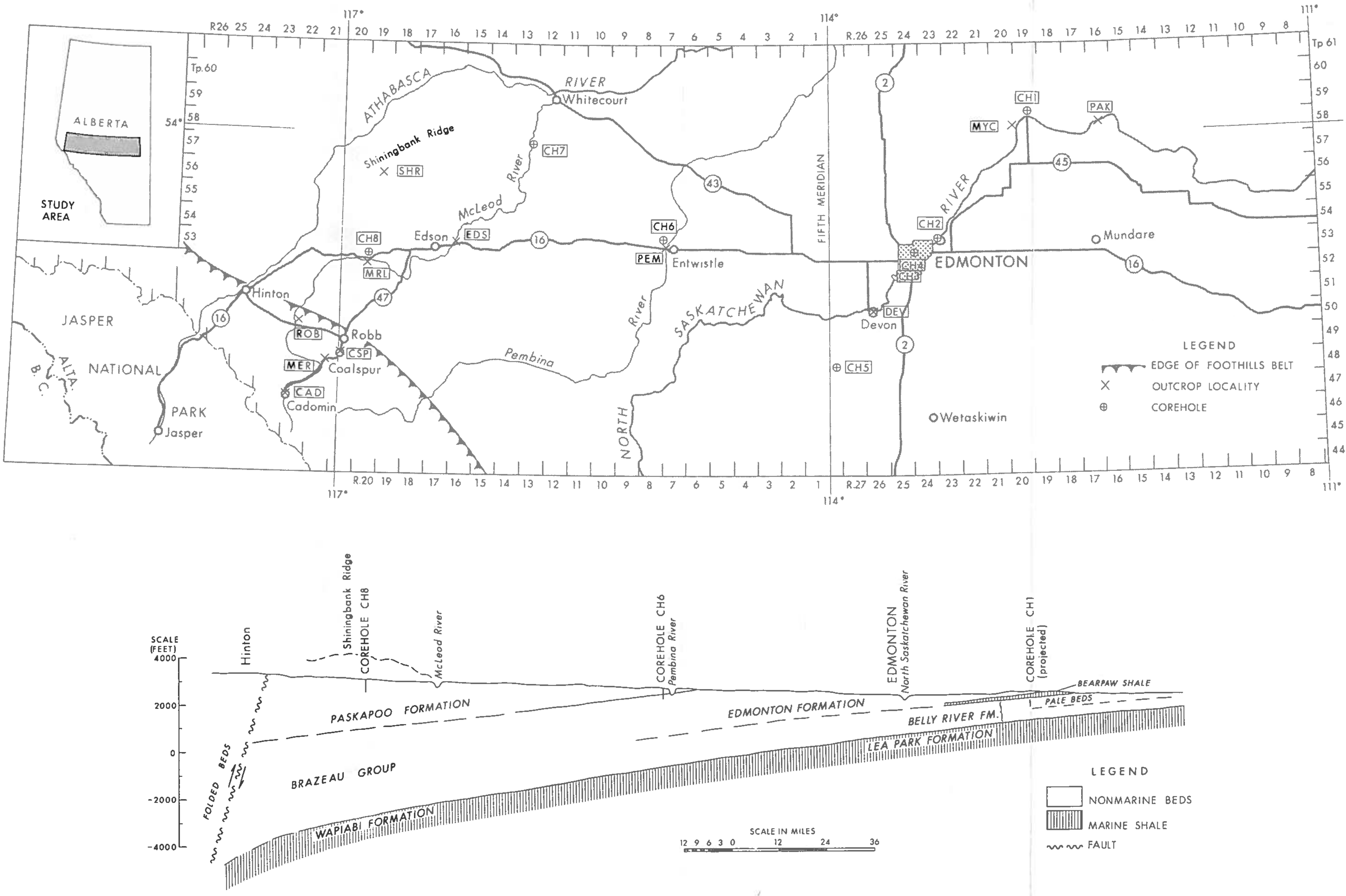


FIGURE 1. Location of sampling localities and geologic cross section.

Table 1. **Description of Sampling Localities**

Locality	Location	Rock Unit	Sample Designation	Number of Samples	Description
OUTCROPS					
Pakan	Sec. 12, Tp. 58, R. 17 W. 4th Mer.	Belly River	PAK	2	Cut 70 ft. high, near mouth of Egg Creek.
Myrtle Creek	Sec. 23, Tp. 58, R. 20 W. 4th Mer.	Belly River	MYC	2	Cut 35 ft. high, near mouth of creek.
Devon	Sec. 3, Tp. 51, R. 26 W. 4th Mer.	Edmonton	DEV	6	Highway cut, N. Sask. River bridge.
Pembina River	Sec. 29, Tp. 53, R. 7 W. 5th Mer.	Upper Edmonton[1]	PEM	6	Riverbank, 180 ft. high.
McLeod River	Sec. 20, Tp. 53, R. 16 W. 5th Mer.	Paskapoo	EDS	4	Riverbank, 165 ft. high.
Shiningbank Ridge	Sec. 30, Tp. 56, R. 19 W. 5th Mer.	Paskapoo	SHR	1	Small gully, 5-10 ft. high.
McLeod River	Sec. 32, Tp. 52, R. 20 W. 5th Mer.	Paskapoo	MRL	7	Riverbank, railway cut, 160 ft. high.
Coalspur	Sec. 28, Tp. 48, R. 21 W. 5th Mer.	Brazeau[2]	CSP	2	Railway cut, dip of beds 40°.
McLeod River	Sec. 14, Tp. 48, R. 22 W. 5th Mer.	Brazeau[2]	MER	4	Road cut, dip of beds 70-80°.
Cadomin	Sec. 5, Tp. 47, R. 23 W. 5th Mer.	Mountain Park[3]	CAD	3	Railway cut, dip of beds 45°.
McLeod River	Sec. 15, Tp. 50, R. 23 W. 5th Mer.	Brazeau[2]	ROB	5	Riverbank, dip of beds 25°.
COREHOLES					
N. Saskatchewan River[4]	Sec. 32, Tp. 58, R. 19 W. 4th Mer.	Belly River	CH 1	2 DS[5] 2 CL[5]	Corehole 60 ft. deep, drilled near river level, Waskatenau Bridge.
Edmonton[6]	Sec. 27, Tp. 53, R. 23 W. 4th Mer.	Edmonton	CH 2	1 DS	Corehole 110 ft. deep drilled at landslide site, northeast Edmonton (Pennell, 1969).
Edmonton[6]	Sec. 32, Tp. 52, R. 24 W. 4th Mer.	Edmonton	CH 3	3 DS 3 CL	Series of shallow coreholes (max. 116 ft. deep) on north edge University campus.
Edmonton[6]	Sec. 4, Tp. 53, R. 24 W. 4th Mer.	Edmonton	CH 4	4 CL	Series of shallow coreholes at site of A.G.T. building, downtown Edmonton.
Wizard Lake[6,7]	Sec. 8, Tp. 48, R. 27 W. 4th Mer.	Upper Edmonton[1]	CH 5	9 CL	Corehole 500 ft. deep, drilled by Research Council of Alberta 1967.
Pembina River[4]	Sec. 29, Tp. 53, R. 7 W. 5th Mer.	Upper Edmonton[1]	CH 6	2 DS 5 CL	Corehole 120 ft. deep, 200 ft. west of locality PEM.
McLeod River[6,7]	Sec. 33, Tp. 57, R. 13 W. 5th Mer.	Upper Edmonton[1]	CH 7	6 CL	Series of shallow coreholes at proposed dam site.
McLeod River[4]	Sec. 32, Tp. 52, R. 20 W. 5th Mer.	Paskapoo	CH 8	2 DS 2 CL	Corehole 85 ft. deep, 150 ft. north and 700 ft. west of locality MRL.

[1] May include basal beds of the Paskapoo Formation
[2] Upper Cretaceous, may include some Tertiary beds
[3] Lower Cretaceous, Foothills
[4] Drilled for investigation
[5] DS = direct shear-tested; CL = other tests
[6] Pre-study corehole
[7] Only air-dried material available

Table 2. List of Tests Performed on Fine-Grained Rocks from Central Alberta

Sample Number	Density	Water Content	Atterberg Limits	Hydrometer Analysis	Slaking and Wet-Dry Tests	X-Ray Diffraction	Chemical Tests	Thin Section Analysis	Direct Shear Test
PAK - 1	X	X	X	X	X	X	X	X	
- 2	X	X	X	X	X	X	X	X	
CH1 -39	X	X	X	X	X	X	X	X	X
-52	X	X	X	X		X	X		
-53	X	X	X	X		X	X	X	X
MYC - 1	X	X	X	X	X	X	X	X	
- 2		X	X	X	X	X	X		
CH2 - 9		X	X	X	X	X	X	X	
- 9A	X	X	X	X	X	X	X	X	X
CH3 - 1[1]	X	X	X	X		X	X	X	
- 2[1]	X	X	X	X		X	X	X	
- 3[1]	X	X	X	X		X	X	X	
- 1A[1]	X	X	X	X		X	X		X
- 2A[1]	X	X	X	X		X	X		X
- 3A[1]	X	X	X	X		X	X		X
CH4 - 1	X	X	X	X	X	X	X	X	
- 2	X	X	X	X		X	X	X	
- 3	X	X	X	X	X	X	X	X	
- 4	X	X	X	X	X	X	X	X	
DEV - 1	X	X	X	X	X	X	X	X	
- 2	X	X	X	X	X	X	X	X	
- 3	X	X	X	X	X	X	X	X	
- 4	X	X	X	X	X	X	X	X	
- 5	X	X	X	X	X	X	X	X	
- 6		X	X	X		X	X		
CH5 - 1			X	X		X	X	X	
- 2			X	X		X	X	X	
- 3			X	X		X	X	X	
- 4			X	X		X	X	X	
- 5			X	X		X	X	X	
- 6			X	X		X	X	X	
- 7			X	X		X	X	X	
- 8			X	X		X	X	X	
- 9			X	X		X	X	X	
PEM - 1	X	X	X	X	X	X	X	X	
- 2	X	X	X	X	X	X	X	X	
- 3	X	X	X	X	X	X	X	X	
- 4	X	X	X	X	X	X	X	X	
- 6								X	
- 7	X	X	X	X	X	X	X	X	
CH6 -33	X	X	X	X	X	X	X	X	
-54	X	X	X	X	X	X	X	X	X
-69	X	X	X	X	X	X	X	X	X
-87	X	X	X	X	X	X	X	X	
-116	X	X	X	X	X	X	X		
CH7 - 1			X	X		X	X	X	
- 2			X	X		X	X	X	
- 3			X	X		X	X	X	
- 4			X	X		X	X	X	
- 5			X	X		X	X	X	
- 6			X	X		X	X	X	
EDS - 1	X	X	X	X	X	X	X	X	
- 2	X	X	X	X	X	X	X	X	
- 4		X	X	X		X	X		
- 5	X	X	X	X	X	X	X	X	
SHR - 1	X	X	X	X	X	X	X	X	
MRL - 0	X	X	X	X	X	X	X	X	
- 1	X	X	X	X	X	X	X	X	
- 2	X	X	X	X	X	X	X	X	
- 3	X	X	X	X	X	X	X	X	
- 4	X	X	X	X	X	X	X	X	
- 9	X	X	X	X	X	X	X	X	
-10	X	X	X	X	X	X	X	X	
CH8 -45	X	X	X	X	X	X	X	X	X
-74	X	X	X	X	X	X	X	X	X
CSP - 1	X	X	X	X	X	X	X	X	
- 2	X	X	X	X	X	X	X		
ROB - 1	X	X	X	X	X	X	X	X	
- 2	X	X	X	X	X	X	X	X	
- 3	X	X	X	X		X	X		
- 4	X	X	X	X	X	X	X	X	
- 5	X	X	X	X	X	X	X	X	
MER - 1	X	X	X	X	X	X	X	X	
- 2	X	X	X	X	X	X	X	X	
- 3	X	X	X	X	X	X	X	X	
- 4								X	
CAD - 1	X				X				
- 2	X				X				
- 3	X				X				

[1] Data from River Bank Stability Report, Dept. of Civil Engineering, Univ. of Alberta, 1968.

Outcrop material was supplemented by samples selected from five coreholes drilled previous to or concurrently with the study (on McLeod River southwest of Whitecourt, at Wizard Lake, and in the City of Edmonton area) and from three coreholes drilled specifically for the purposes of the investigation (on McLeod River west of Edson, on the Pembina River at Entwistle, and on the North Saskatchewan River northwest of Edmonton, Fig. 1). The number of coreholes that could be drilled for the study was limited by economics; in addition, time and equipment placed restrictions on the number of direct shear tests that could be performed effectively. Thus, it was imperative that the coreholes be selected to provide materials representative of the maximum variations in soft rock characteristics across central Alberta.

The locations of the coreholes drilled to provide samples for shear and classification tests were determined from the results of density tests performed on outcrop samples. These tests indicated a relatively systematic variation in the densities of the different rock units across the study area, and the drillholes were spaced accordingly, namely across the Plains portion of the area at roughly sixty-mile intervals in a west-to-east direction (Fig. 1). The coreholes also are situated close to sampled outcrop sections; thus, drilling operations were facilitated by a general knowledge of the lithologic profile.

Drilling was performed with a Failing 1500 rig and by wet-drilling procedures. Where claystone or siltstone was encountered, a continuous sampling method was conducted with a Pitcher sampler, which consists of a 4-inch diameter Shelby tube that advances slightly ahead of a rotating core barrel. The Pitcher sampler has been used successfully in soft rocks of the Edmonton Formation (Pennell, 1969), the Smoky River Group in northern Alberta (Hayley, 1968), and the Belly River Formation east of Edmonton. However, in the Paskapoo Formation in the western portion of the study area, numerous breakdowns and drilling delays resulted from excessive wear on the sampler caused by the highly indurated bedrock.

Analytical Procedures

The samples were subjected to the series of analyses and tests listed in table 2. An attempt was made to subject all of the samples to each test (except the direct shear test), although it was necessary to allow the following exceptions:

(1) bulk density and water content determinations could not be made on air-dried samples from the McLeod River (Whitecourt) and Wizard Lake coreholes (CH7 and CH5 series of samples);

(2) certain samples could not be thin-sectioned owing to their friability;

(3) only density and wet-dry cycle measurements were performed on the highly indurated Lower Cretaceous samples from Cadomin (CAD series).

Direct shear tests were performed only on "undisturbed" samples containing their natural water content from the three coreholes drilled specifically for this purpose. The data obtained from these samples (CH1, CH6, and CH8 series) were augmented by data obtained from similar tests performed on corehole samples from the Edmonton area (CH3 and CH2 series) by the Department of Civil Engineering, University of Alberta, (1968) and a colleague, D. G. Pennell (1969).

PETROGRAPHIC AND ENGINEERING PROPERTIES

Definitions

The fundamental petrographic properties of clastic sedimentary rocks are texture, composition, and structure. Texture can be divided into four subproperties (Griffiths, 1967): particle size and shape (which are properties of the individual grains), and packing and orientation (which describe the position or arrangement of grains in the rock aggregate). Composition refers to the constituents of the individual particles and is expressed usually in terms of the types and proportions of minerals that constitute the aggregate rock specimen. Structure is a derived property that refers to textural or compositional inhomogeneities in a rock and thus may or may not be present, depending on the scale at which the materials are viewed.

In addition to these fundamental properties, rocks possess a number of bulk properties such as color, void ratio, hardness, etc. of which bulk density and plasticity are of particular interest to the engineer. These properties are related to the fundamental petrographic attributes of sedimentary rocks, one of the objectives of this investigation being to define these interrelationships.

Texture

Texture is the size, shape, orientation, and packing of the particles in a sedimentary rock. Of these four properties grain size and, to a lesser extent, grain orientation can be measured and used for classification of fine-grained rocks. Limitations of available laboratory techniques make grain shape and orientation exceedingly difficult to determine.

Grain Size

Grain size analyses of fine-grained sedimentary rocks are performed usually by a combination of sieving and sedimentation techniques, the use of which tacitly assumes that the rocks can be broken down into primary particles. The interpretation of the resulting grain size distribution curves is hampered not only by the inherent limitations of these techniques, but also by the layered (bedded) structure of many siltstones and claystones. Such rocks consist of complexly interbedded laminae of silt and clay a few millimeters to several centimeters thick with the result that slight variation in the *in situ* position or size of a sample will markedly affect the parameters of the resulting size-distribution curve.

Grain size analyses of the fine-grained central Alberta rocks (siltstones and silty claystones) were performed by a hydrometer technique in accordance with A.S.T.M. Designation D-422-63 with the following modifications. All samples were disaggregated by a freeze-thaw technique rather than by a drying and crushing procedure. Also, dispersion of the soil particles was accomplished by adding 10 to 30 cc, 10% sodium hexametaphosphate (Calgon) to the suspension, the quantity depending on the tendency of the sample to flocculate. In some cases washing with distilled water was required to reduce the salt content and promote dispersion.

Results

The data obtained from hydrometer analyses were plotted as cumulative frequency distributions, from which proportions of sand, silt, and clay for each sample were obtained (Table 3, Columns 2 to 4). Also, the percentages of sand plus coarse silt particles in each sample were determined by hydrometer analysis (Table 4, Column 3) and can be compared with the proportions of these constituents determined from point counts of thin sections (Table 4, Column 12). Textural classification of the samples, shown at the right of table 3, is based mainly upon the M.I.T. scale, commonly used by civil engineers.

The average percentages of sand-, silt-, and clay-size detritus in the fine-grained soft rocks of central Alberta are 15, 55, and 30 per cent, respectively, comparable to the textural composition of the average "shale" reported by Pettijohn (1957). However, considerable deviations from the average values exist, indicated in the ternary diagram (Fig. 6) on which the sand, silt, and clay proportions have been plotted. If the samples are grouped by formations, the following average percentages are obtained:

	Sand	Silt	Clay
Belly River (7 samples):	15.6	50.0	34.4
Edmonton* (40 samples):	13.8	51.2	35.0
Paskapoo (14 samples):	13.5	61.7	24.8
Brazeau (10 samples):	17.3	58.8	23.9

*probably includes basal Paskapoo samples - see table 1

The Belly River Formation rocks are the most homogeneous in grain size distribution (sandy and clayey siltstones), but this apparent lack of variation may be due to the limited number of samples analysed. The Edmonton Formation rocks, similar to the Belly River rocks in average composition, exhibit much wider sample variation and include the only samples with clay percentages exceeding 40 per cent. In contrast, rocks from the western Plains (Paskapoo Formation) and the Foothills (Brazeau Group) contain on the average more silt and less clay, although the textural fields encompassed by samples from these units in figure 6 are overlapped by highly silty Edmonton Formation samples. The tendency for the

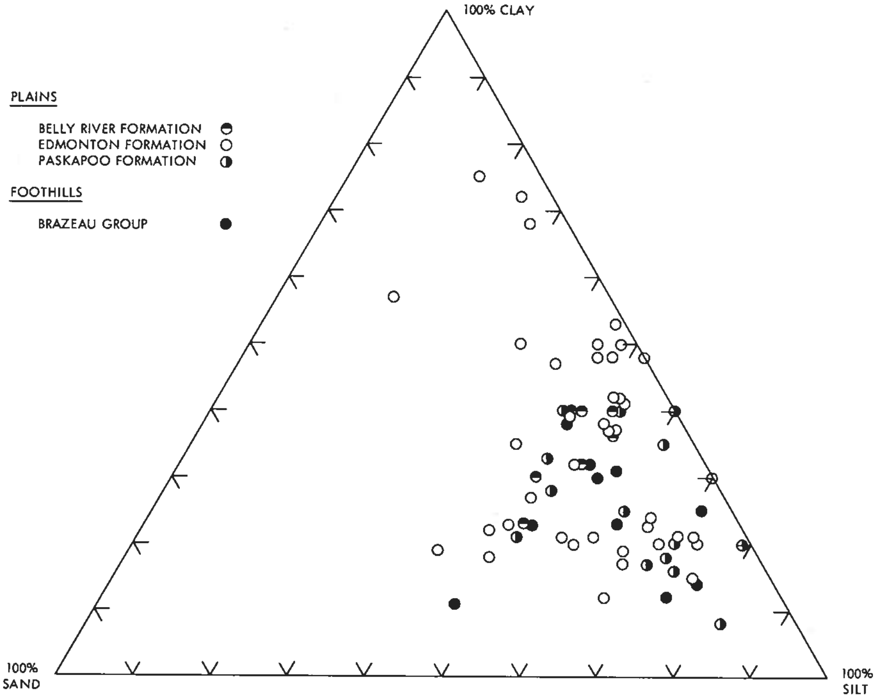


FIGURE 6. Sand, silt, and clay ratios, fine-grained rocks of central Alberta.

rocks from the western part of the area to contain more silty detritus can be attributed to closer proximity to the source area and the effects of selective sorting by the transporting agencies, although, in general, the majority of the rocks in the study area as a whole can be described as siltstones.

The results of thin section examinations substantiate in a general way the results obtained from hydrometer analyses: the data in table 4, column 13, show that most of the rocks contain at least minor amounts of coarse silt- and fine sand-size detritus in the form of quartz, feldspars, micas, and finely crystalline rock fragments. However, a comparison of the hydrometer and thin section data (Table 4, Columns 3 and 12) shows discrepancies ranging to 40 per cent between results obtained by the two techniques. About 10 per cent of the two sets of values are within 5 per cent of each other, about 50 per cent of the values are within 10 per cent of each other and 45 per cent of the values exhibit differences in silt content exceeding 10 per cent. In 80 per cent of the cases the hydrometer values exceed the point count values.

The variation between the results of the two techniques can be attributed to the following factors:

(1) breakdown of the rocks by the freeze-thaw technique is not complete. Consequently, the percentage of sand plus coarse silt as determined by hydrometer analysis is higher.

(2) considerable vertical variation in the grain size distribution of the rocks exists on both macroscopic and microscopic scales. Hence, the two subsamples selected from the same piece of rock for grain size determination may have different lithologies owing to the "lamination effect."

Of the two explanations, the first appears to be the dominant fact in light of the difficulty in breaking down some of the samples and the generally higher values obtained from the hydrometer analyses. Thus, it appears that the effectiveness of the freeze-thaw technique is open to question and that in order to fully evaluate the procedure closer control over local (micro) variation in lithology must be exercised. The influence of the number of freeze-thaw cycles to which a sample is subjected also may reveal the relative efficiency of the procedure.

Grain Shape

Particle "shape" is usually described in terms of grain sphericity and grain roundness (Pettijohn, 1957). No attempt has been made to determine either of these properties on a systematic basis, but the following observations can be made.

In terms of sphericity, the clastic constituents of the fine-grained rocks under consideration can be divided into two groups: nearly equidimensional silt-sized quartz, feldspar, and rock fragment grains, and platy silt- to clay-sized mica and clay mineral particles. The quartz and feldspar grains are angular, suggesting that the detritus was deposited and buried relatively quickly after erosion. Micas appear as lath-like plates or fine shreds in thin sections cut perpendicular to the bedding, although often distorted owing to their flexible nature.

Variations in particle size and shape impart various overall textural effects to the rocks in thin sections, as noted in the following photomicrographs:

Plate 1, Fig. 1:	coarse-grained, distorted mica plate and coarse-grained, silt-sized quartz fragments floating in clay matrix.
Plate 1, Fig. 2:	fine-grained, shredded mica "floating" in silty clay matrix.
Plate 4, Fig. 1:	abundant coarse silt-sized material in clay matrix.
Plate 4, Fig. 2:	scattered "floating" silt grains in very fine-grained clay (bentonite).

The photomicrographs in plate 5 exhibit a special form of grain shape termed "shard-texture." Shards in their original state are needle-like or curved spicule-like forms of volcanic glass which devitrify and alter to montmorillonite. The alteration, however, does not necessarily destroy the original shard shape, hence "shard-ghosts" may be preserved. Plate 5 shows excellent examples of the overall texture which these pseudomorphs impart to some fine-grained bentonites. The bentonitic claystones from the Lesueur slide exhibit an altered shard texture, in which many of the shards have lost their original shape because of the compression of the bentonite after alteration. Similar textures in many of the soft rocks in central Alberta confirm the volcanic origin of the vast quantities of montmorillonite in these rocks.

Grain Orientation

The orientation of particles in a clastic rock is a reflection of depositional processes and environment, and subsequent compression and shear forces. The measurement of particle orientation has been confined largely to measurements of pebbles and sand grains because silt and clay particles are difficult to resolve under the light microscope in thin sections of conventional thickness. However, the direction and degree of preferred orientation of aggregates of clay particles may be observed in thin sections with the aid of polarized light, e.g. Mitchell (1956), Morgenstern and Tchalenko (1967a,b,c), and it is this phenomenon that was studied in the fine-grained central Alberta rocks.

Most clay mineral aggregates are birefringent to some degree if they are studied under a polarizing microscope with their basal planes perpendicular to the plane of the thin sections. That is, the clay particles viewed under crossed nicols transmit zero light intensity when one of the optical axes is parallel to the wave front emerging from the polarizer, and transmit maximum light intensity when the optical axis is at 45 degrees to it. Thus, if an individual clay crystal is rotated through 360 degrees on the stage of a polarizing microscope, four extinction positions and four positions of maximum illumination will be viewed. If an aggregate of clay crystals is studied, the same phenomenon will be observed, but total minimum and maximum light intensity will seldom occur owing to different degrees of orientation of the particles. If the clay particles are arranged in a random fashion, no variation in light intensity is observed when the thin section is rotated under crossed nicols. However, if preferred orientation is present, the variation in light intensity will be a function of the degree of orientation.

The study of particle orientation was restricted primarily to clay aggregates, because measurement of the alignment of sand and coarse silt particles is difficult in most rocks. An example of alignment of coarser-grained materials is provided by the photomicrograph in plate 12, where the particles show a tendency for a change in alignment from parallel to the bedding to parallel to the walls of an infilling. Clay aggregate orientation was determined in sections cut perpendicular to the plane of the bedding as observed in outcrop or core sections, the degree of preferred orientation being evaluated by a ranking system. The thin sections were cut from samples which were slowly air-dried and then impregnated with Canada balsam. Most researchers (Mitchell, 1956; Morgenstern and Tchalenko, 1967a,b) have used Carbowax 6000 to impregnate the saturated sample in order to avoid possible changes in orientation that might be caused by shrinkage during drying. Carbowax 6000 was not used for impregnation of the samples reported in table 4; in many cases cracking developed, and some rocks, particularly outcrop samples, disintegrated. Sutherland and Singh (1967) reported similar findings in partially saturated clays with natural water contents close to or less than the shrinkage limit. The same phenomenon may cause the disintegration of the Alberta outcrop samples, for all of the rocks were not completely saturated (calculated values of the degree of saturation of outcrop samples vary from 82 to 100 per cent). Air-drying of samples from their natural water contents should not alter the orientation of the clay aggregates because the natural water contents of the samples are below or very close to the shrinkage limit; hence, no further volume change with drying can occur. Some cracking did appear during air-drying, but it is suggested that the cracks developed at the sites of microfissures inherent in the specimens (e.g. bedding planes).

Initially, the degree of preferred orientation was rated as the percentage of the total area of the thin section which varied from a position of maximum illumination to extinction. Preliminary observations revealed that clay aggregate orientation generally is poorly developed in the fine-grained rocks of central Alberta, in which case the adoption of a sophisticated evaluation technique, such as that employed by Morgenstern and Tchalenko (1967b), was not justified. The percentage rating system also appeared too refined in light of the subjective nature of the technique, with the result that a rating number from zero to five was assigned to each sample to describe the gross degree of preferred orientation, together with the descriptive terms listed below:

Degree of orientation	Rating
nil	0
very low	1
low	2
medium	3
high	4
very high	5

The orientation also was described as uniform or nonuniform according to whether one portion or portions of the thin section displayed a greater degree of orientation than others.

Results

Clay aggregate orientation is generally poorly developed in fine-grained rocks of central Alberta, with only 20 per cent of the 60 samples examined showing orientation values of 3 or higher (Table 4, Column 14). Of these samples 8 out of 13 are from beds adjacent to the Edmonton-Paskapoo Formations contact in the central part of the study area (PEM, CH5, and CH7 series), 3 from the lower beds of the Edmonton Formation in the eastern part of the area, and the remaining 2 from the Paskapoo Formation near Edson (Fig. 1). None of the Foothills samples show well-developed clay particle orientation, including the two samples from Lower Cretaceous beds at Cadomin (not described in Table 4).

Where developed, clay orientation is more commonly of patchy or nonuniform type, showing up best in samples containing concentrations of very finely crystalline micaceous or montmorillonitic matter, e.g. plates 1 (Fig. 2), 6, 7, and 9 (Fig. 2). Plate 7 shows a distinct band of highly oriented material which may represent either a change in environmental conditions or composition, or a zone within which shear displacements have occurred. In other samples the boundaries are irregular, with no apparent relation to the bedding; this phenomenon may be due to postdepositional slumping.

Clay aggregate orientation has been commonly observed in argillaceous rocks from many localities, having been attributed primarily either to depositional causes (the clay plates settle parallel to the depositional or bedding surface) or to shear strains imposed by compressive forces (as during postdepositional compression of the sediments). The absence or poor development of particle orientation in the fine-grained near-surface rocks of central Alberta, including those of the highly folded and faulted Foothills region, is therefore puzzling. Possibly the reason is to be found in the hindering action of the silt content of many of the rocks, although the correlation between grain size parameters and orientation is quite low (see Table 7). Moreover, thin sections of some samples with high clay and low silt content show little or no preferred particle orientation, which substantiates the correlation data. An alternative explanation is that the bulk of the clay (montmorillonite, kaolinite, and chlorite) is probably of diagenetic origin. For example, subsequent alteration of volcanic ash to montmorillonite would not lead to the formation of oriented aggregates, except in those rocks subjected to local stresses contemporaneous with diagenesis. However, the nature and extent of such stresses is uncertain, and the apparently "random" distribution of clay particle orientation effects in the central Alberta rocks remains unexplained.

Mineral Composition

The mineral constituents of detrital sedimentary rocks are of either clastic or chemical origin. The clastic constituents are formed by the break-up of parent source material and are mechanically transported and deposited as discrete grains.

The chemical constituents are formed subsequently through alteration or replacement of preexisting materials or by precipitation in the intergranular pores.

Although the mineral compositions of the coarse-grained detrital rocks (conglomerates, sandstones) can be determined largely by macroscopic or thin section techniques, the mineral compositions of the fine-grained rocks (siltstones, claystones) normally can be determined only by a combination of procedures. A knowledge of the chemical composition of these rocks is often helpful but usually cannot be used as a basis for accurate mineral identification (Underwood, 1967). Thus, the investigator must employ a combination of microscopic, X-ray, chemical, and size analyses techniques to determine the approximate proportions of mineral constituents in fine-grained sedimentary rocks.

Sand- and Silt-size Particles

These constituents were identified in thin sections (cut from air-dried samples perpendicular to the bedding) from their morphological and optical properties. Because of the fine-grained nature of the rocks, the materials were grouped into the following classes for estimating their proportions (Table 4, Columns 15 to 17, 19, 21): quartz plus feldspars, rock fragments, micas, organic detritus, and carbonates. The percentages of these groups of constituents were determined for each sample by a point-count (volumetric) technique, although the amounts present are reported only as abundant (Ab) or present (P) in table 4. An "abundant" rating requires that the constituent comprises at least 40 per cent of the sand plus coarse silt fraction of the rock (particles must be greater than 0.02 mm to be readily identifiable).

The results of point-count analyses are shown in table 4, columns 12, 13, and 15 to 21 inclusive. The average sand plus coarse silt (>20 microns) content of the 60 samples examined is 14.7 per cent by volume, with the majority of samples (37) containing 10 per cent or less. The major constituents in this group are subequant, angular quartz and feldspar grains (difficult to distinguish from one another in this size range) and platy mica flakes (largely biotite with minor muscovite and chlorite). Finely crystalline rock fragments (chert, volcanic and metasedimentary detritus) are present in many samples but abundant in only a few. The only other common clastic constituent is finely comminuted carbonaceous (coaly) material, which, like mica flakes, tends to "placer" along certain bedding planes in the laminated rocks (Plate 11, Fig. 2).

Comparison of the sand plus coarse silt volumetric contents of the rocks with the weight percentage contents obtained from hydrometer analysis (Table 4, Column 3) indicates that the latter values generally are substantially higher than the thin section values, although some inconsistencies in the differences between individual pairs of determinations are evident. The average percentages grouped by formations are as follows:

	Hydrometer	Thin section
Belly River (3 samples):	29.0	15.0
lower Edmonton (14 samples):	27.1	8.9
upper Edmonton* (23 samples):	24.5	16.3
Paskapoo (11 samples):	27.8	18.5
Brazeau (9 samples):	36.5	14.7

*probably includes basal Paskapoo samples - see table 1

Possible reasons for this discrepancy between the two sets of results are discussed in the preceding section of the report. The results themselves are compared here to indicate some of the pitfalls involved in quantitative analysis of fine-grained clastic rocks.

Clay Minerals

Of particular interest to civil engineers are the kinds, proportions, and distributions of clay minerals in the fine-grained central Alberta rocks which were determined by a combination of X-ray, size analyses, and thin section techniques. Briefly, the relative proportions of clay minerals in each sample were obtained from conventional X-ray diffraction patterns of untreated, heated, and glycolated oriented clay fractions sedimented on glass slides. The diffraction patterns were interpreted along the lines suggested by Johns, Grim, and Bradly (1954), and semi-quantitative estimates of each constituent were obtained from relative peak heights using a procedure suggested by D. W. Scafe, Research Council of Alberta. The criteria for the identification of the four major groups of clay minerals are:

illite (hydrous mica): by 10 Å reflection in the glycolated state;

montmorillonite: by 17 Å reflection in the glycolated state;

chlorite: by 13.2 Å reflection after heat treatment;

kaolinite: by 7.1 Å reflection in the glycolated state and subsequent comparision with chlorite reflections.

This procedure should provide a quantitative determination of the relative proportions of each clay mineral present in the total clay fraction with a precision of approximately 5 per cent (D. W. Scafe, personal communication). For example, some error is introduced by the sample preparation technique in which the clay

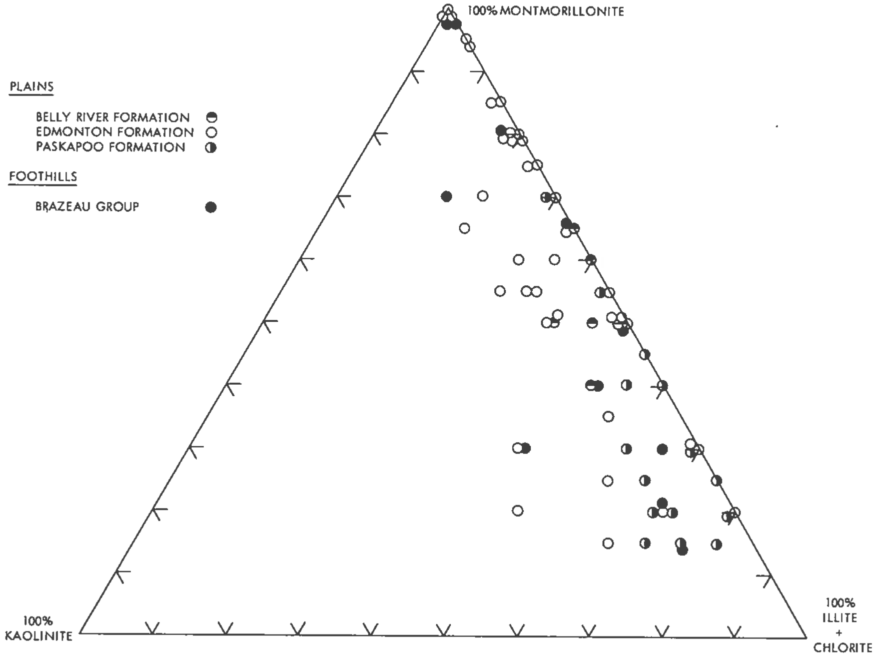


FIGURE 7. Clay mineral ratios, fine-grained rocks of central Alberta.

fraction is sedimented on glass slides: the finest particles, e.g. montmorillonite, will settle last, with the result that the diffraction pattern will indicate a higher proportion of montmorillonite than actually exists in the sample.

The amounts of individual clay minerals in each sample were calculated by multiplying the percentages of total clay content determined by hydrometer analyses (Table 3, Column 4) by the relative proportions of clay minerals determined from the X-ray diffraction patterns. These amounts are shown in table 3, columns 5 to 8, and the relative proportions of clay minerals in each sample are plotted on the ternary diagram in figure 7.

The data reveal that montmorillonite is the dominant clay constituent in the eastern part of the study area, whereas illite is most common in the western part. If the relative proportions of clay constituents are grouped by formation, the following average percentages are obtained (excluding four samples listed as "bentonites" in table 3):

	Mont.	Illite	Kaol.+ chlor.
Belly River (7 samples):	57	21	22
lower Edmonton (13 samples):	78	17	5
upper Edmonton* (25 samples):	51	34	15
Paskapoo (14 samples):	28	53	19
Brazeau (8 samples):	40	45	15

*probably includes basal Paskapoo samples - see table 1

All of the rocks contain at least small amounts of montmorillonite (Fig. 8): the eastern ones (Belly River and Edmonton Formations) contain an average of 23 per cent by weight (of total rock) with a range of 5 to 75 per cent, and the siltier western ones (Paskapoo Formation and Brazeau Group) an average of 9 per cent with a range of 4 to 38 per cent. In most thin sections montmorillonite is disseminated throughout the finely crystalline, moderately birefringent clayey matrix of the rocks and is difficult to distinguish from finely shredded micas (illite) and other clay constituents. However, in a few specimens it is present as nearly pure, discrete patches or lenses, forming irregular brownish, fibrous to spherulitic aggregates with moderately high birefringence (Plate 2, Figs. 1, 2; Plate 9, Fig. 2; Plate 11, Fig. 1). In a few highly bentonitic samples outlines of glass shards are preserved (Plate 5, Figs. 1, 2), indicating a volcanic origin for much of the finely crystalline clastic detritus in the central Alberta rocks. This glassy or opalline material has altered since to form montmorillonite, and possibly kaolinite and other finely crystalline constituents (quartz, carbonates), during the early stages of burial and diagenesis of the rocks.

Illite accounts for an average of 10 per cent of the total rock composition in the eastern part of the study area with a range of 0 to 30 per cent, and an average of 12 per cent in the western part with a range of 0 to 26 per cent. However, the high silt content of the western rocks (Paskapoo Formation and Brazeau Group) mask the fact that illite is relatively more abundant than montmorillonite in them, especially the Tertiary rocks of the Paskapoo Formation. In thin sections illite is indistinguishable from coarse-grained micas (biotite, muscovite) except for its finer grain size, appearing as nearly colorless to pale green or brown, moderately birefringent shreds or flakes that show some signs of aggregate orientation in many samples. Some of the finely crystalline rock fragments in the coarser-grained rocks (slates, phyllites) are composed partly of illite-chlorite aggregates, their presence indicating a clastic origin for at least some of the finely crystalline micas, in contrast with the probable authigenic origin of the associated montmorillonite.

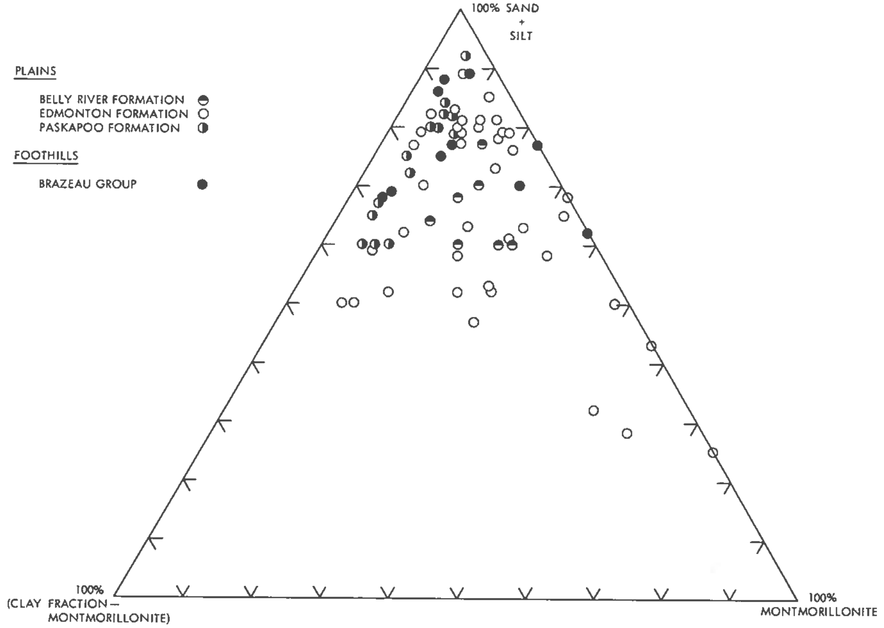


FIGURE 8. Sand-silt, illite-chlorite-kaolinite, and montmorillonite ratios, fine-grained rocks of central Alberta.

The other two clay minerals in the central Alberta fine-grained rocks, kaolinite and chlorite, are relatively minor constituents, the combined amounts contributing less than 5 per cent of the average rock composition by weight. Of the two constituents, chlorite appears to be the more common (present in 55 out of 71 samples), although it is possible that kaolinite (present in 30 out of 71 samples) is more abundant than the X-ray diffraction patterns would indicate. In thin sections their presence is difficult to confirm, owing to the masking effect of the much more abundant illite and montmorillonite.

Other Constituents

Organic carbon, carbonates, and pyrite are present in small amounts in many of the central Alberta fine-grained rocks, having been identified and analysed by a combination of thin section observations and chemical procedures. The total carbon contents of the rocks were determined by the use of a Leko induction furnace and a gasometric procedure,[1] and the inorganic carbon (CO_2) contents by use of an absorption train technique described by Hillebrand and Lundell (1953).[2]

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[1] Performed by Soils Division personnel, Research Council of Alberta.
[2] Performed by Geology Division personnel, Research Council of Alberta.

The organic carbon content was taken to be the difference between the total carbon and CO_2 contents. The amounts of both constituents also were estimated semi-quantitatively from thin sections. Neither procedure, chemical or microscopic, yields precise results where the amounts of organic carbon or carbonates are low, i.e. less than 1 per cent.

The sample distributions of organic carbon and carbonates are given in table 3, columns 9 and 10, and the corresponding thin section estimates in table 4, columns 19 and 21. Organic carbon is relatively abundant in the nonmarine Cretaceous and Tertiary strata of central Alberta, forming coal beds of considerable thickness and extent, especially in the Cretaceous Edmonton Formation and correlative strata of the Foothills. However, apart from coal beds and associated dark colored carbonaceous shales, most of the central Alberta rocks contain only minor amounts of organic detritus, ranging from 0 to 2.8 per cent for the siltstones and claystones listed in table 3. If the rocks are grouped by formations, the following average percentages are obtained:

	Organic carbon
Belly River (7 samples):	1.13
lower Edmonton (15 samples):	0.85
upper Edmonton* (25 samples):	0.58
Paskapoo (14 samples):	0.34
Brazeau (10 samples):	0.78

*probably includes basal Paskapoo samples - see table 1

The data suggest decreasing organic carbon content from older (Belly River) to younger (Paskapoo) strata, although the content rises again in the Brazeau Group (Edmonton-equivalent?) samples from the Foothills.

In thin sections, organic carbon appears as disseminated flakes or elongate "partings" usually lying parallel to the bedding (Plate 9, Fig. 1; Plate 11, Fig. 2). It appears to have undergone considerable alteration, for most of it resembles coal when viewed in hand specimens or thin sections. Also, a few samples (Belly River siltstones of the CH8 series) contain, in addition to small flakes of coal, numerous translucent, amber-colored, isotropic patches believed to be resinous bodies of organic origin. There is no apparent relation between organic carbon distribution and grain size as suggested by Pettijohn (1957): it is equally abundant in siltstones and silty claystones in the central Alberta rocks.

Calcite and siderite are the most common carbonates in the central Alberta rocks, with calcite predominating. The sample distribution of these constituents (Table 3, Column 10) is highly erratic: most samples (52 out of 71) contain no chemically detectable amounts, whereas the remainder contain from 0.3 to 11.0 per cent by weight. However, these data do not accord entirely with thin section observations (Table 4, Column 21) from which some of the samples (e.g. MYC-1) obviously contain detectable amounts of carbonates. The discrepancies presumably are partly due to the erratic distribution of carbonates even at the hand specimen or thin section level, and partly to the poor precision in the chemical technique (see above). This phenomenon also is apparent in outcrops, where hard carbonate-cemented lenses are interbedded with soft uncemented or clay-cemented sandstones and siltstones.

In thin sections carbonates appear as scattered small "grains," some of which are replacements of silt particles, and as irregular patches and dendritic patterns of presumably authigenic origin (Plate 3, Figs. 1, 2). As such, they are the only visible authigenic "cementing" agents in the rocks and where abundant greatly enhance the strength of the rocks. In this connection, some of the rocks also may contain substantial amounts of silica cement, although it cannot be detected or identified as such in thin sections of conventional thickness. For example, the Paskapoo siltstone from Shiningbank Ridge (SHR-1) may be silica-cemented in view of its resistance to breakdown by freeze-thaw action and of the existence of a strong quartz reflection on the X-ray diffraction pattern.

Small amounts of pyrite are present in most of the rocks, being especially common in those with a high proportion of organic matter. It is observed in thin sections as small opaque flecks or irregularly shaped growths up to 2 to 3 mm in size (Plate 12, Figs. 1, 2).

Soluble Salt Composition

Soluble salts present in clays or fine-grained rocks affect the adsorbed ion complex and the electrolyte in the pore water system. The types and concentrations of cations that make up the salt content depend, among other factors, on the salt content of the original depositional medium and the movement and chemistry of subsequent groundwaters. The influence of cation type and concentration on such properties as plasticity, strength, compression, etc. is well documented, e.g. Grim, 1962; Thomson, 1963; Locker, 1963; Mead, 1964; Kenney, 1967.

The total cation exchange capacities (C.E.C.), types and quantities of adsorbed cations, and concentrations of soluble salts in the fine-grained central Alberta rocks were determined by flame photometer and titration procedures on solutions obtained from leaching powdered air-dried material. With the flame photometer, a value for the total salt content was determined by finding the amounts of sodium, potassium, calcium, and magnesium present. The titration procedures provided a value for the cation exchange capacity. The concentration of salts in the pore water was taken as the difference between the cation exchange capacity and the total salt content. The error associated with the flame photometer determinations is in the order of 1 to 3 per cent; the titration error is not known but may be assumed to be approximately 4 to 6 per cent (Locker, 1963).[3]

Results

The results of the cation analyses (Table 3, Columns 11-15)[4] show that calcium, sodium, and magnesium in that order of abundance are commonly present as adsorbed ions in the pore water of the Alberta rocks. Potassium is found only in negligible quantities. If the rocks are grouped by formations, the following average values in milliequivalents per 100 grams of air-dried soil are obtained (excluding four samples listed as "bentonites" in table 3):

	Na^+	Ca^{++}	Mg^{++}	PWS	CEC	Mont*
Belly River (7 samples):	12.4	16.5	5.1	6.0	28.8	19.5
low. Edmonton (13 samples):	9.4	33.2	9.9	12.1	41.2	27.0
upp. Edmonton** (25 samples):	11.6	34.4	6.8	21.7	31.8	17.4
Paskapoo (14 samples):	2.5	37.4	9.2	22.6	27.1	6.9
Brazeau (8 samples):	5.3	29.5	9.4	15.5	27.5	8.9

*per cent montmorillonite - table 3, column 5; **probably includes basal Paskapoo samples - see table 1

From these data, it appears that the cation exchange capacities of the rocks are associated with the montmorillonite content, being highest in the Belly River and Edmonton Formations in the eastern part of the study area. Conversely, the pore water salt contents increase from older to younger strata of the Plains, dropping somewhat in the folded Brazeau Group (Edmonton-equivalent?) rocks of the Foothills.

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[3] The above procedures do not distinguish between cation types adsorbed and those actually present in the pore water (i.e. the values in table 3 are for the total cation complex). To evaluate only the electrolyte, excessively high pressures, perhaps in the order of 3000 to 4000 psi, would be required to expel the pore water.

[4] Performed by Geology Division personnel, Research Council of Alberta.

The distributions of exchangeable cations are less consistent with respect to formations, rock types, and localities. The sodium content is higher in the rocks of the eastern area (Belly River and Edmonton Formations), where it is associated with higher montmorillonite content, whereas calcium content is low in the Belly River rocks but uniformly higher in the other formations. Magnesium also shows no obvious relationship with montmorillonite content, following the distribution of calcium except in the upper Edmonton-basal Paskapoo samples in the central part of the area.

Inspection of data in table 3 shows that substantial variation in soluble salt composition and properties exists both within formations and within individual sampling localities. For example, the CH2 and CH3 sets of samples, both within the City of Edmonton area (and also the lower part of the Edmonton Formation) contain bentonitic claystones with entirely different exchangeable cation complexes. At other localities (CH4, CH5), the sodium content tends to increase at depth, a situation that indicates strong local control on the type and distribution of soluble salts, probably associated with local leaching and redistribution by groundwaters. Obviously, in the light of these examples, any apparent regional areal or stratigraphic trends in the kinds and distribution of soluble salts in the fine-grained rocks of central Alberta must be treated with caution.

Structures

Structures of sedimentary rocks are textural or compositional inhomogeneities usually visible at the hand specimen or megascopic level. They can be classed as:

(1) primary (or depositional)

(2) secondary (or postdepositional) $<\begin{array}{l}\text{early}\\ \text{late}\end{array}$

Primary structures are those produced during deposition, such as bedding, laminations, and various types of ripple and flow structures. Secondary structures are produced by organisms, physico-chemical agencies, or tectonic forces after deposition and can be classified into two groups. Early diagenetic structures are formed while the sediment is still in a soft state; examples are slump structures, burrow structures, and various types of nodules. Late secondary structures are those formed by tectonic forces during the final stages of diagenesis, or by the release of overburden pressures during uplift and subsequent erosion of the rock mass. They include such features as fissility, faults and joints, and fissures.

Primary Structures

Of particular interest to the engineer are various types of physical discontinuities in siltstones and claystones associated with bedding phenomena. In most sedimentary rocks bedding is manifested by the presence of lamination, i.e. segregation of clastic or chemical constituents on the basis of compositional and textural differences. Laminae, which are bedding units less than one centimeter thick, appear to be of two main types in fine-grained rocks:

(1) alterations of coarse and fine particles (silt and clay);

(2) alterations of material of different composition, (quartz and organic debris, calcium carbonate and quartz silt, etc.).

Laminae probably are due to differential settling rates of the various constituents associated with local fluctuations in conditions of deposition. Some may be associated with a yearly climatic cycle in the same way as varved clays (Pettijohn, 1957), although the absence of laminae is more remarkable than the laminae themselves, for only the existence of very uniform sedimentation over a long time will produce a structureless sediment.

Primary structures in the fine-grained rocks of central Alberta are reported in table 4, columns 6 to 8. Laminae, which are found in the majority of the materials studied, are reported as either faint or strong, depending on their definition. In many of the rocks, laminated structure is defined by the presence or absence of organic matter, which if present imparts a dark color, e.g. plate 4, figure 1; plate 9, figure 1. The individual particles or lenses of organic material are generally oriented parallel to the bedding but may cut across it in some cases, e.g. plate 11, figure 2. It may be reasoned that the smaller particles of organic matter settle out in conjunction with the detrital grains and align themselves parallel to the bedding surfaces during deposition or compression, whereas longer lenses or "partings" of organic matter, which originally may have been short tree branches or plant fronds, have settled in a random fashion and resisted realignment during compression. Hence, these materials cut across the apparent bedding planes of some rocks.

Laminae which are developed by variations in grain size (Plate 8, Fig. 1) in conjunction with variation in clay and organic content are present in numerous samples (Plate 8, Fig. 1; Plate 9, Fig. 1; Plate 12, Fig. 1). These features may be explained by local fluctuations in the influx of sediment-laden waters due to storms or seasonal factors.

Some laminae can be attributed to both primary (depositional) and secondary (diagenetic) effects. Laminae developed by alternation of silt and authigenic calcium carbonate are present in a few samples but are not clearly defined. In such cases carbonates are present as subovoid patches composed of finely crystalline "concretionary" material (Plate 3, Fig. 1), as irregularly concentrated, optically continuous patches filling intergranular areas (Plate 3, Fig. 2), or as disseminated patches of cement. Whether or not the distribution of carbonate structures constitutes a "laminated" structure depends upon the scale of study, i.e. a lenticular patch of carbonate-cemented material may appear as a laminated structure in hand specimen but irregular if viewed in thin section.

A particularly interesting type of lamination is that developed by thin, irregular partings of montmorillonite in six specimens. For example, the specimen in plate 11, figure 1, shows a one millimeter thick parting of well-oriented montmorillonite parallel to the bedding with a neck or plug extending down from the base of the parting into the underlying material. The vertical neck of this parting appears to be an infilling of montmorillonite into what may have been a burrow structure or dessication crack. The last-named structure requires the following sequence of events: a subaerial plane of freshly deposited sedimentary material, drying and cracking of this surface, and finally the filling of the cracks by volcanic ash deposited subaerially or subaqueously. The ash subsequently has altered to form a thin layer of pure montmorillonite, which with increasing thickness would be called a bentonite bed on a megascopic scale.

Pellets, which appear as small, rounded aggregates of clay, often highly oriented, impart a primary structure to a number of samples (Plate 10, Fig. 1). Pellet formation has been attributed to the action of water currents (Pettijohn, 1957), but the large size and irregular shape supports a local origin. That is, they probably have been derived from the breakup and redeposition of nearby clayey sediments, temporarily exposed to drying and hardening, with a minimum of abrasion and sorting.

"Brecciated" structures, as illustrated in plate 10, figure 2, are composed of angular (brecciated) fragments of clay-sized material which can be distinguished from the surrounding clay matrix by differences in shape and texture, such as a distinct change in the degree of direction of preferred orientation of the enclosed clay particles as compared to that of the clay matrix. These materials are susceptible to cracking at the fragment borders as illustrated in plate 10 and when subjected to wet-dry cycle tests, show a preference for the matrix to break up first and the fragments later. The origin of some of these fragments is debatable but the following mechanisms may be considered:

(1) Large fragments of volcanic debris or glass were carried to the depositional area by rivers and subsequently altered. However, the strong orientation of the clay minerals in the breccia fragments refutes this hypothesis, for in other samples composed of altered volcanic glass with remnant shard texture, the clay matrix is not oriented.

(2) The fragments may be "shale" detritus from the original source area to the west but a relatively soft rock of this nature would not retain its angularity or inordinately large size during transport.

(3) A more realistic hypothesis attributes the origin to dessication of freshly deposited subaerial sediments to form irregular angular

> fragments which, in turn, were reworked and buried by later influxes of fine sediment. Dessication must have been severe enough to impart sufficient strength to the fragments to allow them to maintain their angularity during the relatively short reworking process. With increased amount of transportation and erosion, such fragments grade into rounded pellets described above.

Homogeneous, i.e. structureless, rocks are present, at least as observed within the areal extent of the thin sections (approximately 2 x 3 cm), although the bulk of the specimens show some evidence of primary structures.

Secondary Structures

Early Diagenetic Types

Secondary structures believed to have developed in the early stages of diagenesis in the fine-grained rocks of central Alberta include slump features and ironstone nodules, observed in both hand specimens and thin sections.

Microslump structures are found in several samples, an example of which is shown in plate 12, figure 1. The slumping and rotation of the small blocks are emphasized by the relative displacements of laminated organic matter (dark colored). It is of interest to note that this slump feature is comparable in character to the massive slumping which occurs in Edmonton Formation strata along the valley walls of the North Saskatchewan River in the eastern part of the study area, i.e. it is a block movement that has left a relatively steep scarp and has slipped on a horizontal lower boundary. The microscopic fault planes are filled with material comparable in size and composition to that of the ambient material; a flow texture comparable to that described by Carozzi (1960) is found in these cracks. The silt particles are aligned parallel to the walls of the crack, and when the structure is viewed under crossed nicols, the clay matrix also appears to follow this pattern. Slump structures and flow textures may be considered to characterize sedimentary deposits that have been submitted to alternating periods of dehydration and wetting.

"Swirly" structures (Plate 2, Fig. 2) also may be a form of flow structure. The swirly arrangement of montmorillonite aggregates is no doubt due to slight flow of freshly formed montmorillonite.

Iron-bearing concretions ("ironstone" nodules) which appear as pellet structures in thin sections are commonly found in the soft rocks of central Alberta. They range in size from fractions of an inch to a foot in diameter and may be found collectively in bands referred to as "clay-ironstone" beds. They are believed to be composed of segregations of iron minerals (mainly siderite and iron oxides such as geothite) and clay minerals, which formed during or shortly after deposition as a product of diagenesis (Krumbein and Sloss, 1951; Carozzi, 1960).

Late to Postdiagenetic Types

Fissility, which is the ability of rocks to split into sheets along certain preferred planes (usually parallel to bedding surfaces), is a structural feature that forms one of the bases for the classification of fine-grained clayey rocks. It has been attributed to parallel orientation of the platy constituents of the rocks (micas, clay minerals, organic matter), accentuated by compaction and possibly concomitant recrystallization (Pettijohn, 1957). Thus, although a tendency towards fissility is inherent in certain rocks (especially laminated ones) from the outset, the property usually is best developed during the later stages of diagenesis, becoming quite noticeable in partly recrystallized rocks of metamorphic origin (slates, schists).

Ingram (1953) recognized three major groups of breaking characteristics in fine-grained sedimentary rocks: massive, flaggy, and flaky. He also noted the following features with respect to fissility:

(1) fissility is associated with parallel arrangement (orientation) of clay particles;

(2) fissility increases with an increase in organic matter;

(3) cementing agents decrease fissility;

(4) weathering increases fissility by the removal of cementing agents and by the expansion of clay particles.

Well-developed fissility is uncommon in the fine-grained rocks of central Alberta, most of which therefore can be classified as siltstones or claystones. A crude form of fissility may be observed in certain lithologic units in outcrops, normally associated with laminae rich in organic matter, but weathering of soft rocks is known to produce this phenomenon (Ingram, 1953). Fissility, as formed by weathering, should be considered an induced property of the rocks and not an inherent characteristic of the material for classification purposes. The lack of abundant well-oriented clay minerals plus the presence of carbonate cement in some beds no doubt contributes to the paucity of fissility.

Associated with fissility in fine-grained sedimentary rocks are various types of physical discontinuities that manifest themselves as cracks or gaps or potential gaps in the rock framework. Some of the more common types of physical discontinuities are classified in table 5, together with the presumed causes and effects. Bedding and fissility surfaces are listed as potential rather than actual breaks, often serving as the loci for fractures developed by tectonic forces during compression and uplift of the rock mass.

Table 5. **Types of Physical Discontinuities Commonly Observed in Sedimentary Rocks**

Type	Structure	Attitude	Major Causes
Primary (during deposition)	Bedding planes	Parallel to depositional surface	Variations in competence of transporting agents; variations in sediment type supplied.
Secondary (during diagenesis or subsequent rebound)	Fissility surfaces	Generally parallel to bedding	Parallel orientation of platy particles; presence of organic matter.
	Syneresis cracks	Random	Shrinking and swelling of colloidal matter.
	Fissures	Variable	Tectonic forces; dessication; rebound; weathering.
	Faults and joints	Variable	Tectonic forces.

Fissuring, in general, refers to the network of small hairline cracks developed in many partially indurated claystones and siltstones. These cracks may be microscopic or macroscopic, dividing the soil mass into roughly equidimensional fragments from a few feet to a fraction of an inch in dimension.

Fissures may develop along planes of weakness in a soil or soft rock mass subjected to rebound. Because rebound occurs perpendicular to the plane of the distributed load which was removed, fissures may develop parallel to a planar surface in a level area or parallel to valley walls where material has been removed, e.g. by a degrading river. However, the stresses which develop the fissures seldom will be uniformly distributed throughout the mass. Complex mineralogy results in nonuniform swelling, which, in turn, produces differential movement. Also, poorly bonded regions will succumb to rebound stresses quicker than strongly bonded areas; consequently, nonuniform deformation will occur. Thus, the direction of fissure planes will follow the direction of load removal in a general manner, although to some extent modified by the inherent characterisitics of the soil mass.

In conjunction with the development of fissures by rebound, the destructive powers of weathering contribute to fissuring. Variations in water content and temperature subject the soft rock to wet-dry cycles (shrinkage and expansion) and freeze-thaw cycles. Both of these actions cause displacement and ultimately fissuring in near-surface materials. The visual effect of weathering is often marked by discoloration of material adjacent to the fissures, which may be attributed to slight mineralogical changes such as alteration of cementing agents. The depths to which weathering affects the material may be limited to 30 to 40 feet, whereas fissuring due to rebound may extend to depths of a hundred feet or more.

All of the fine-grained rocks examined during the course of the study exhibit complex fissure patterns in outcrops. In addition, the rocks of the Foothills region exhibit large-scale faulting and widespread jointing, which features are outside the scope of this investigation.

Detailed studies of fissure orientation were not made in the field, but it was noted that the degree of fissuring decreases in an east-to-west direction, as indicated by an increase in "fragment" size toward the west. In fact, in the eastern portion of the study area much of the near-surface mass exposed in outcrop has either reverted to a soil or is very close to this condition. The fine-grained rock recovered from coreholes also exhibits considerable fissuring up to depths of 10 to 20 feet below the upper surface of the bedrock. These fissures are generally badly stained by iron oxides, which indicates that some weathering of these rocks has occurred either before or after Pleistocene glaciation.

Fissures or cracks noted in thin sections are considered as artificially induced structures because most appear to have developed during thin section preparation. However, these cracks may reflect planes of inherent weakness within the sample, i.e. they form along inherent potential fissure planes of the rock. The distribution of these cracks is presented in table 4, columns 10 and 11, along with information on their attitude and degree of staining. About 75 per cent of cracks are parallel to the bedding; this indicates that the presence of laminated clayey and organic matter constitute planes of weakness that control fissuring (Plate 8, Fig. 1). Many of the cracks have developed in laminations with a high clay content, in particular montmorillonite partings (Plate 9, Fig. 2; Plate 11, Fig. 1). Very few cracks are found within laminations of high silt content or in a direction perpendicular to the bedding. The presence of staining (believed to be due to iron oxides) adjacent to about one-third of the cracks indicates that at least some of these cracks existed *in situ* as microfissures. Fissuring, therefore, is a common form of discontinuity in the fine-grained rocks of central Alberta on both a macroscopic and microscopic scale.

In contrast to the more regular fissure patterns found in laminated rocks, the brecciated and shard-textured rocks exhibit random cracking. The cracks are found throughout the "matrix" of the rocks, but extend around the shards or breccia fragments which indicates that these features have a higher intrinsic strength. Random cracking patterns develop blocky or nugget-type fragments which may be observed in the field or as the product of wet-dry cycle testing in the laboratory.

A peculiar form of cracking found in microscopic partings or pockets of montmorillonite (Plate 2, Fig. 1) is attributed to syneresis. Syneresis is a colloidal process whereby the particles draw themselves together under the action of attractive forces and expell some of the pore water; this process may be responsible for fissures in London Clay (Skempton and Northey, 1952). These concentrated pockets of montmorillonite probably were colloidal gels during the earlier stages of formation. The concentric ring pattern illustrated in plate 2 may correspond to the rearrangement and adjustment of the colloidal particles during wetting and drying cycles of the fresh deposit, i.e. syneresis cycles.

In summary, widespread fissuring in the near-surface fine-grained bedrock of central Alberta is in part a result of stress release (rebound) which occurred in conjunction with and following the erosion of up to 2000 feet of Tertiary sediments (Rutherford, 1928). The stress cycle (or perhaps cycles) imposed by the advance and retreat of thick ice sheets during Pleistocene time also affected the development of near-surface fissures. The susceptibility of montmorillonite to extensive volume change (shrinking and swelling) likely established conditions of nonuniform stress distribution that led to the development of fissures. In addition, other processes during the geologic history of the rocks, such as periglacial phenomena, may have contributed to the present highly-fissured nature of the fine-grained rocks of central Alberta.

Plasticity

Plasticity, defined as the ability of a material to deform under stress without rupture, may be expressed by quantitative parameters, i.e. Atterberg limits. The plasticity characteristics of soils are used for classification and identification purposes as well as indices of soil behavior.

The plasticity characteristics of a soft rock may vary widely in accordance with the kinds and percentages of clay minerals present, and the types and concentrations of adsorbed cations and cations in the pore water (Grim, 1962; Seed *et al.*, 1964a). The degree of influence of these factors is variable, but extremely high plasticity values are found in clays composed of pure montmorillonite with a sodium adsorbed ion complex and zero salts in the pore water. Many soft rocks of the Great Plains region of North America exhibit high plasticity characteristics due to the high montmorillonite content.

The liquid limits and plastic limits were performed in accordance with A.S.T.M. designations D-423-61T and D-424-59, respectively, with the following exceptions:

(1) the soil was not air-dried but rather broken down from the natural water content by a freeze-thaw procedure (samples received in air-dried state were subjected to the same treatment);

(2) alterations in the water content required to change the consistency of the soil for liquid limit determinations were allowed to come to equilibrium for a minimum period of 24 hours;

(3) the Casagrande grooving tool was used in the liquid limit test.

Air- or oven-drying of soils will generally cause a decrease in the liquid limit of a soil due to either irreversible aggregation of colloidal material or irreversible dehydration of organic matter (Yong and Warkentin, 1966). However, as the fine-grained rocks described here were broken down from natural water content by freeze-thaw cycles, the liquid limits should be representative of the natural state.

Results

The Atterberg limits and associated indices for the fine-grained rocks of central Alberta are given in table 3, columns 17 to 21. Activity index (A) values were determined by dividing the plasticity index (I_P) by the per cent clay-sized materials (Skempton, 1953), and the liquidity index (I_L) by dividing the plastic limit subtracted from the natural water content by the plasticity index.

All the fine-grained rocks from central Alberta exhibit plasticity except those from Lower Cretaceous beds at Cadomin in the Foothills (CAD samples) and a highly organic sample (ROB-1) from the Foothills region near Hinton. The range of plasticity values is high, as might be expected from rocks with such a wide variation in clay content and mineralogy (sandy siltstones to bentonite). The data in table 3 and the plasticity chart (Fig. 9) indicate that 53 per cent of the samples can be classed as inorganic clays of high plasticity, 26 per cent as inorganic clays of medium plasticity, 14 per cent as organic or inorganic silts and silty-clays of medium plasticity, and 6 per cent as organic clays and silts. The low number of "organic" rocks seems to conflict with the abundance of organic matter in them. However, the organic material in the soft rocks of central Alberta has undergone considerable alteration to an inactive coal-like substance which does not appear to affect plasticity.

The natural water contents (Table 3, Column 24) are less than the plastic limits in all but one of the samples and are believed to be less than the shrinkage limit in at least 90 per cent. (Shrinkage limits were not determined by laboratory tests but may be approximated by extending a straight line, parallel to the A-line in figure 9, through the point representing the soil on the plasticity chart to cut the W_L-axis at the water content of the shrinkage limit.) With such low natural water contents, the liquidity indices, with one exception, are all zero or negative and drop to values as low as -2.58.

If the rocks are grouped by formations, the following average values are obtained for plasticity and associated indices (excluding four samples listed as "bentonite" and one highly organic sample [ROB-1] in table 3):

	I_p	A	I_L	Mont*
Belly River (7 samples):	50.8	1.48	-0.10	19.5
lower Edmonton (13 samples):	59.2	1.50	-0.31	27.0
upper Edmonton** (25 samples):	46.3	1.22	-0.84***	17.4
Paskapoo (14 samples):	24.3	1.20	-0.93	6.9
Brazeau (7 samples):	21.1	0.91	-1.40	8.9

*per cent montmorillonite - table 3, column 5; **probably includes basal Paskapoo samples - see table 1; ***data available for only ten samples

Obviously, rocks from the eastern part of the area (Belly River and Edmonton Formations) are the most highly plastic materials, which would be expected from their correspondingly higher montmorillonite contents. Similarly, average activity and liquidity index values are higher in the Edmonton and Belly River Formations, although individual samples exhibit much greater variation than the average formational values indicate.

The relationship between liquid limit and plasticity index is plotted on the plasticity chart in figure 9, which was devised by Casagrande (1948) on the basis of the analysis of plasticity characteristics of many soil types of different geologic origins and mineral compositions. Casagrande showed that soils having a common geological origin plot along a line parallel with the empirically derived A-line defined by the equation, $I_p = 0.73 \ (W_L\text{-}20)$. The "best fit" line for the relationship between the liquid limit and the plasticity index of the fine-grained rocks of central Alberta is defined by the equation, $I_p = 0.91 \ (W_L\text{-}23.39)$ which is not parallel to the A-line. This deviation may be attributed to differences in the "origin" of the mineral constituents of the rocks despite the fact that they have a common geographical source of sediments and were deposited in similar depositional environments (nonmarine). That is, the common clastic constituents (quartz, feldspars, micas) are erosional products from similar parent rocks, but the associated clay minerals have been in large part derived from post-depositional alteration of volcanic detritus. In addition, the clay content has undergone the later effects of diagenesis, most noticeable in the Foothills where much of the original montmorillonite content may have altered to illite and chlorite (Carrigy and Mellon, 1964). Thus, the best fit line on the plasticity chart would not be expected to fall parallel to the A-line as suggested by Casagrande (1948).

Plots of plasticity index *versus* clay content for a specific soil type produce a straight line which extrapolates back through the origin (Skempton, 1953). In a similar plot (Fig. 10) the Alberta rocks show a wider scatter of points through which a number of such lines could be drawn, each of which would represent a

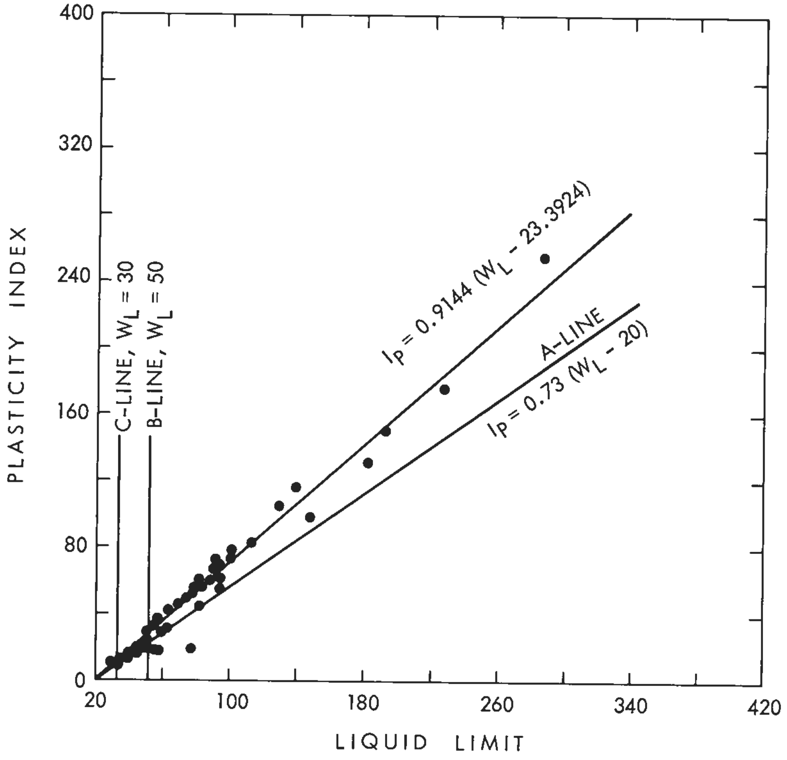

FIGURE 9. Plasticity chart, fine-grained rocks of central Alberta.

specific activity. This diagram emphasizes the variations in mineralogical composition and the associated ion complexes that exist in these rocks, which fall in approximately equal numbers into three broad groups – active, normal, and inactive – based on criteria devised by Skempton (1953). The majority of samples from the eastern part of the area (Belly River and Edmonton Formations) are normal to active rocks, whereas most from the western part of the area including the Foothills, (Paskapoo Formation and Brazeau Group) are inactive to normal rocks.

Seed *et al.* (1964a) presented plots illustrating many interesting plasticity relationships, among which is a plot of liquid limit *versus* activity for different fabricated soil types with variable clay contents. They noted that for any specific clay content, a unique relationship exists between activity and liquid limit regardless of the kinds of clay minerals present (montmorillonite, illite, and kaolinite). A similar relationship exists for the fine-grained soft rocks of central Alberta (Fig. 11), although it is necessary to accept a range of clay contents for each curve due to the

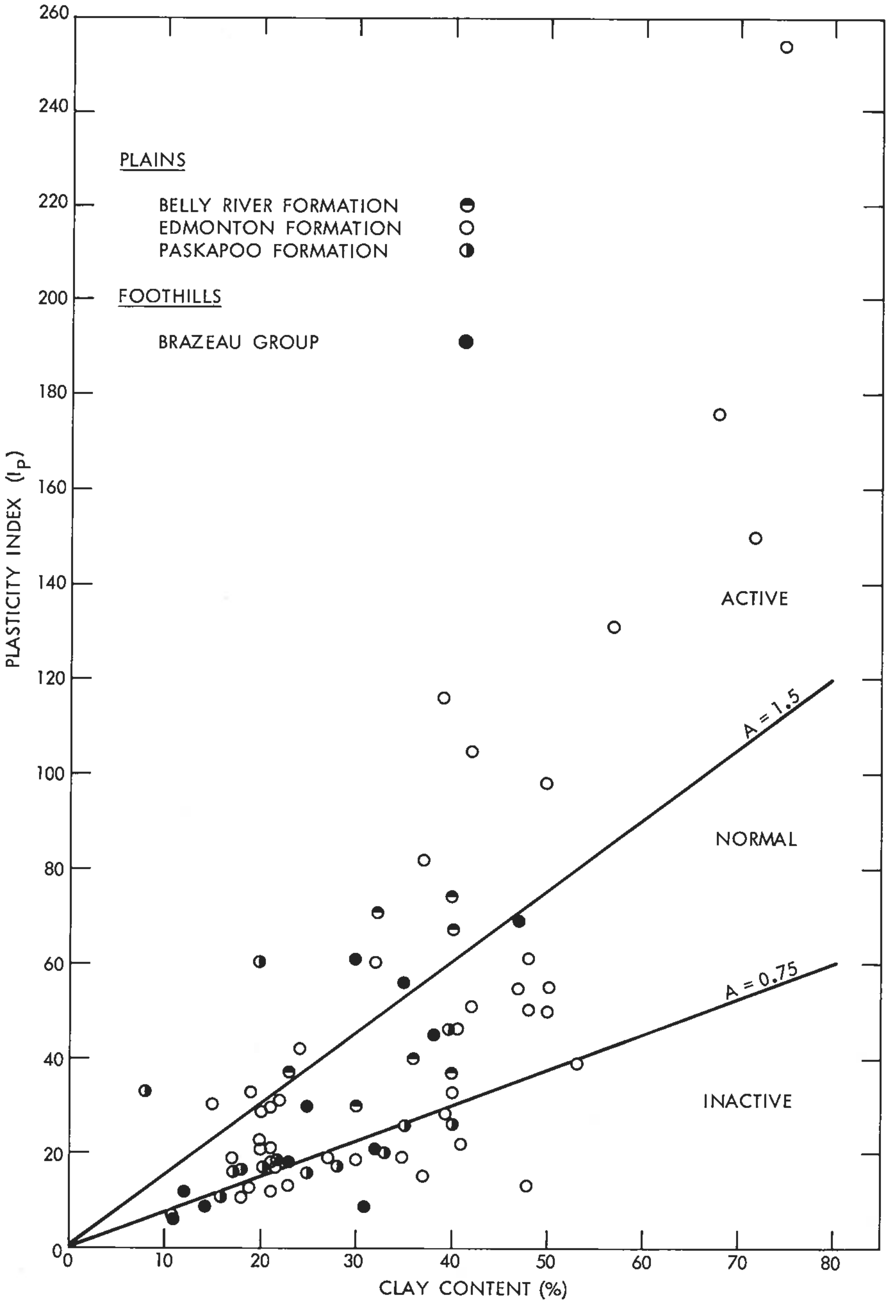

FIGURE 10. Relationship between plasticity index and clay content, fine-grained rocks of central Alberta.

extreme variability in the clay contents of the samples. The degree of scatter is acceptable in view of the fact that the samples are not "pure" systems but are natural mixtures of many minerals which are susceptible to the effects of physicochemical phenomena (e.g. electrolyte concentrations.)

The distributions of clay, montmorillonite, and sodium ion contents show excellent correlations with the plasticity parameters, discussed in the next section of the report.

Bulk Density and Related Properties

Density is defined here as total unit i.e. the total weight of a naturally occurring sample divided by its total volume. Densities of fine-grained sedimentary rocks generally vary from approximately 105 pcf to 170 pcf in accordance with the degree of induration. However, densities also are subject to changes caused by such factors as weathering and rebound, which tend to counteract the effects of compression and other diagenetic agencies. Related properties are void ratio and natural water content of the rocks, values of which are normally closely related to corresponding density values.

The densities of the central Alberta rocks were determined by direct measurements of the sample weights, the corresponding volumes being found by mercury immersion.[5] Natural water contents were determined from the loss of weight incurred by drying samples to 110° C. Void ratios subsequently were calculated from the relationship among bulk density, specific gravity, and water content of each sample.

Results

The results of density and water content measurements and void ratio determinations are given in table 3, columns 22 to 24. The three properties are highly correlated (Table 7), and it is obvious that both water content and void ratio can be predicted from measurements of bulk density alone.

The fine-grained rocks of central Alberta exhibit wide variation in bulk density values, ranging from 103 pcf for a bentonite from the Edmonton Formation in the eastern part of the area to 160 pcf for "shale" from the Lower Cretaceous beds in the Foothills at Cadomin (Fig. 1). In general, there appears to be a systematic increase in bulk density from east to west across the study area as indicated in figure 12, where bulk density values are plotted against projected

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[5] Air-dried corehole samples were not included in the bulk density study.

distance across the strike of the beds from an arbitrary datum.[6] Two linear regression lines are illustrated in figure 12: one for corehole samples and another for outcrop samples. Each sample also is classified according to the gross amount of montmorillonite present. Six samples (Fig. 12) were excluded from the regression analysis because they yield bulk density values well below the expected values for those locations. Five of these are highly montmorillonitic rocks (bentonites or bentonitic claystones), which might be expected to yield lower densities, except that other highly bentonitic samples from the same and other localities fit the general trend. The reasons for these deviations are unknown, but the apparent wide discrepencies among the density values at any one location demonstrate that distance is only one of several factors associated with variation in rock density and that a high degree of correlation cannot be expected. Significance of other factors, including montmorillinite content, is discussed in the next section of the report, which deals with multivariate analysis.

If the wide local variations in sample densities are ignored, the regression analyses (Fig. 12) illustrate three distinct relationships concerning the densities of the fine-grained rocks of central Alberta:

(1) Density increases systematically in an east-to-west direction, i.e. towards the margin of the Rocky Mountains;

(2) A difference in density exists between corehole and outcrop samples, with corehole samples having greater average densities;

(3) A systematic decrease in the density difference between outcrop and corehole samples exists in an east-to-west direction.

Similar trends are evident from examination of natural water contents and void ratios, except that these values decrease in an east-to-west direction as bulk density increases.

Why does density increase in an east-to-west direction? Variation in density cannot be correlated with geologic age, for the oldest rocks (Upper Cretaceous) that might be expected to be the densest are less dense than the younger rocks (Tertiary) to the west. The geologic history of the strata provides some possible explanations.

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[6] The distance for each sample location has been projected and measured with respect to a line that is perpendicular to the strike of the folded Foothills belt (Fig. 1). The origin of the distance scale in figure 12 is an arbitrarily chosen point on the line approximately 20 miles east of Cadomin. Within the Foothills the distance scale has been expanded by a factor of 2 to compensate for crustal foreshortening.

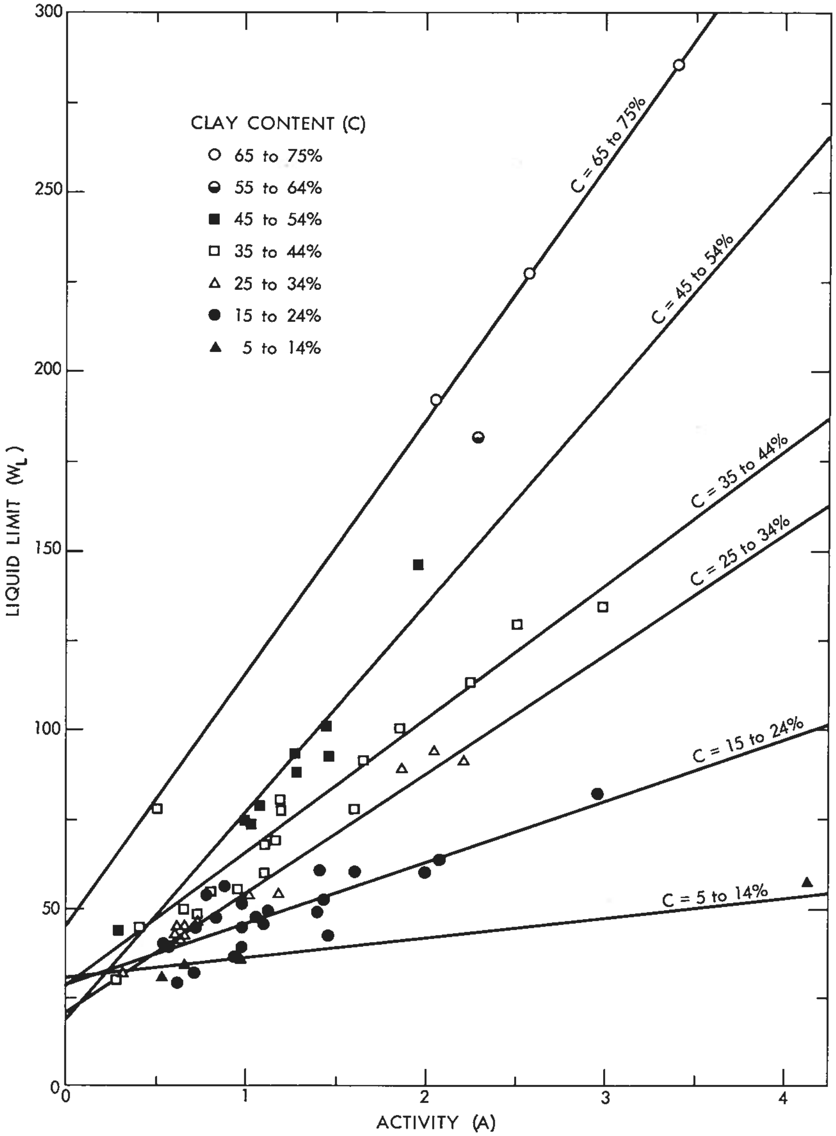

FIGURE 11. Relationships among liquid limit, activity, and clay content, fine-grained rocks of central Alberta.

By the end of the early Tertiary time, the wedge-shaped deposit of clastic sediments that thickens towards the west was subject to uplift and erosion which stripped off hundreds of feet of overburden (Fig. 4). However, since the tectonic

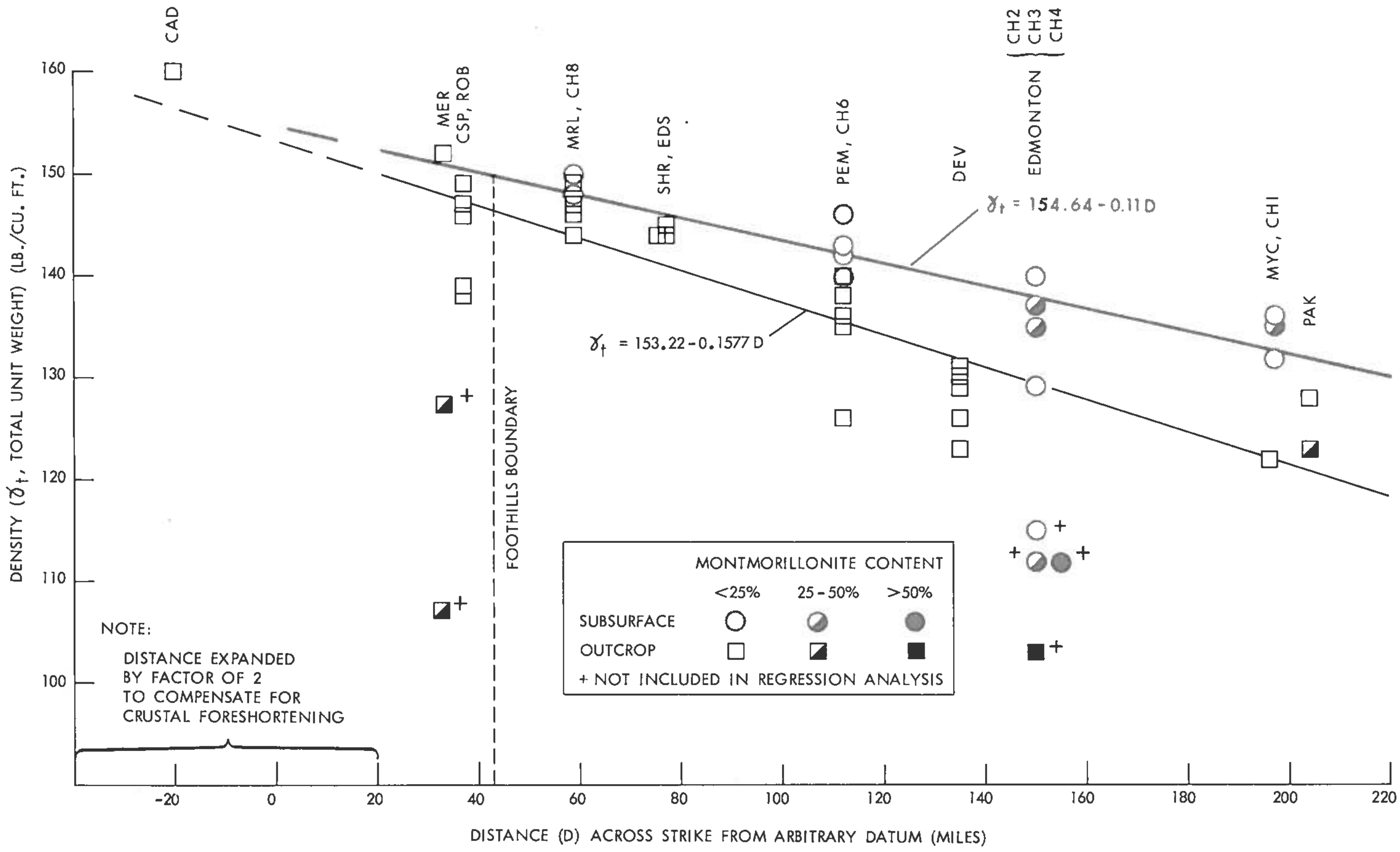

FIGURE 12. Relationship between bulk density and distance from Foothills boundary, fine-grained rocks of central Alberta.

activity which brought about uplift was centered in what is now the Rocky Mountains, it is likely that uplift and, consequently, erosion was the greatest in the west. Thus, beds which are at or near the surface today were once buried under successively greater amounts of sediments in a westerly direction towards the Foothills. Since density is related to overburden, it follows that the densities should increase in a similar fashion regardless of the age of the rocks.

In this connection the effects of Pleistocene glaciation on rock density are difficult to assess, if only because the actual ice loads which existed and the distribution of these loads are unknown. The effects of the loads imposed by the thick ice sheets depend upon the degree of induration of the rock mass at the time of glaciation. It is reasonable to assume that the rocks attained their present indurated state prior to glaciation. Hence, the least dense (or indurated) rocks in the eastern part of the study area (Edmonton and Belly River Formations) would be more likely to exhibit the effects of glaciation. Locally (Edmonton area) this is the case where bedrock has been gouged or contorted due to ice action, but there is little evidence to show to what depths such effects persist or whether any systematic variation in the distribuion of these effects exists. In summary, the permanent effects of glaciation and subsequent deglaciation on the physical properties of the near-surface Cretaceous-Tertiary bedrock formations are largely hypothetical.

In addition to the postulated effects of depths of burial and glaciation on the density of bedrock formations of central Alberta, the effects of "tectonic" forces must be considered. That these forces played a significant role in bringing the rocks to their present state of induration is suggested by the density of the sample from Shiningbank Ridge (SHR), north of Edson (Fig. 1). The density of this sample is comparable to that of the samples from outcrops on the Pembina River near Entwistle (PEM series). Both of these locations are at equal distances (across the strike of the rocks) from the Foothills, but because Shiningbank Ridge is an erosional remnant 1500 to 2000 feet above the general Plains level, the SHR sample should have a much lower density, if depth of burial is a major contributing factor. However, the rocks of central Alberta have been subjected to enormous horizontal compressive forces resulting from the tectonic activity which built the highly folded and faulted strata of the Rocky Mountains. It is probable that the effects of these same forces extended eastward into the apparently undisturbed strata of the adjacent Plains, although with diminishing intensity, with the result that rock density (or degree of induration) increases as the Foothills are approached. The similarity of the rock densities at Shiningbank Ridge and Entwistle, separated by about 1500 feet in elevation, suggests that these compressive forces were a major contributing factor to this and related properties of the rocks of central Alberta.

The effects of rebound, associated with the stripping of overburden during middle Tertiary to Recent times, on density are difficult to assess. The amount of rebound in the rocks depends, among other factors, upon the amount of overburden removed, the composition of the rocks, and the bond strengths between the particles of the mass. The amount of montmorillonite in the rocks, which is known to augment rebound, shows a tendency to increase towards the east. An increase in bond strength associated with diagenesis and which will hinder rebound, is evident towards the west. These two factors contribute to greater rebound, hence lower densities, towards the east. However, the amount of overburden removed, associated with a greater degree of rebound, is thought to have increased in a westerly direction, thereby counteracting the effects of composition and diagenesis. Because of the complexity of these interactions, the effect of rebound on density is uncertain.

The densities of outcrop samples should be lower than those of corehole samples because weathering action decreases the density by the destruction of bonds and the associated uptake of water (Varnes, 1950). For example, sample CH6-33, which was selected from just below the bedrock-drift contact in the Entwistle corehole (Fig. 1), has a density similar to outcrop samples (PEM series) from the same locality (Table 3, Column 22). Other samples from the same corehole, however, have consistently higher densities than nearby outcrop samples, presumably because they were not subjected to the same degree of pre-Pleistocene weathering as the sample at the top of the bedrock succession, beneath the drift.

In summary, the marked systematic decrease in differences between corresponding corehole and outcrop sample densities as the study area is traversed from east to west appears to be synonymous with a greater resistance to weathering and to mechanical "rebound" exhibited by the fine-grained rocks in this direction. This increased resistance to these factors in turn can be attributed to (1) the composition of the rocks, e.g. montmorillonite, a material susceptible to weathering, tends to decrease in amounts towards the west, and (2) to the increase of bond strength in a westward direction, as indicated by results of wet-dry cycle tests (Table 3, Column 25). (The danger of extrapolating the regression beyond the data, i.e. beyond the depositional basin, should be noted.)

Wet-Dry Cycle Tests

The reaction of fine-grained rocks to alternating cycles of wetting and drying can be used to evaluate the following interrelated properties:

(1) the degree of interparticle bonding, at least in a relative sense (Terzaghi and Peck, 1967); and

(2) susceptibility to weathering (Philbrick, 1950).

In addition, the results of wet-dry cycle tests are useful in evaluating the distinction between "compacted" and "cemented" rocks (Philbrick,1950) and the relationship between bond strength and energy.

For the tests described here, chunks of intact rock approximately 1 to 2 inches in size, obtained from outcrops and coreholes, were used without further preparation. Attempts to cut the samples to cubes proved futile because of uncontrollable breakage. Initially, the samples were immersed in distilled water for a period of up to 64 days to allow slaking. If the chunks disintegrated into soil particles during this period, the time required was noted; otherwise, the samples were subjected to alternate cycles of immersion in distilled water for 5 days and air drying at room temperature for 5 days. The samples were subjected to 5 such cycles of alternating wetting and drying (Philbrick, 1950) unless the sample broke down to 90 per cent soil particles first, in which case a rating was then assigned.

Each sample was assigned a rating from 1 to 20 depending upon the degree of breakdown, in accordance with a qualitative rating system devised by the writer (Table 6). The upper and lower limits, i.e. 20 and 1, are considered to represent

Table 6. Rating System for Wet-Dry Cycle Tests

Description of Residue		Numerical Rating
SLAKING		
Breakdown to at least 90%[1] soil particles within:	4 days	1
	8 days	2
	12 days	3
	16 days	4
	20 days	5
WET-DRY CYCLES		
Breakdown to at least 90% soil particles after:	1 cycle	6
	2 cycles	7
	3 cycles	8
	4 cycles	9
	5 cycles	10
Condition after 5 cycles		
50-90% soil particles		11
10-50% soil particles		12
66% 1/16 - 1/8 inch lumps:		
remainder smaller		13
remainder larger		14
66% 1/8 - 1/4 inch lumps:		
remainder smaller		15
remainder larger		16
66% 1/4 - 1/2 inch lumps:		
remainder smaller		17
remainder larger		18
badly cracked, or 2 to 3 lumps		19
intact		20

[1] Percentages based on volume.

true "rock" and true "soil," respectively, and those materials ("soft rocks") with intermediate values are considered to form transitional materials

Results

The results of the slaking and wet-dry cycle tests are presented in table 3, column 25. The tests show that the Alberta rocks vary widely in degree of breakdown, with ratings ranging from 1 to 20. Ratings of samples from the Belly River Formation in the eastern part of the area range from 1 to 7, of the samples from the Edmonton Formation (including basal beds of overlying Paskpoo Formation) in the central part of the area from 1 to 14, and of the samples from the Cretaceous and Tertiary beds in the western Plains and Foothills from 1 to 20. Four of the 50 samples tested broke down almost immediately when immersed in distilled water (wet-dry rating = 1); three of these samples, which are representative of true "soils," are from the Edmonton or Belly River Formations, and the remaining sample is a bentonite from the Foothills. At the other limit of the scale (wet-dry rating = 20) are "true" rock (shale) specimens from Lower Cretaceous strata in the Foothills.

If the rocks are grouped by formations, the following average wet-dry cycle ratings are obtained (excluding two bentonite samples from the Foothills, MER-1 and MER-2):

	W.D.R.	Mont.*
Belly River (5 samples):	4.6	19.2
lower Edmonton (10 samples):	7.1	27.4
upper Edmonton** (10 samples):	10.7	9.6
Paskapoo (13 samples):	15.2	6.6
Brazeau (7 samples):	11.4	6.7
Lower Cretaceous (3 samples):	19.7	-

*per cent montmorillonite - table 3, column 5; **probably includes basal Paskapoo samples - see table 1

Thus, there is a general increase in wet-dry cycle ratings from east to west, although the Edmonton-equivalent Brazeau Group rocks of the Foothills exhibit ratings lower than expected, possibly due to inherent compositional factors. This trend reflects in a sense an increase in the "bond strength" of the rock in a westerly direction, in which the swelling and shrinkage forces imposed by the wet-dry cycles are testing the inherent strength of the interparticle bonds. Bond strength of fine-grained "clayey" rocks is in turn a function of composition, especially the proportions and kinds of clay minerals present, and the nature of the adsorbed salts. In particular, the amount of montmorillonite present would appear to play a significant role in determining the overall bond strength or cohesiveness of a rock owing to that mineral's capacity to expand and shrink with change in water content. This indeed appears to be the case in comparing the wet-dry cycle ratings of the fine-grained central Alberta rocks: those of the eastern Plains (Belly River and lower part of the Edmonton Formations) contain significantly higher amounts of montmorillonite than those of the western Plains and Foothills, although the comparisons of average values given above indicates that clay mineral composition is not the only factor involved in evaluating bond strength. Other factors, including diagenetic effects, must contribute to the wet-dry cycle ratings (and hence bond strength) of the rocks, as discussed in succeeding sections of the report.

Both slaking and wet-dry cycle tests have been used to evaluate the susceptibility of fine-grained rock to weathering (Mead, 1936; Philbrick, 1950; Knight, 1963). Those Alberta rocks classed as "bentonites" in outcrop disintegrate rapidly when submerged in water in the laboratory (wet-dry cycle rating of 1); in outcrop these materials are usually mushy on the surface. However, further back from the weathered outcrop face, bentonites may be quite hard, and a pick may be required to dislodge fragments for analysis.

Other fine-grained rock types from central Alberta illustrate a general relation between wet-dry cycle ratings and their susceptibility to weathering processes in outcrops. Rocks from both the Belly River and lower part of the Edmonton Formations tend to break down within two cycles of wet-dry testing; in outcrops these rocks are very soft, and the derived talus is very fine and crumbly, having reverted to a soil-like material composed of a mixture of sand, silt, and clay particles. Further west, along the Pembina River in the central part of the study area, fine-grained rocks from the upper Edmonton-basal Paskapoo succession are noticeably harder, yielding talus slopes composed of fine rock fragments. In the Edson-Foothills area, the rocks break down into coarse fragments up to one-half inch in dimension after prolonged wet-dry testing or exhibit no reaction at all. In outcrops, these rocks appear hard and dense, especially in the Foothills, and yield talus composed of coarse, angular rock fragments up to several inches in dimension.

The wet-dry cycle test is often used (Philbrick, 1950) to distinguish between what Mead (1936) classified as compaction and cemented shales. Compaction shales are "soil-like" materials that have been compressed by the weight of overlying sediments and lack significant amounts of intergranular cements. Cemented shales are "rock-like" materials with significant amounts of cementing materials or strong bonds developed by recrystallization of the clay minerals. No sharp line of demarcation exists between these two rock types, for most fine-grained rocks are partially cemented and partially compacted. The simple weathering test (wet-dry cycle test) appears to be the procedure which most clearly reveals the coherent quality of a fine-grained rock. In discussing this test Philbrick (1950) states:

> "Those shales which are reduced by this process to uncohering aggregates of approximately grain-sized particles are compaction shales. Those which are entirely unaffected or reduce only to flakes are cemented shales. This test also indicates the behavior of the shale upon exposure to atmospheric conditions during construction."

On this basis all fine-grained rocks with a wet-dry cycle rating of 11 or less are considered as compaction rocks and those greater as cemented rocks. Thus, if an Alberta rock is classified as a compacted rock, at least 50 per cent of the sample breaks down to individual soil grains when subjected to the wet-dry cycle tests described above. If the test rocks are grouped by formations, they can be classified as follows:

	Number of Samples	
	Compacted	Cemented
Belly River (5 samples):	5	0
lower Edmonton (10 samples):	10	0
upper Edmonton* (10 samples):	4	6
Paskapoo (13 samples):	2	11
Brazeau (9 samples):	7	2
Lower Cretaceous (3 samples):	0	3

*probably includes basal Paskapoo samples - see table 1

The above grouping shows that of the fifty rocks tested, twenty-two are cemented, none of which are found in the eastern portion of the study area, and twenty-eight are compacted, fifteen of which are found in the eastern portion and thirteen in the western portion of the study area. The fine-grained rocks in the eastern half of the area revert to a highly fissured, overconsolidated clay upon exposure to the atmosphere, whereas the fine-grained rocks in the western portion generally appear as indurated rock fragments, the average size of which is dependent upon the strength of the bonds (as indicated by the wet-dry cycle rating).

STATISTICAL EVALUATION OF ROCK PROPERTIES

Analysis of Results

Statistical techniques have been used in the earth sciences for more than a quarter of a century, and their application is now universal in all branches of geology. However, in soil mechanics conventional statistical procedures are seldom used, in spite of the fact that geotechnical studies lend themselves to such treatment equally as well as studies in other fields. In this investigation several sets of samples were subjected to a variety of analytical techniques from which a large amount of data on the petrographic, chemical, and bulk physical properties of the shallow bedrock materials of central Alberta were generated. In all, information on twenty properties which lend themselves to a statistical evaluation was collected from outcrop and corehole samples, although not all samples were subjected to the complete series of tests and analyses.

The first step in the analysis of the data was to calculate on the University of Alberta IBM 360 computer the linear regression equation[7] for each pair of variables, together with the corresponding sample correlation coefficient. Plots or scatter diagrams of the values for each variable pair also were obtained from the computer plotter in order to detect any noticeable departures from linearity.

Although the linear regression equations yield worthwhile information for certain variable pairs, a more useful statistic in determining the degree of association between variables is the correlation coefficient, r (Table 7). This statistic has values ranging from -1 through 0 to +1, which indicate both the degree of association and correlation, (i.e. high or low, where ±1 is perfect correlation) and the type of association (negative or positive). Its "significance" in terms of probability theory depends on the number of samples involved, but in practice the value of r which can be accepted as an indicator of a meaningful degree of association between the two sample attributes depends on the field of study (Snedecor, 1956). For this study, the value of the square of the correlation coefficient, r^2, has been used to define the levels of association; as indicated below.

r	r^2	Degree of association
0.35	0.13	
		. . . . .low
0.50	0.25	
		. . . . moderate
0.71	0.50	
		. . . . high
1.00	1.00	

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[7] Equations from Neville and Kennedy (1964).

Table 7. Correlation Coefficients (r) for Textural, Compositional, and Physical Properties of Fine-Grained Rocks from Central Alberta

	Textures			Composition								Plasticity				Bulk Properties				Distance
	Clay	Q_{50}	Orien.	Mont.	Ill.	Na	Ca+Mg	PWS	CEC	Org.	Carb.	W_L	W_P	I_P	A	γ_t	e	W_N	WDR	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	--	-.71	.28	.75	.50	.66	-.13	.01	.30	.18	-.38	.78	.38	.78	.28	-.44	.34	.50	-.39	.37
2	-.71	--	-.20	-.35	-.52	-.33	.31	-.35	-.09	-.24	.47	-.39	-.11	-.40	.00	.21	-.22	-.24	.07	-.30
3	.28	-.20	--	.15	.33	.11	.07	.15	.23	-.08	-.27	.16	.24	.13	.00	-.19	.26	.10	-.09	.03
4	.75	-.35	.15	--	-.22	.72	.15	.11	.63	.06	-.21	.90	.64	.86	.53	-.77	.65	.72	.61	.41
5	.50	-.52	.33	-.22	--	.10	-.24	-.05	-.26	.00	-.39	-.03	-.22	.02	-.32	.37	-.27	-.20	.26	-.24
6	.66	-.33	.11	.72	.10	--	-.20	.06	.42	.01	-.18	.76	.26	.77	.50	-.30	.30	.28	-.52	.14
7	-.13	.31	.07	.15	-.24	-.20	--	.72	.44	-.34	.46	.02	.49	-.07	-.03	-.45	.16	.68	.06	-.12
8	.01	-.35	.15	.11	-.05	.06	.72	--	-.06	-.30	.64	.14	.10	.13	.17	.05	-.18	.33	.31	-.11
9	.30	-.09	.23	.63	-.26	.42	.44	-.06	--	-.15	-.44	.43	.76	.33	.14	-.72	.60	.72	-.53	.05
10	.18	-.24	-.08	.06	.00	.01	-.34	-.30	-.15	--	-.45	.12	-.11	.15	.07	-.21	.23	-.05	-.26	.26
11	-.38	.47	-.27	-.21	-.39	-.18	.46	.64	-.44	-.45	--	-.26	-.58	-.22	-.07	.57	-.58	-.37	.68	.36
12	.78	-.39	.16	.90	-.03	.76	.02	.14	.43	.12	-.26	--	.53	.99	.69	-.58	.50	.59	-.41	.35
13	.38	-.11	.24	.64	-.22	.26	.49	.10	.76	-.11	-.58	.53	--	.40	.17	-.68	.67	.79	-.40	.17
14	.78	-.40	.13	.86	.02	.77	-.07	.13	.33	.15	-.22	.99	.40	--	.72	-.52	.44	.48	-.37	.35
15	.28	.00	.00	.53	-.32	.50	-.03	.17	.14	.07	-.07	.69	.17	.72	--	-.21	.15	.18	-.06	.24
16	-.44	.21	-.19	-.77	.37	-.30	-.45	.05	-.72	-.21	.57	-.58	-.68	-.52	-.21	--	-.94	-.91	.75	-.51
17	.34	-.22	.26	.65	-.27	.30	.16	-.18	.60	.23	-.58	.50	.67	.44	.15	-.94	--	.95	-.63	.59
18	.50	-.24	.10	.72	-.20	.28	.68	.33	.72	-.05	-.37	.59	.79	.48	.18	-.91	.95	--	-.72	.36
19	-.39	.07	-.09	.61	.26	-.52	.06	.31	-.53	-.26	.68	-.41	-.40	-.37	-.06	.75	-.63	-.72	--	-.53
20	.37	-.30	.03	.41	-.24	.14	-.12	-.11	.05	.26	.36	.35	.17	.35	.24	-.51	.59	.36	-.53	--

KEY - Col. 1 (% clay content); Col. 2 (median diameter, mm.); Col. 3 (clay aggregate orientation); Col. 4 (% montmorillonite content); Col. 5 (% illite content); Col. 6 (sodium ion content, millequivalents); Col. 7 (calcium plus magnesium ion content, millequivalents); Col. 8 (pure water salts content, millequivalents); Col. 9 (cation exchange capacity, millequivalents); Col. 10 (% organic matter); Col. 11 (% carbonate content); Col. 12 (liquid limit); Col. 13 (plastic limit); Col. 14 (plasticity index); Col. 15 (activity); Col. 16 (bulk density, p.c.f.); Col. 17 (void ratio); Col. 18 (% natural water content); Col. 19 (wet-dry cycle rating); Col. 20 (distance across strike, miles).

This rating is based on the fact that $r^2 \times 100$ is a measure of the percentage of variation in one variable associated with another. A cause and effect relationship is not implied, although it may exist. Thus, an r^2 value of 0.50 ($r = \pm 0.71$) means that 50 per cent of the variation in one variable is associated with the second (and *vice versa*), and the remainder of the variation is left unexplained (due to either sampling or technique error, or due to some other factor not accounted for in the analysis). Accordingly, the interpretation of the physical meaning of correlation between the two properties for which $r = \pm 0.50$ should be made with caution.

In most studies which involve a large number of variables, linear regression and simple correlation techniques are inadequate to assess the complex interrelationships among variables. Some alternative multivariate technique must be sought, such as multiple regression analysis,[8] used here to evaluate interrelationships between properties arbitrarily designated "dependent" variables (y) and "independent" variables ($x_1, x_2 \ldots x_n$). Such an analysis yields an equation of the form:

$$y = a + b_1x_1 + b_2x_2 + \ldots b_nx_n$$

The b values are the partial regression coefficients and indicate the average increase (or decrease) in the dependent variable per unit increase in the corresponding x, independent of the other variables in the equation.

Several procedures are available for evaluating the relative importance of the independent variables in the equation, i.e. for testing their relative statistical significance. These are discussed in a number of standard reference works on the subject, such as Snedecor (1956). However, no unique approach exists for the interpretation of multivariate systems in terms of causes and effects; such an interpretation depends mainly on a knowledge of fundamental physical laws and their implied relationships to the system under investigation. This aspect of the analysis is brought out clearly in the succeeding sections of the report.

Plasticity

Interrelated variables associated with sample "plasticity" (liquid limit, plasticity index, activity) show moderate to high correlations with a number of other properties (Table 7) notably montmorillonite content (in turn related to total clay content and sodium ion concentration) and, to a lesser extent, bulk density and related properties (void ratio, water content). Liquid limit and the closely associated ($r = 0.99$) plasticity index show particularly high correlations with montmorillonite content and associated properties, whereas plastic limit and activity do not. This may be partly due to the lack of precision (operator and/or

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[8] Multiple Linear and Nonlinear Regression Analysis for IBM 1620, IBM Library File No. 6.0.001, by Dan Leeson.

technique error) involved in the determination of plastic limits (Liu *et al.*, 1965). It is interesting to note that plastic limit values show a significantly higher correlation with cation exchange capacity and bulk density than do the liquid limit values; the underlying causal relationships appear somewhat dissimilar for the two properties.

Nothing new is advocated in the recognition of these relationships; the effects of clay composition and sodium ion content on plasticity have been reported by Grim (1962), Locker (1963), and Seed *et al.* (1964a,b) among others. Some of these relationships are illustrated in the scatter diagrams in figure 13 for the fine-grained rocks of central Alberta. It is of interest to note that for clayey soils, the clay portions of which exhibit liquid limits of approximately 300, Seed *et al.* (1964b) report an increase in liquid limits of 25 with a corresponding increase of 10 per cent clay contents. The Cretaceous-Tertiary fine-grained rocks exhibit a comparable increase if it is assumed that the clay contents of all the rocks have liquid limits in the order of 300 (e.g., sample CH5-6, Table 3, which contains 75 per cent clay, has a liquid limit of 286). The rate of increase of the liquid limit of the Alberta rocks with increasing montmorillonite content is comparable to that reported by Seed *et al.* (1964a). However, Liu *et al.* (1965), working with natural samples containing illite and montmorillonite, found less pronounced increases in liquid limit with corresponding changes in either clay or montmorillonite contents. It is unfortunate that neither of these studies reported the influence of salt contents, variations in which can greatly alter the plasticity and render simple comparisons difficult.

Among the other variables known to affect plasticity, organic matter has received attention (Casagrande, 1932; Liu *et al.*, 1965). Liu *et al.* state:

> "Furthermore, it is believed that there may be variations in the "activity" of the various types of soil organic material that are as significant as those exhibited by various types of clay minerals. These differences may account for the divergence of opinions regarding relative importance of the organic fraction in controlling the index properties of natural soils."

However, no obvious correlation exists between organic content and plasticity for the fine-grained rocks of central Alberta (Table 7). Undoubtedly, the organic matter in these rocks, of Cretaceous and Tertiary ages, has been altered or "metamorphosed" to an inert coal-like material, in contrast to the more active material reported in younger deposits. The increase in plasticity with organic matter has been attributed in part to the ability of organic matter to absorb water owing to its porous structure. If this is true, then the inertness of the organic matter in the Alberta soft rocks may be due to the denser, coaly nature of this material, which would inhibit its absorptive properties to varying degrees.

The correlation between pore water salt content and plasticity is not significantly greater than zero, despite experimental results and theoretical

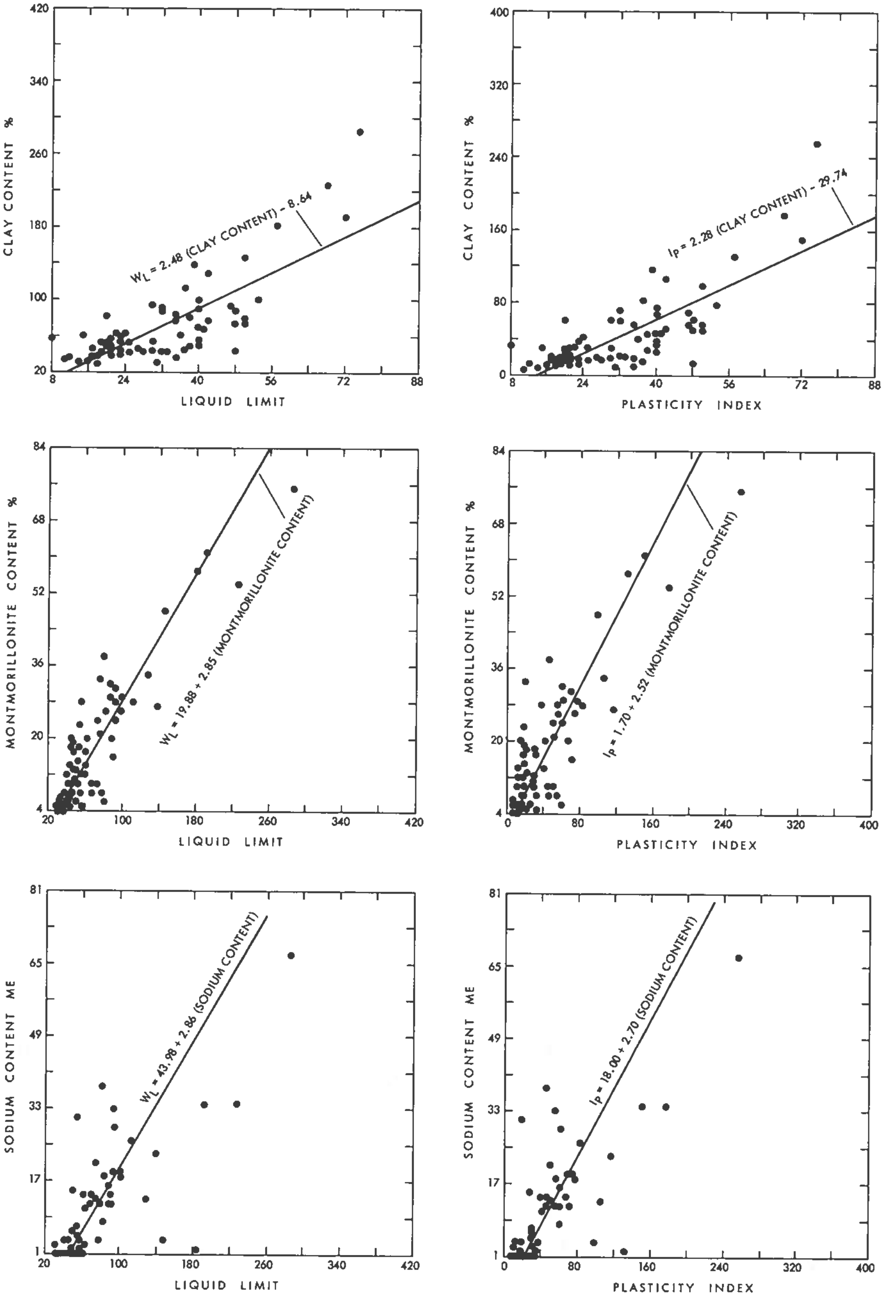


FIGURE 13. Relationships between clay, montmorillonite, and sodium contents and liquid limit and plasticity index, fine-grained rocks of central Alberta.

considerations that show a decrease in liquid limit with an increase in pore water salt content, in particular with sodium (e.g., Grim, 1962; Locker, 1963). The lack of correlation in the soft rocks from central Alberta can be attributed in part to experimental or technique error in the determination of the pore water salt content as described previously. Similarly, calcium, magnesium, and potassium ion contents show no correlation with plasticity, although these cations are generally not sufficiently active to significantly influence the plasticity in relation to their salt contents in the pore water.

To evaluate the relative effects of clay composition and sodium content (cumulative value of adsorbed plus pore water contents) on plasticity, a multiple regression analysis was performed on the data in table 3, with plasticity index the dependent variable (y) and clay content, montmorillonite content, and sodium ion concentration the independent (and presumably "casual") variables (x's).

The solution to the analysis, which assumes linear relationships among the variables, yields a regression equation of the form:

$$y = -13.7960 + 0.6802\, x_1 + 1.4924 x_2 + 0.9137 x_3$$

where x_1 = per cent clay

x_2 = per cent montmorillonite

x_3 = milliequivalents sodium ion concentration.

The meaning is this: the plasticity index of the samples increases an average of 0.6802 for each per cent increase in clay content, 1.4924 for each per cent increase in montmorrillonite, and 0.9137 for each milliequivalent increase in sodium ions. Thus, the equation not only provides an indication of the closeness of the association between changes in plasticity index and the independent variables but, if the relationships are statistically significant, may be used to predict values of the dependent variable (plasticity index) from measured values of the independent variables. The object of this study, however, is not to predict sample plasticity index values by regression analysis (they can be measured quickly and efficiently by other means) but to interpret the regression equation in terms of the relative contribution of each independent variable to variation in plasticity index values.

There is no unique approach to the interpretation of the results of multiple regression analyses because of the fact that the "independent" variables themselves are related (Snedecor, 1956; Krumbein and Graybill, 1965). Thus, the addition or subtraction of variables will change the entire complex to varying degrees, depending on the amount of intercorrelation among the variables. However, several standard approaches to interpretation are available, based on sequential deletion of "least important" variables. The simplest is to calculate and compare the standard partial regression coefficients (b') described in Snedecor(1956, p. 416 *et seq.*). The partial regression coefficients (b) themselves cannot be used directly to compare the relative contributions of each of the independent variables to variation in the dependent variable, for in most cases the standard deviations of the independent variables are dissimilar.

The procedure employing the standard partial regression coefficients (b′) is demonstrated in conjunction with table 8. For ease of comparison, these values (calculated from the corresponding partial regression coefficients, b) also have been recalculated as fractions of the highest standard partial regression coefficient (montmorillonite content) to yield relative b′ values. The value for R^2 (square of the multiple correlation coefficent, R) represents the fraction of the total variation in the dependent variable (plasticity index) attributable to the regression.

In the first trial, in which all three independent variables are entered in the regression, montmorillonite content accounts for the largest portion of variation in plasticity index in comparision with the two other independent variables. (The standard partial correlation coefficient, b′, for one independent variable represents the degree of variation in the dependent variable attributed to it when the other independent variables are held fixed). Clay content is next in its efficiency to predict plasticity index, and sodium ion concentration last. Together, the three variables "account for" or "explain" 81 per cent of the total variation in plasticity index values; the remaining 19 per cent is unaccounted for and is attributed to technique error or unknown factors.

To evaluate further the relative importance of the three independent variables, the least efficient (sodium ion content) is omitted from the analysis, and the multiple regression equation recalculated for the two remaining independent variables. The corresponding standard partial regression coefficients are shown under the heading "second trial" in table 8, from which it can be seen that montmorillonite is still the more important contributor to variation in plasticity index. The R^2 value has dropped from 0.81 to 0.78, indicating only a minor loss (3 per cent) in the efficiency of the regression when sodium ion concentration is omitted. In other words, clay content and montmorillonite content together account for 78 per cent of the total variation in plasticity index values, with an additional 3 per cent associated with sodium ion concentration. If the linear regressions of the three independent variables on plasticity index are considered separately, the corresponding r^2 (square of the sample correlation coefficient) values show that montmorillonite content alone accounts for 74.5 per cent of the variation in plasticity index (Table 8). Since both clay content and montmorillonite content together account for 78 per cent of the variation, it can be inferred that the addition of clay content to the regression analysis explains only an additional 3.5 per cent of the variation in plasticity index.

The conclusion reached is that montmorillonite content is the most efficient predictor of variation in plasticity index of the soft rocks of central Alberta. The

Table 8. **Multiple Regression Analysis of Properties Associated with Plasticity Index**

Independent Variable	First Trial			Second Trial			r^2
	b	b'	Relative b'	b	b'	Relative b'	Linear Regression
Clay content (%)	+ 0.6802	+0.3932	0.70	+ 0.8798	+0.5086	0.71	0.6015
Montmorillonite content (%)	+ 1.4924	+0.5650	1.00	+ 1.8857	+0.7139	1.00	0.7452
Sodium content (m.e.)	+ 0.9137	+0.2314	0.41	---	---	--	0.5933
a	-13.7960			-18.5972			
R^2	0.8129			0.7813			

inclusion of closely correlated variables, clay content and sodium ion content, to the regression analysis increases the efficiency of the relationship only slightly. If the samples contained negligible amounts of montmorillonite, it could be assumed that total clay content would be the predominant factor controlling plasticity index. However, where montmorillonite content is variable, as it is in the rocks under consideration, its influence on the plasticity index overshadows that of other related variables.

The interrelationships discussed above can be depicted in the form of a schematic "cause and effect" diagram, (after Miller and Kahn, 1962) in which some *a priori* knowledge of these factors exists (Fig. 14). In such a system the effects of one variable on another are indicated by an arrow: positive correlations are shown by a plus sign, negative ones by a minus sign. In the diagram, all of the variables show high positive correlations, from which it may be inferred that an increase in one is reflected by concomitant increases in the other three. Thus, if clay content is taken as the arbitrary starting point, an increase in this variable is associated with an increase in montmorillonite content, which in turn will affect the sodium ion concentration. All three variables together show high positive correlations with plasticity index, as confirmed by correlation analysis (Table 7). In a sense, all three variables may be considered causal factors with respect to plasticity index, although their relative importance varies, as indicated by the multiple regression analysis.

Bulk Density

Bulk density and related properties (void ratio, water content) show moderate to high correlations with a number of mineralogical, chemical, and physical properties of the fine-grained rocks from central Alberta (Table 7). There

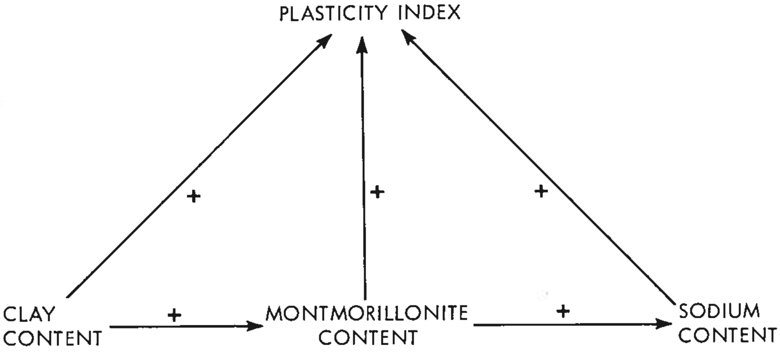


FIGURE 14. Effects of causal factors on plasticity index.

also exists a moderate correlation between density and distance, the latter being defined as the distance across the strike of the strata from an arbitrary datum.

The important compositional variables are montmorillonite and carbonate content, although clay content also shows a distinct but slightly lower correlation with density. This is to be expected, for natural clay deposits generally have higher void ratios than granular deposits (Peck, Hanson, and Thornburn, 1953) owing to:

(1) granular mixtures are generally well graded with a tighter packing system than fine-grained deposits;

(2) granular systems are less active in a chemical sense and hence do not resist packing owing to factors such as large adsorbed water "hulls" or high repulsive forces found in clay sediments.

Thus, the Alberta rocks conform to theory by showing a decrease in bulk density with increasing clay content.

The same relationship holds true for bulk density and montmorillonite content. Montmorillonite naturally adsorbs considerable quantities of water, resulting in a less dense rock. Additional adsorption and swelling may take place upon erosion and rebound of montmorillonite-bearing sediments, resulting in a still lower rock density at or near the surface.

Carbonate content shows a moderate positive correlation with bulk density, which is to be expected if the carbonates are cements which are filling voids that would otherwise contain water. However, if the carbonates are clastic (i.e. granular), then they do not contribute to an increase in bulk density. The distribution of carbonates is erratic, and the effect of carbonates on density is enhanced by a few samples that contain relatively high proportions of these minerals, whereas most contain little or none. If these few samples are excluded from the analysis, then there is no apparent relationship between carbonate content and bulk density.

Bulk density shows distinct negative correlations with plasticity index and Atterberg limits and also with the cation exchange capacities of the rocks. These relationships in turn can be attributed partly to the effect of montmorillonite, an increase in which tends to increase the values for Atterberg limits and cation exchange capacity but decrease the bulk density of the samples. In other words, montmorillonite content is interpreted here as a causal factor, affecting both the chemical and derived physical or bulk properties of the rock.

To evaluate more effectively the interrelationships between bulk density and other properties of the rocks, a multiple regression analysis was performed with bulk density the dependent variable (y) and clay content, montmorillonite content, carbonate content, and distance across strike as independent variables (x's). The data are those given in table 3 and include both outcrop and subsurface samples.

The analysis, which assumes linear relationships among the variables, yields the following equation:

$$y = 144.2806 + 0.2525x_1 - 0.8274x_2 + 1.4081x_3 - 0.0396x_4$$

where x_1 = per cent clay

x_2 = per cent montmorillonite

x_3 = per cent carbonate

x_4 = distance across strike in miles.

As such the equation gives the impression that carbonate content is the most important variable associated with density, but examination of the data in table 9 in which the standard partial regression coefficients (b') and R^2 values are tabulated, shows that this is not the case. The first trial, which takes all four independent variables into account, suggests that montmorillonite content is the most effective predictor of density, followed by clay content and distance. Carbonate content is quite ineffective in a relative sense, by a wide margin. Total variation in density explained by concomitant variation in the independent variables is 70 per cent.

The second and third trials, which involve dropping the least effective variables in turn from the analysis and recalculating the pertinent statistics, show that montmorillonite content maintains its position as the most effective predictor with little loss of overall efficiency in the equation (from 70 to 66 per cent).

Table 9. Multiple Regression Analysis of Properties Associated with Bulk Density

Independent Variable	First Trial			Second Trial			Third Trial			r^2
	b	b'	Relative b'	b	b'	Relative b'	b	b'	Relative b'	Linear Regression
Clay content (%)	+ 0.2525	+0.0567	0.48	+ 0.2555	+0.0573	0.47	+ 0.2369	+0.0531	0.40	0.1958
Montmorillonite content (%)	- 0.8274	-0.1183	1.00	- 0.8545	-0.1222	1.00	- 0.9251	-0.1322	1.00	0.5869
Carbonate content (%)	+ 1.4081	+0.0094	0.08	---	---	--	---	---	--	0.3207
Distance (miles)	- 0.0396	-0.0339	0.29	- 0.0435	-0.0373	0.31	---	---	--	0.2572
a	+144.2608			+145.5565			+142.6293			
R^2	0.6966			0.6882			0.6578			

However, clay content does contribute an additional 7 per cent to the "explainable" portion of the bulk density variation, if the R^2 value for the third trial (0.66) is compared with the r^2 value (0.59) obtained from the linear regression of montmorillonite content on bulk density alone. In other words, about two-thirds of the variation in density of the samples can be attributed to or "explained by" variation in montmorillonite and clay content.

An equally interesting aspect of this analysis is found in the original multiple regression equation for density in which clay content is associated with a positive partial regression coefficient for density (+0.2525) and montmorillonite with a negative one (-0.8274). This situation persists through successive trials to the final equation in which only these two independent variables are kept:

$$y = 142.6293 + 0.2369x_1 - 0.9251x_2$$

where x_1 = per cent clay

x_2 = per cent montmorillonite.

This means that the bulk density decreases with increasing montmorillonite content, in accordance with other experimental data. On the other hand, the bulk density increases with increasing clay content when montmorillonite content is held constant, which is the reverse relationship of that obtained by looking at the regression of clay content on bulk density alone.

The question arises as to how to explain the 30 per cent of the variation in bulk density that cannot be attributed to the four independent variables discussed above. Part of this "unexplained" variation can be attributed to experimental error, as demonstrated graphically in figure 12, where bulk density is plotted against distance across the strike of the rocks for both outcrop and corehole samples. The two regression lines, one for corehole samples and one for weathered outcrop samples, both show a progressive decrease in density away from the Foothills, but at different rates. Therefore, by grouping both the corehole and outcrop samples in the regression analysis without regard to their origin, some precision is lost and the "unexplained" portion of the variation in bulk density is affected. Also, experimental errors in measuring clay and carbonate contents and especially montmorillonite contents augment the lack of precision in the regression analysis.

A portion of the "unexplained" variation in bulk density also can be attributed to potential causal factors not included in the regression analysis. Cation concentration or pore water composition is one such factor which on theoretical grounds might affect the compressibility and hence the ultimate bulk density of the rocks. However, among the various chemical properties measured, only cation exchange capacity shows a moderate correlation with bulk density, in turn attributable to a common factor, montmorillonite content. Moreover, it seems

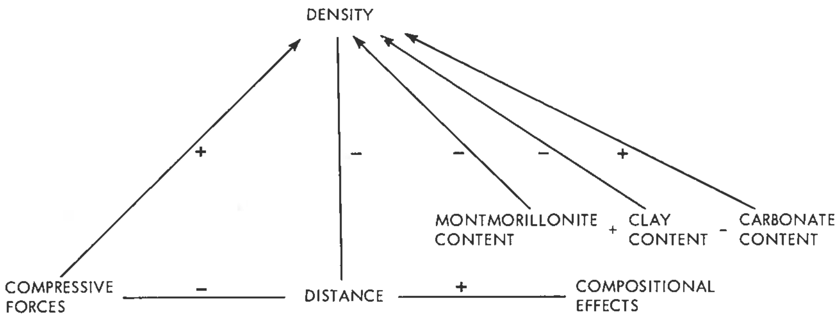


FIGURE 15. Effects of causal factors on bulk density.

likely that some changes in cation content and composition have occurred since the deposition of the rocks. Thus, the chemical properties of the pore waters as now measured may differ radically from those properties which existed during compression of the rocks in Late Cretaceous and Tertiary times. Accordingly, it is difficult to interpret the present chemical properties of the samples in terms of cause and effect on bulk density.

The interrelationships between bulk density and associated attributes of the fine-grained rocks of central Alberta are summed up schematically in figure 15, in which "causal" factors are shown by arrows and noncausal factors by straight lines. Two generalized causal factors are postulated; *compressive forces,* (resulting from tectonic and overburden forces) and *compositional factors,* both of which are related to (but not caused by) distance as measured eastwards across the strike of the strata (i.e. away from the source of sediments). Compressive forces, which presumably decrease away from the source of sediments (which is somewhere to the west of the area under consideration), cannot be measured directly; their effect is measured in part by distance, as shown in figure 12.

Distance also is associated with the compositional variables, each of which is measured as a percentage of the total rock sample. Each tends to increase in amount away from the source area (the direction in which the rocks as a whole become finer grained, i.e. more clayey), although the individual effects on bulk density are variable. An increase in montmorillonite content, the most important of the three compositional properties, decreases the bulk density of the rocks, providing the same effect as distance. However, because montmorillonite content and distance are positively correlated, the individual effects of the two variables on bulk density are "confounded" or scrambled. No unique procedure exists for unscrambling these effects and assessing each independent of the other, although regression analysis indicates that the montmorillonite content is the more important factor.

Similar interpretations can be made for the other independent variables, although the ultimate choice of "causal" relationships depends on *a priori* knowledge of fundamental physical laws.

Wet-dry Cycle Rating

Wet-dry cycle rating, obtained from the alternate slaking in water and drying tests, is an attribute devised to evaluate, among other factors, the inherent bond strength of the fine-grained rocks from central Alberta. Forces which "test" the strength of these bonds are developed internally in the sample, e.g. swelling pressures.

As measured on a ranking or ordinal scale, wet-dry cycle ratings of the Alberta rocks show moderate to high correlations with several compositional and physical properties of the samples (Table 7). Among these are clay and especially montmorillonite contents, both of which generate destructive shrinkage and swelling forces within the rocks (Yong and Warkentin, 1966). Carbonate cementation, on the other hand, enhances the cohesive forces, i.e. acts against the effects of wet-dry tests. Bulk density, as an indicator of overburden (vertical) and tectonic (horizontal) pressures, can be related to particle packing and thus should inhibit the effects of wet-dry tests (Fig. 16).

These four "independent" variables were selected for multiple regression analysis of wet-dry cycle ratings, the latter being the dependent variable. The analysis, based on the data in table 3, assumes linear relationships among the variables, yielding the following equation:

$$y = -30.6779 + 0.2923x_1 + 0.0058x_2 + 0.0285x_3 + 0.6807x_4$$

where x_1 = density in lbs/cu ft

x_2 = per cent clay

x_3 = per cent montmorillonite

x_4 = per cent carbonates.

Together, the four independent variables account for 71 per cent of the total variation in wet-dry cycle ratings, leaving 29 per cent unexplained (Table 10). However, bulk density and carbonate content appear to be the most efficient predictors of wet-dry cycle ratings, which is confirmed by calculation of the standard partial regression coefficients in table 10. Successive recalculations of the equation and the corresponding coefficients (second and third trials, Table 10), in which the lowest variable is dropped, confirm this interpretation; neither clay

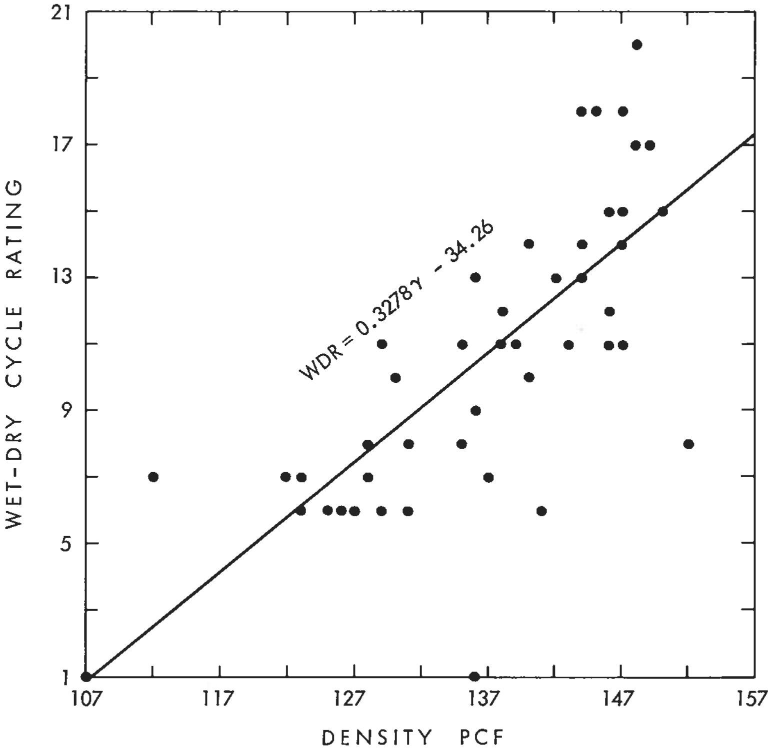


FIGURE 16. Relationship between wet-dry cycle rating and bulk density, fine-grained rocks of central Alberta.

content nor montmorillonite content account for any additional variation in wet-dry cycle ratings not associated with the other two independent variables. If bulk density is considered alone ($r^2 = 0.56$), then only 56 per cent of the variation in wet-dry cycle ratings is accounted for, the remaining 15 per cent being attributable to carbonate content.

These findings are in line with theoretical expectations, bulk density being a measure of the inherent bonding of the rocks, and carbonate content a measure of chemical cementation. It might be expected that montmorillonite would play a major role, but the interrelationships between the dependent and independent variables are masked to some extent by moderate to high correlations among the latter. Schematically, these relationships are summed up in figure 17, in which arrows indicate causal effects and straight lines noncausal associations.

Table 10. Multiple Regression Analysis of Properties Associated with Wet-Dry Cycle Ratings

Independent Variable	First Trial			Second Trial			Third Trial			r^2
	b	b'	Relative b'	b	b'	Relative b'	b	b'	Relative b'	Linear Regression
Density (p.c.f.)	+ 0.2923	+3.4433	1.00	+ 0.2948	+3.4727	1.00	+ 0.2689	+3.1676	1.00	0.5635
Clay content (%)	+ 0.0058	+0.0146	0.00	---	---	--	---	---	--	0.1493
Montmorillonite content (%)	+ 0.0285	+0.0403	0.01	+ 0.0347	+0.0490	0.01	---	---	--	0.3767
Carbonate content (%)	+ 1.9307	+0.1633	0.05	+ 1.9252	+0.1629	0.05	+ 1.9093	+0.1615	0.05	0.4634
a	-30.6779			-30.9489			-26.9465			
R^2	0.7091			0.7090			0.7067			

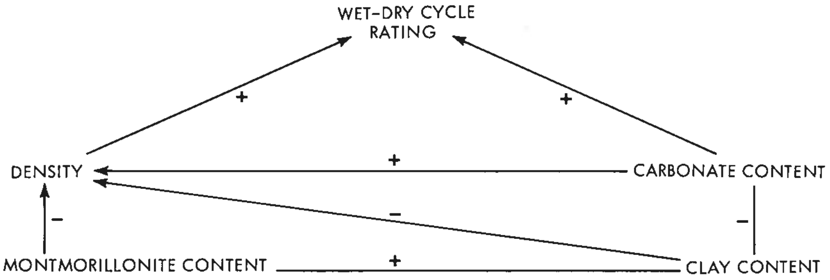


FIGURE 17. Effects of causal factors on wet-dry cycle rating.

Miscellaneous Correlations

In addition to the relationships among the various properties of the rocks established by means of multiple regression analyses in the preceeding sections, a number of additional variable-pair relationships (as determined from the linear regression studies) remain to be discussed (Table 7). In some of these cases, it is the lack of significant correlation between properties that is of interest.

Particle Orientation

Particle orientation does not exhibit well developed relationships with the other properties. The highest correlation ($r = 0.3297$) is with illite content, undoubtably reflecting the fact that this constituent shows up in thin sections cut perpendicular to the bedding as minute shreds or plates which tend to enhance the visual particle orientation effect. It is possible that part of the lack of correlation between orientation and other variables is due to the difficulty in quantitatively measuring this property; certainly, the procedure used in this study is subjective and lacks in precision. The fact remains, however, that a distinct impression has been obtained from examination of numerous thin sections of rocks from across central Alberta that the presence of well-developed particle orientation is a "random" effect.

Median Diameter (Q_{50})

As expected, the sample median diameter, a measure of grain size, exhibits a correlation trend similar to that of clay content. Both variables are determined from the same grain-size frequency survey, and, as a result, show a moderately high negative correlation. However, it is worth noting that the absolute values of the two sets of correlation coefficients are generally lower for the median diameter; this suggests that clay content is the more useful (or efficient) parameter for evaluating relationships between texture and other rock properties.

Mineral Composition

The most outstanding correlations in the entire statistical analysis are those associated with montmorillonite, which exhibit high correlations with all plastic and physical properties. Illite, a commonly occurring clay mineral in soft rocks of central Alberta, exhibits low to negligible correlation with plasticity and bulk properties, in a way reflecting its relatively inactive nature.

The carbonate content of the soft rocks has some influence on the concentration of the salts in the pore water; this relationship is to be expected for the rocks generally have high salt contents only when carbonates are present. The carbonate content also influences the wet-dry cycle rating values and related factors.

The organic content of the rocks appears to be randomly distributed, in a manner similar to particle orientation, for it shows little correlation with the variations in other properties.

Chemical Composition

The pore water salt content is related to carbonate content, and hence also to calcium and magnesium ion concentration, but does not exhibit a significant correlation with plasticity or bulk properties as noted above. The sodium ion concentration, on the other hand, shows relationships with other properties in much the same manner as montmorillonite content, but the correlation coefficients are generally lower.

SHEAR STRENGTH

Recent studies of slope stability in overconsolidated clays and clay-shales have emphasized the application of peak and residual shear strength concepts (Skempton, 1964; Bjerrum, 1967). The fine-grained rocks of central Alberta appear to increase in shear resistance in an east to west direction as exemplified by a decrease in propensity for slope failure in that direction. Thus, it is desirable to determine peak and residual strength parameters and relate these parameters to other geotechnical characteristics of the Alberta rocks.

Description of Samples

Drained direct shear tests were performed on two rock types from each of three shallow coreholes drilled during the course of the investigation (CH1, CH6, and CH8, Fig. 1). To augment data obtained from these tests, drained direct shear results for the Edmonton area (CH2 and CH3, Fig. 1) were selected from an unpublished report (River Bank Stability Report, 1969) prepared by the Department of Civil Engineering, University of Alberta, and from a study of a slide area near the east boundary of the city (Pennell, 1969). Summary descriptions of the sampling localities are given in table 1.

The pertinent properties of the fine-grained rocks subjected to shear tests are summarized in tables 10, 11, and 12 (additional information on each sample series is presented in table 3). A brief description of each rock type follows:

Corehole CH1:	Tp. 58, R. 19, W4th Mer. - Belly River Formation
CH1-39	brownish-grey, compacted, clayey siltstone of high plasticity; abundant organic matter; quartz and feldspar; montmorillonite major clay mineral.
CH1-53	grey, compacted, sandy clayey siltstone of high plasticity; little organic matter; abundant quartz and feldspar; montmorillonite major clay mineral.
Corehole CH2:	Tp. 53, R. 23, W4th Mer. - Edmonton Formation
CH2-9A	greenish-grey, compacted, bentonitic silty claystone of very high plasticity.
Corehole CH3:	Tp. 52, R. 24, W4th Mer. - Edmonton Formation
CH3-1A	greenish-grey, compacted, bentonitic claystone of very high plasticity.
CH3-2A	greenish-yellow, almost pure bentonite of very high plasticity.
CH3-3A	brownish-grey, compacted, sandy clayey siltstone of high plasticity.

Table 12. Petrographic Properties of Direct Shear Specimens as Determined from Thin Sections

Sample Number	Distance (miles)	> 20 Microns (%)[1]	Montmorillonite (%)[2]	Color	Structure				Texture			Composition						
					Homo.	Laminations		Pell.	% >20μ	Silt size	% clay orient.	Q+F	RF	Micas	Mont.	Org.	Pyr.	Car
						Org.	Clay-silt											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CH1 -39A	197	30	14	Gr		X	X		25	C	10	Ab	P	P	P	Ab		P
-39B				Gr-Br		X	X		10	C	10	Ab	P	P		Ab	P	
-39R[3]				Br-Gr	X				30	C	10	Ab	P	P		Ab		P
CH1 -53A	197	48	26	Br-Gr			X		20	C	0	Ab	P	P			P	P
-53B				Br-Gr			X		20	C	0	Ab	P	P	P	P	P	
-53C				Gr			X		30	C	10	Ab	P	P			P	P
-53D				Br-Gr			X		25	C	0	Ab					P	
CH6 -54A	112	10	10	Gr		X	X		10	M	10	Ab		P		Ab	P	P
-54D				Br		X			0		30					Ab		
-54G				Br		X			0		10					Ab		Ab
-54R[3]				Gr-Br				X	10	M	0	Ab		P		P	P	P
CH6 -69A	112	35	8	Gr		X			5	M	10-20	P		P			P	
-69B				Br		X			10	M	20-30	P		P	P	P	P	
CH8 -45A	59	65	5	Br-Gr	X				40	C	10	Ab	P	P			P	P
-45B				Gr	X				40	C	10	Ab	P	P				P
-45C				Gr	X				35	C	10	Ab	P	P				P
-45D				Gr	X				30	C	10	Ab	P	P			P	P
-45E				Gr	X				35	C	10	Ab	P	P				P
-45F				Gr	X				55	C	10	Ab	P	P			P	P
-45G				Gr	X				45	C	10	Ab	P	P			P	P
-45I				Gr	X				40	C	10	Ab	P	P			P	
-45J				Gr	X				45	C	10	Ab	P	P				
CH8 -74B	59	62	5	Gr	X				70	C	0	Ab	P	P				Ab
-74C				Gr			X		50	C	0	Ab	P	P				Ab
-74D				Gr			X		35	C	0	Ab	P	P				Ab
-74E				Gr			X		75	C	10	Ab	P	P				Ab
-74F				Gr		X	X		25	C	10	Ab	P	P				Ab
-74G				Gr			X		40	C	10	Ab	P	P				Ab
-74R[3]				Gr			X		1	M	10	Ab	P	P				Ab

[1] From hydrometer analysis. [2] From grain-size X-ray data. [3] R = remoulded samples.

KEY - Col. 5: Br = brown, Gr = grey; Cols. 6-9 (Homogeneous, organic, clay-silt, pelleted): X = present; Col. 11: M = medium, C = coarse; Cols. 13-19 (Quartz plus feldspars, rock fragments, micas, montmorillonite, organic matter, pyrite, carbonates): P = present, Ab = abundant.

Corehole CH6:	Tp. 53, R. 7, W5th Mer. - Paskapoo and Edmonton Formations
CH6-54	dark grey, compacted siltstone of medium plasticity; abundant organic matter, very fine-grained micaceous material, montmorillonite, and illite present; moderate carbonate content.
CH6-69	grey-green, cemented, sandy siltstone of medium plasticity; low organic content; quartz, feldspar, mica, montmorillonite, and illite present.
Corehole CH8:	Tp. 52, R. 20, W5th Mer. - Paskapoo Formation
CH8-45	grey, carbonate-cemented siltstone of medium plasticity; no organic matter; high quartz and feldspar content; illite major clay mineral.
CH8-74	grey, carbonate-cemented siltstone of high plasticity; no organic matter, very high quartz and feldspar and very low clay contents; laminated structure.

Direct Shear Tests

Sample Preparation

The relatively soft corehole samples from the Belly River Formation northeast of the City of Edmonton (Loc. CH1) were cut to fit the direct shear box (6 cm x 6 cm x 2.54 cm) with a bandsaw and a sharp blade. However, corehole material from the Edmonton and Paskapoo Formations in the western part of the study area (Locs. CH6, CH8) were too indurated to suit this procedure. Samples from these localities were cut to approximate size by a diamond saw and then ground to true size with silicon carbide grit on a lap wheel. Water was employed as a cutting lubricant since the cutting time was so short and the permeability of the samples so low that significant changes in water content did not occur. The samples were wiped dry after the cutting operation. Both cutting procedures require care and caution to acquire a sample of true size, for blade vibrations tend to promote fissuring and chipping. Samples with precut failure planes were cut on the diamond saw to ensure a true precut surface.

Remoulded samples were consolidated in a large oedometer from a water content slightly higher than the liquid limit to a final pressure of 25 tons per square foot. These samples were trimmed to size with a sharp blade.

Description of Apparatus

To facilitate determination of residual strength parameters, a standard Clockhouse direct shear machine was modified to allow automatic reversal of the shear box, by utilizing a time clock to reverse the power supply to the motor at precalculated (displacement) time intervals.

Loads and displacements were measured with calibrated 2000 pound load cells and linear variable differential transducers (LVDT), respectively. Readings of these instruments were taken automatically and printed out with the aid of a digital recorder (Rennie, 1966).

Test Procedure

Test specimens from each sample series were placed in the shear box and subjected to normal loads of 53.8, 99.6, or 145.4 psi (series CH1-39 was the first series tested and different normal loads were employed for no specific reason). All specimens were submerged in distilled water in the shear box, and the normal load was applied in one increment. The vertical deformations noted under the normal loads are generally either very small or nonexistent and are attributed mainly to seating of the specimen into the box.

When the vertical deformation was considered complete, the shear force was applied at a predetermined rate of displacement. The samples were subjected initially to a shear displacement of 0.1 inches, during which the peak resistance was always exceeded. The samples were then sheared in a reverse direction, past their original positions, and on for another 0.1 inches; this procedure was repeated with total displacements of 0.2 inches per reversal cycle until the shearing resistance had dropped to a steady minimum value (residual strength). The displacement of 0.1 inches in either direction was chosen because (1) the construction of the direct shear box promotes loss of soil at greater displacements and (2) no correction for change of area caused by shearing displacement was made. Therefore, it was desirable to keep the effects of such at a minimum.

The number of direct shear tests performed per Mohr envelope varies from one sample series to another. The testing of a sample series was not considered complete until either a well-defined envelope was achieved or all available samples were used.

After the direct shear tests were completed, the samples were bound together with rubber tape and impregnated with Carbowax 6000 to keep the sample intact for thin-sectioning. The carbowax did not cause further disintegraion of these samples, as it did with the outcrop samples, possibly because they were fully saturated. In this case epoxy cement was used to mount the specimens on the glass plates. The thin sections were cut parallel to the direction of shear and parallel to the normal stress (perpendicular to the bedding), thereby incorporating the failure plane.

Rate of Displacement

The rate of displacement for the determination of effective strength parameters must be slow enough to ensure fully drained conditions. A suitable rate can be established either by a trial and error procedure or by a theoretical equation (Bishop and Henkel, 1957). The trial and error procedure is not suitable for this study for insufficient samples and time were available for a detailed study of each rock type. The theoretical approach utilizes the theory of consolidation, although available equipment is of insufficient capacity to determine directly the consolidation characteristics of the majority of the rocks tested. Thus, the rate of displacement chosen for the determination of peak strength, i.e. 7 x 10^{-5} inches/minute, (approximately 24 hours to failure) is based on previous investigations of Edmonton Formation rocks (Sinclair and Brooker, 1967) and on the findings of Van Auken (1963) on somewhat similar materials. This rate of deformation allows the strength results to be compared on a common basis.

If the rate of deformation is kept within the normal range used in direct shear tests, it has little influence on residual strength parameters (Sinclair and Brooker, 1967; Kenney, 1967). A rate of displacement of 1.54 x 10^{-3} inches per minute (approximately 2 hours per cycle) was chosen to facilitate the use of a time clock and a digital recorder (i.e. the time clock was mechanically limited to a minimum time increment and test time of 2 hours allowed the recorder to acquire sufficient readings). A rate of displacement of 5.0 x 10^{-3} inches (4 hours per cycle) provided identical results to the chosen rate, but a rate of 1.53 x 10^{-2} inches (13 minutes per cycle) caused an increase in residual shear resistance of approximately 10 per cent (Fig. 18). Similar results are reported by Pennell (1969) in his studies on fine-grained rocks from central and northern Alberta, although de Beer (1967) reported the opposite trend with the Boom clay, i.e. tests at higher rates of deformation gave lower residual shear angles than at slower rates. The difference in the two sets of results is presumably due to different material behavior.

Mechanism of Shear

To determine the action of shear during a test on natural materials such as the rocks described here is a difficult task. Morgenstern and Tchalenko (1967c) noted the mechanism of shear of remoulded kaolinite by studying a succession of thin sections taken from direct shear specimens interrupted at different stages of deformation. Although a study of shear action was not an integral part of this investigation, the following relevant observations associated with the mode of shearing action in the fine-grained rocks were noted.

The presence of dilatency or volume increase during the peak shearing action is not known. Measurements of vertical displacement during shear indicated erratic movements of less than a hundredth of an inch in either direction, i.e. expansion or contraction. These readings appeared as a result of factors other than internal action of the samples – for example, uneven sample thickness, tilting of the shear box, etc. Therefore, they were discontinued during subsequent tests. Similar inconsistencies in the measurement of vertical displacement have been reported elsewhere (Pennell, 1969; P. Ali, pers. comm.).

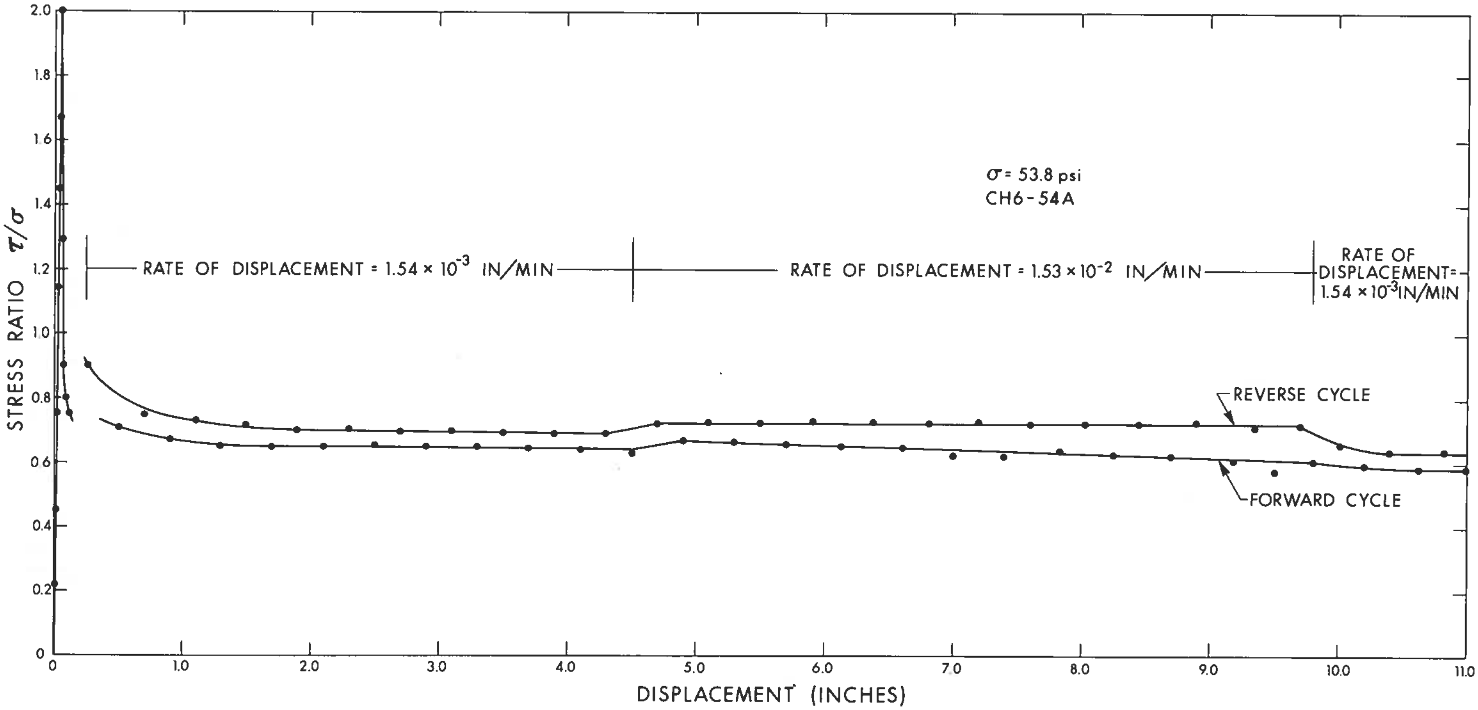
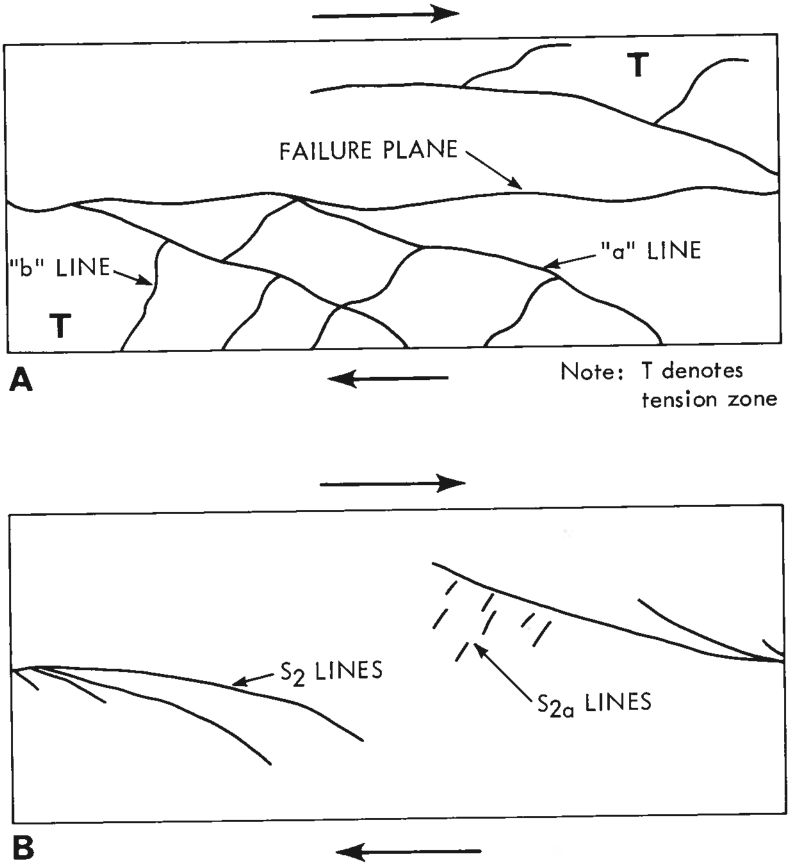


FIGURE 18. Typical plot of stress ratio versus *displacement.*

Vertical displacement measurements were even more erratic during the shear cycles, but these inconsistencies are a direct result of a loss of soil. The loss of material is a result of tilting or upward lifting of the shear box caused by irregular failure planes and a jacking effect by soil or rock fragments lodged between the two halves of the box. Removal of the samples at the completion of the test required extreme care to keep the sample intact for subsequent thin section preparation. In most cases the samples were cracked in what appeared to be a random fashion and pea-sized fragments dislodged readily along the edges perpendicular to the shear direction. Two samples were so badly broken that their removal resulted in a pile of rubble.

Observations of sample cracking in thin section revealed that two general patterns could be distinguished, type I and type II cracking patterns. Type I patterns (Fig. 19) have two families of cracks designated as "a" lines and "b" lines.



Note: T denotes tension zone

FIGURE 19. Type I cracking patterns. (A) As observed in fine-grained rocks from central Alberta. (B) Edge structures (shear perpendicular to original fabric) as reported by Morgenstern and Tchalenko (1967c).

The "a" lines point down from the failure plane against the direction of movement; they leave the failure plane at a low angle, then steepen within a short distance to an average angle of 20°, finally intersecting the bottom of the sample at an average angle of 30°. In a number of samples a slight change in direction of the "a" lines is observed at their intersections with the "b" lines. The pattern is best developed in the bottom half of the sample, but the top half of the sample can exhibit a comparable pattern. The "b" lines usually possess a flattened S-shape and are inclined at an average angle of 70° to the horizontal. The "b" lines may cut across "a" lines but normally join them at an intersection. The type I cracking pattern is generally found in the more brittle, cemented rocks and is best illustrated in the CH8 series from west of Edson (Pl. 13; Figs. 1, 2, 3).

The type II cracking pattern (Fig. 20) has two families of cracks designated as "c" lines and "d" lines. The "c" lines are horizontal lines found at any location within the sample. The "d" lines usually possess a flattened S-shape and are inclined at an average angle of 80° to the horizontal, ranging as low as 40°. The "d" lines seldom cut across "c" lines and are more numerous in the central portion of the sample. The type II cracking pattern is found in the more plastic, compacted rocks with high organic content and is best illustrated in the CH1 series of the eastern edge of the study area. (Pl. 14; Figs. 1, 2).

These cracking patterns can be compared to microstructures which develop in remoulded kaolinite subjected to direct shear. The "a" lines of the type I cracking pattern appear comparable in attitude and position to the microstructures which develop in remoulded kaolinite subjected to direct shear. The "a" lines of the type I cracking pattern appear comparable in attitude and position to the microstructure designated as S_2 in Morgenstern and Tchalenko's (1967c) studies of specimens which were sheared perpendicular to the fabric. Morgenstern and Tchalenko noted that these lines, which are the first features to develop with shear, form a family of cracks which originate at the edge of the box and extend towards the centre (Fig. 19). The "c" lines of the type II cracking patterns (Fig. 20) are approximately parallel to the bedding and resemble the pattern of curvilinear discontinuities which produced a slip-line field in samples of remoulded kaolinite with a horizontal fabric (Morgenstern and Tchalenko, 1967c).

If both major discontinuities, i.e. the "a" and "c" lines, are in fact comparable to the microstructures noted by Morgenstern and Tchalenko, then they may be attributed to the high stress concentrations which develop from compression forces exerted by the vertical loading edges of the shear box. However, since the two cracking patterns are different in themselves, the rock properties themselves must play a role in their development. The "c" lines are approximately parallel to the bedding, are most marked in strongly laminated rocks, and are comparable to slip-lines which develop in those kaolinite specimens sheared parallel to original fabric by Morgenstern and Tchalenko. Therefore, it is tacitly assumed that the horizontal structure – the laminations or bedding structure – controls the

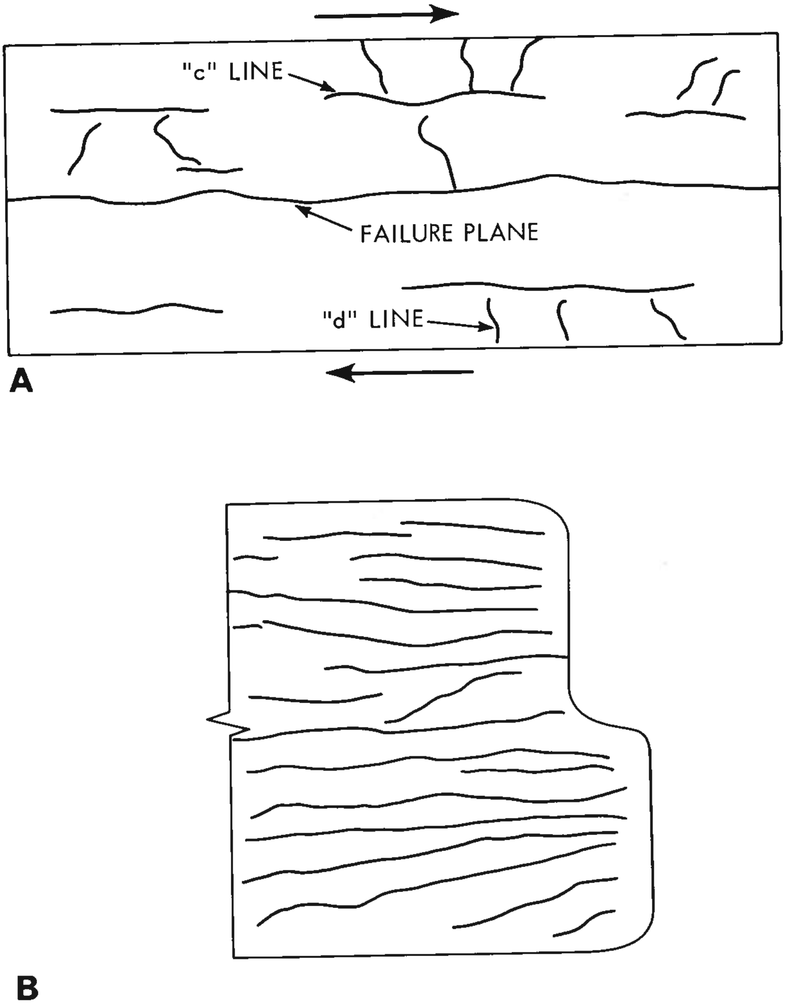


FIGURE 20. Type II cracking patterns. (A) As observed in fine-grained rocks from central Alberta. (B) Edge structures (shear parallel to original fabric) as reported by Morgenstern and Tchalenko (1967c).

attitude of the microstructures developed by the edge effects of the shear box. Conversely, the "a" lines of the type I cracking pattern are found most commonly in cemented rocks of high silt content which are not laminated and are comparable to the S_2 lines developed in those kaolinite specimens sheared perpendicular to the original fabric by Morgenstern and Tchalenko. It appears that the stress concentrations at the edges of the shear box favor the development of microstructures comparable to that of the "a" lines unless there are controlling features, for example laminations and their inherent weaknesses, which cause horizontal microstructures to form.

The "b" lines of the type I cracking patterns appear to be an extension of the S_{2a} lines reported by Morgenstern and Tchalenko (1967c). It is conceivable that a "b" line is composed of a series of S_{2a} lines which join to form a flattened S-shaped discontinuity as displacements continue. The "d" lines of the type II cracking patterns are undoubtably a manifestation of a secondary structure, similar to the "b" lines.

An explanation of similar cracking patterns in samples subjected to direct shear also has been proposed by Roscoe (1953), who claims that tension zones occur at the ends of such samples (Fig. 19) and that the cracking associated with such zones appears to develop to a greater extent in more brittle materials. Roscoe also points out that the tension stress is greater when the shear stress exceeds the normal load. It is not known if tension zones are developed at these locations in the samples described here, but the concept may explain type I cracking patterns, most pronounced in the more brittle rocks, in which the shear load is greater than the normal load in many cases.

The "a" or "c" lines ultimately join to form failure surfaces which are described as smooth, concave, undulating, or irregular at the macroscopic scale (Table 13, Columns 2 to 5). The majority of the compacted rocks (Edmonton and Belly River Formations) developed failure planes with a smooth, concave, or undulating surface, whereas the cemented rocks (Paskapoo Formation) contain mainly irregular failure planes. Further study under the microscope revealed these failure surfaces to be either smooth or rough with the latter commonly found in rocks with a high sand plus coarse silt content. Fracturing of the rocks during shear also developed intact fragments of all sizes and shapes, which are termed shear lenses by Skempton (1966). Their distribution is noted in table 13, column 9.

Direct Shear Results

Mohr Diagrams

The results of direct shear tests on the fine-grained rocks of central Alberta are presented numerically in table 11, and as Mohr rupture lines in figure 21. The rupture lines were fixed by the method of least squares. (The test results used to establish the Mohr envelopes are plotted for the materials tested by the writer but not for the materials tested by others). As a preface to the discussion of the shear resistances of the rocks, the major features of each set of results illustrated in figure 21 are listed below.

Corehole CH1:	Tp. 58, R. 19, W4th Mer. - Belly River Formation
CH1-39	moderate peak strength parameters; residual (undisturbed) cohesion is very high; residual strength of remoulded specimen deviates considerably from that of undisturbed material.

CH1-53	high peak angle of shearing resistance; moderate to high residual angle of shearing resistance.
Corehole CH2:	Tp. 53, R. 23, W4th Mer. - Edmonton Formation
CH2-9A	residual cohesion higher than peak cohesion; moderate to low values of peak and residual strength parameters.
Corehole CH3:	Tp. 52, R. 24, W4th Mer. - Edmonton Formation
CH3-1A	moderate peak angle of shearing resistance but very low residual angle; residual cohesion is higher than peak cohesion ($C_P = 0$ psi).
CH3-2A	moderate values of peak and residual strength parameters.
CH3-3A	moderate values of peak and residual strength parameters.
Corehole CH6:	Tp. 53, R. 7, W5th Mer. - Paskapoo and Edmonton Formations
CH6-54	peak strength results exhibit considerable scatter; high peak strength parameters; residual (undisturbed) cohesion is very high.
CH6-69	residual strength of remoulded samples deviates considerably from that of undisturbed material; very high peak and residual strength parameters.
Corehole CH8:	Tp. 52, R. 20, W5th Mer. - Paskapoo Formation
CH8-45	very high peak strength parameters; peak rupture line (1) statistically correct; peak rupture line (2) excludes data at highest normal load but may be more representative of strength parameters; very high residual (undisturbed) strength.
CH8-74	exceptionally high peak and residual (undisturbed) strength parameters; remoulded and precut samples exhibit comparable strengths but are both lower than the undisturbed case.

Scatter of Peak and Residual Strength Results

The scatter of peak shearing resistance values about the statistically determined Mohr rupture lines in figure 21 varies widely among samples. In general, the scatter of results is more pronounced in the highly indurated, cemented rocks from the western portion of the study area, e.g. compare the low scatter of the CH1 series with the wide scatter of the CH8 series. However, this lack of precision is to be expected in testing fine-grained sedimentary rocks, which exhibit wide variations in composition, texture, and structure on both macroscopic and microscopic scales. A study of the samples reveals that the following factors influenced the scatter:

(1) Wide variation in grain size on a macroscopic and microscopic scale (Pl. 8, Fig. 1) is present from sample to sample. A plot of clay content versus the peak angle of shearing resistance, ϕ_p' (Fig. 22) illustrates the relationship between grain size and peak strength. At low clay contents (high silt plus sand contents), such as exist in the rocks from the western portion of the study area, large variations in the peak angle of shearing resistance develop from minor variations in the coarser-sized fraction. However, at high clay contents, such as exist in the eastern portion of the study area, minor changes in the peak angle of shearing resistance occur with fluctuations in grain size distribution.

(2) Variations in shearing resistance within one rock type depend upon the location of the failure planes with respect to inherent structural weaknesses or reinforcements. Weak zones coincide with microfissures, laminations of organic matter, or microseams of bentonite. Structural reinforcement is supplied by cements or recrystallized zones.

(3) Variations in computed shearing resistance arise from failure plane irregularities (Table 13), for shear resistance calculations are based on plane surfaces.

(4) Variations in bulk properties such as density and water content undoubtedly contribute to scatter, but in most samples they are masked by the above-mentioned factors.

The Mohr rupture lines for two sample series, CH8-45 and CH6-54 require some comment. The points for series CH8-45 show exceptionally wide scatter, and two peak rupture lines are shown in figure 21: the first considers all points but the second excludes test results at $\sigma = 145.4$ psi, which fall well below the least squares fit of the data in the first line. Strength parameters resulting from the second line appear more representative of the rock type (Paskapoo Formation) at this locality, but no independent basis exists for rejecting the test results at $\sigma = 145.4$ psi. Therefore, the first line, which is based on all the data, has been used in subsequent analysis of the peak strength results, although the distribution of points may be non-linear.[9]

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[9] Curvature of Mohr rupture lines has not been reported at these normal loads. Also, a curvilinear envelope would result in an upper slope that would be much flatter than the residual angle of shearing resistance (22.5°) which it should approach (Patton, 1966; Sinclair and Brooker, 1967).

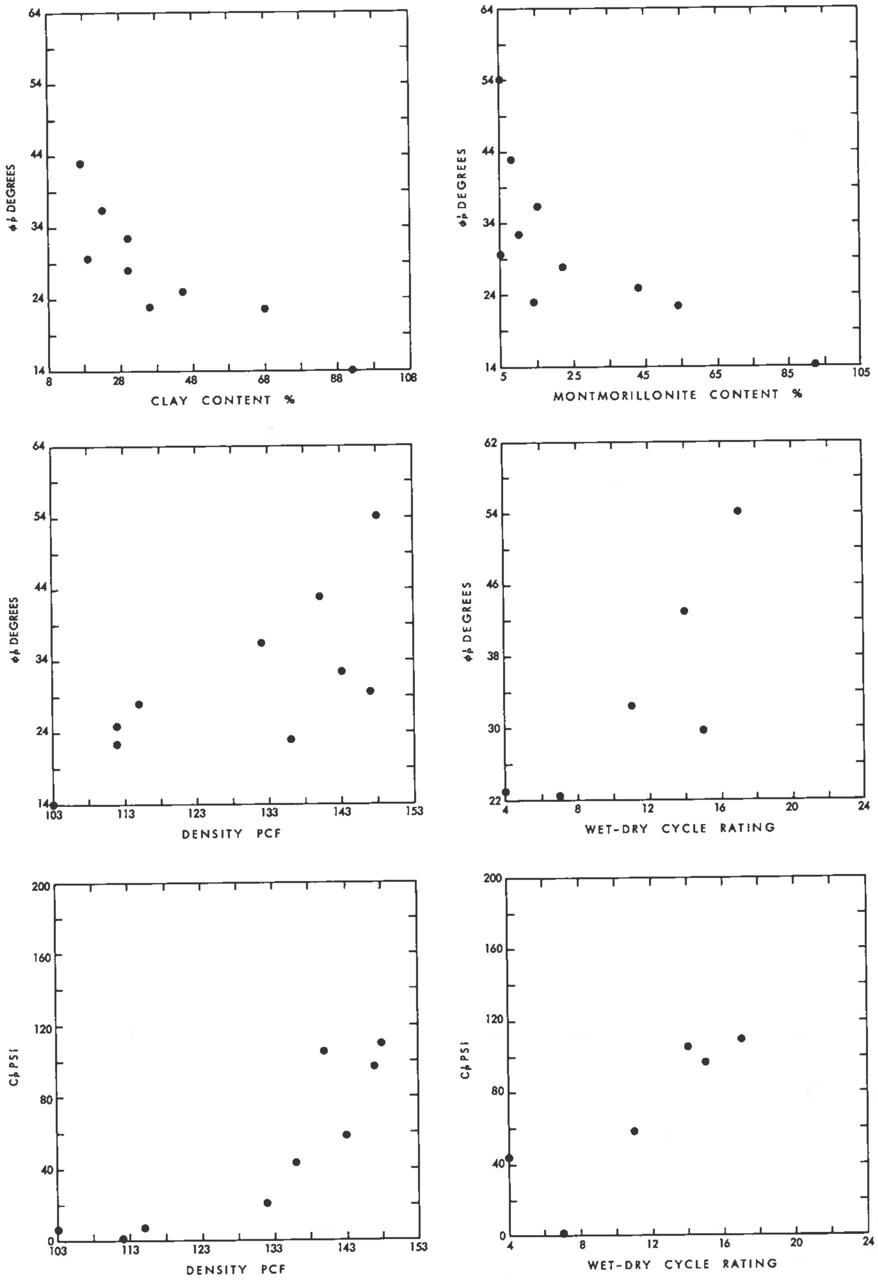

FIGURE 22. Relationships between effective peak strength parameters and other rock properties, fine-grained rocks of central Alberta.

The CH6-54 series illustrates that scatter can be attributed to a variation in peak cohesion. Rupture lines may be fitted by least squares to the results (excluding the very uppermost point) to form two other rupture lines, one above and one below the best fit line shown. The slopes of these lines differ from that of the best fit line by a maximum of one degree, but a variation in the cohesion intercept from 76 psi to 35 psi is present. The low cohesion values are attributed to microfissures and structural weaknesses associated with the organic content.

The deviations of residual shearing resistance test results from the statistically determined Mohr rupture lines are slight. The most noticeable variations are found in the tests on undisturbed samples of rocks from the western portion of the study area. Factors considered to contribute to the scatter are:

(1) inherent variation in the microstructure of the rocks;

(2) variations in irregularities in the failure planes, due in part to (1) above;

(3) machine or technique error: the forward shearing displacement produces a smaller limiting stress ratio (residual strength) than the reverse direction (Fig. 18).[10]

Selection of Related Rock Properties

The relationships between peak and residual strength parameters and selected petrographic, chemical, and bulk physical properties of the sheared corehole samples are indicated by the corresponding correlation coefficients in table 14. The statistical data are based on analyses of only ten samples; thus the conventional level of significance is high, 0.576 at the 5 per cent probability level (Snedecor, 1956). Hence, inferences based on these correlations and on the results of multiple regression analysis described subsequently must be made with caution.

The data in table 14 suggest that the major factors associated with the strength parameters are clay and montmorillonite content, bulk density and related properties, wet-dry cycle ratings, and distance as expressed in miles across the strike of the strata. Examination of plots for each pair of variables (Figs. 22, 23) shows that some of these relationships are curvilinear and recalculation of the correlation coefficients using logarithmic transformations of clay and montmorillonite contents and distance shows marked improvement in most of the r values (in brackets in table 14). However, logarithmic transformations of density determinations cause little change in r values, and the relationship of this property to shear strength is assumed to be linear.

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[10] This phenomenon existed with Ottawa Sand or no soil in the shear box. The source could not be detected but was ascribed to machine error. The average of the two curves was used.

Table 14. Correlation Coefficients (r) for Shear Strength Parameters and Other Properties of Ten Direct Shear-Tested Specimens

		Composition							Plasticity				Bulk Properties				Distance
		Clay	Mont.	Ill.	Na	Ca + Mg	PWS	Org.	W_L	W_P	I_P	A	γ_t	e	W_N	WDR	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Peak Strength Parameters	ϕ'_P	-.83 (-.94)[1]	-.72 (-.78)[1]	-.39	-.26	-.41	-.20	-.26	-.63	-.56	-.63	.15	.73	-.57	-.74	.83	-.53 (-.57)
	c'_R	-.72 (-.82)[1]	-.67 (-.89)[1]	.12	-.58	-.26	-.23	-.56	-.70	-.60	-.70	-.20	.87	-.76	-.72	.85	-.77 (-.79)
Residual Strength Parameters	ϕ'_P	-.72 (-.90)[1]	-.59 (-.77)[1]	-.07	-.30	-.31	-.12	-.39	-.56	-.50	-.57	.10	.71	-.56	-.64	.95	-.73 (-.79)
	c'_R	-.15	-.37	.49	-.11	-.35	-.08	.08	-.37	-.55	-.32	-.50	.51	-.34	-.42	-.49	-.04

[1] Bracketed values determined from log-transformed values of clay, montmorillonite, and distance variables.

KEY - Col. 1 (% clay content); Col. 2 (% montmorillonite content); Col. 3 (% illite content); Col. 4 (sodium ion content, milliequivalents); Col. 5 (calcium plus magnesium ion content, millequivalents); Col. 6 (pore water salts content, millequivalents); Col. 7 (% organic matter) Col. 8 (liquid limit); Col. 9 (plastic liquid); Col. 10 (plasticity index); Col. 11 (activity); Col. 12 (bulk density, p.c.f.); Col. 13 (void ratio); Col. 14 (% natural water content); Col. 15 (wet-dry cycle rating); Col. 16 (distance across strike, miles).

Several generalizations can be made from the data in table 14. The first is that the three strength parameters, ϕ'_P, C'_P, and ϕ'_R, exhibit similar correlation patterns with the other rock properties. This indicates that these parameters themselves are closely interrelated. These correlations are:

(1) high with clay and montmorillonite content, density, and related properties such as wet-dry ratings and distance (the relative magnitude of the r values varies somewhat, but the signs are the same for each parameter);

(2) moderate with Atterberg limits and plasticity index;

(3) generally nonsignificant with chemical properties.

The fourth parameter (C'_R) shows generally low or nonexistent correlations with the other rock properties. Hence, either the random technique error associated with the determination is high, or this parameter is related to a set of causal parameters other than those studied.

Effective Peak Strength

Angle of Shearing Resistance

Classically, rock strength is divided for analytical purposes into two measurable attributes: the effective peak angle of shearing resistance (ϕ'_P) and peak cohesion (C'_P). The degree of correlation between these attributes and various other properties of fine-grained rocks from central Alberta is indicated in table 14 and by the corresponding scatter diagrams in figure 22.

Multiple regression analyses of some of these relationships were performed with individual strength parameters as the dependent variables. The analyses are based on a small sample size (N = 10), and the interpretation of results therefore must be made with caution.

The multiple regression equation for the effective peak angle of shearing resistance, ϕ'_P, is:

$$y = -2.3774 + 0.5740x_1 + 40.2272x_2 - 61.1377x_3 - 0.0466x_4$$

where $y = \phi'_P$ in degrees

x_1 = density in lbs/cu ft

x_2 = log per cent montmorillonite

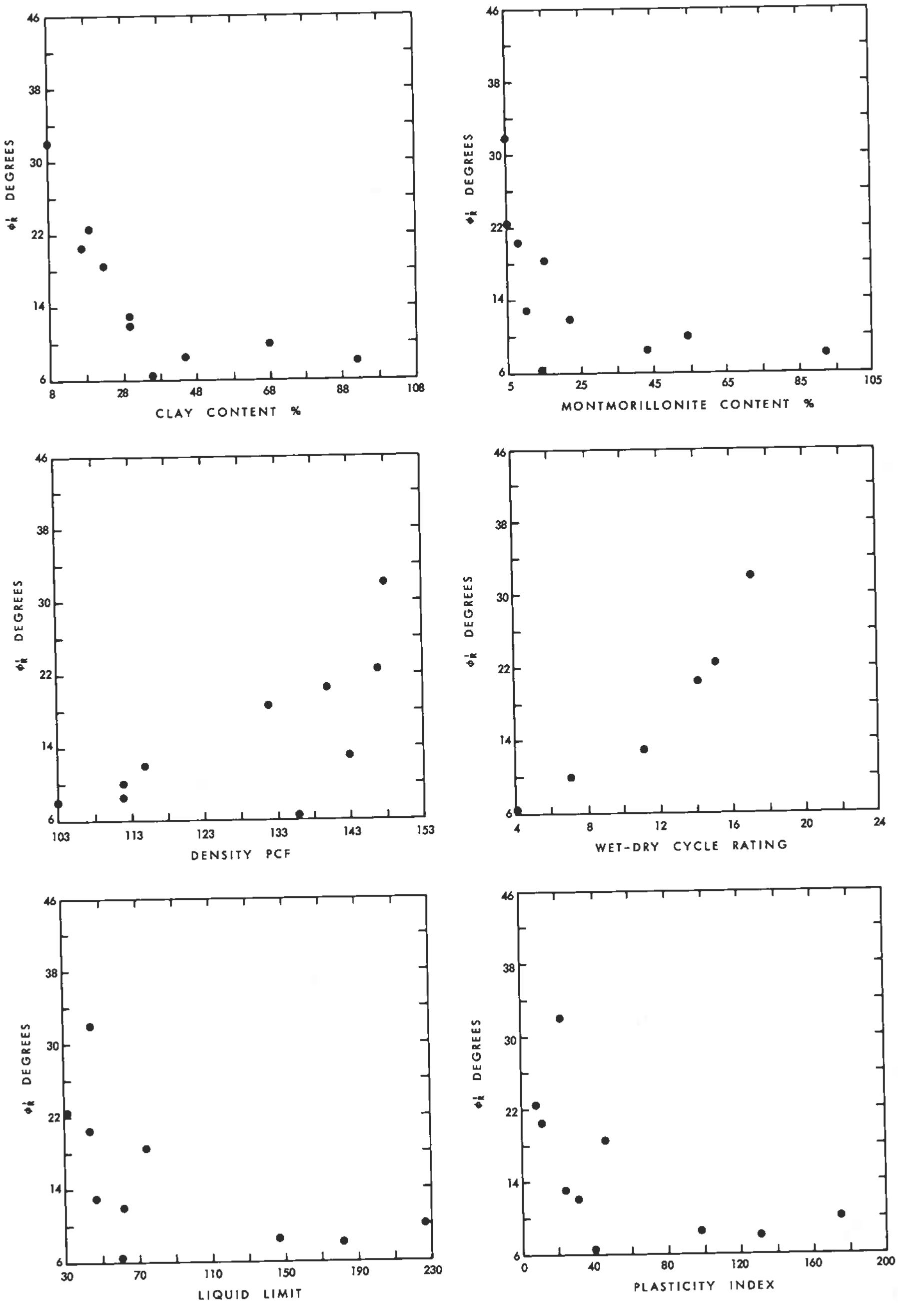

FIGURE 23. Relationships between effective residual angle of shearing resistance and other rock properties, fine-grained rocks of central Alberta.

x_3 = log per cent clay content

x_4 = log distance in miles

The four independent variables together "explain" 95 per cent of the variation in ϕ'_p (R^2, Table 15), but, as indicated by the standard partial regression coefficients (b′), distance contributes little to the efficiency of the equation. This is confirmed by deleting the distance factor and recalculating the equation: the R^2 value remains constant (Table 15, second trial). In the third trial montmorillonite content is dropped from the equation with a small loss in efficiency (6 per cent); thus it appears that clay content and density are the main factors associated with the effective peak angle of shearing resistance. In fact, clay content alone appears as efficient a predictor of ϕ'_p as the two variables combined, if the difference between R^2 and r^2 values (.89 and .88, respectively) is taken as a criterion. Confirmation of clay content as the most important single "contributor" to variation in peak angle is suggested by grouping and analyzing the related data in table 11 by coreholes. In each case, where more than one series of samples was tested (CH1, CH3, CH6, and CH8 series), the highest peak angle is associated with the lowest clay content, and *vice versa*. Thus, although some degree of association with density exists, it is masked to a large degree by local variations in clay content.

The scatter diagram in figure 22 shows the relation between variation in clay content and ϕ'_p, in which the peak angle values drop approximately 30 degrees with a corresponding increase in clay content of 25 per cent. Similar plots are shown for montmorillonite content, density, and wet-dry cycle ratings, the last two variables being directly related to "bond strength."

The physical basis for the apparent relationship between clay content and peak angle values has been studied by a number of investigators (e.g. Mitchell, 1956; Trollope and Chan, 1960), but their findings are not necessarily applicable to this study. In the fine-grained Alberta rocks shear occurs either through or around the individual particles, depending on the strength of the grains relative to the interparticle bond strength. Generally, failure occurs around rather than through the sand- and silt-sized particles, chiefly quartz and feldspars which exhibit relatively high strength. However, failure through grains is conceivable, e.g. in a micaceous or clay-sized material bonded by strong cement. Microscopic examination of the failure plane surfaces reveals that the majority of the surfaces are rough or have irregularly shaped projections as a result of failure occurring around the particles (Table 13, Columns 6, 7). These irregularities are most common in rocks with high sand plus silt content. Thus, the surface along which peak strength develops is much like that of a piece of sandpaper with the "grade" dependent upon the grain size of the material. This "sandpaper surface," in turn, is imposed upon the macroscopic failure plane configuration, which may be straight, concave, undulating, or irregular (Table 13, Columns 2, 5).

Table 15. **Multiple Regression Analyses of Properties Associated with Effective Peak Cohesion (above) and Effective Peak Angle of Shearing Resistance (below)**

Independent Variable	First Trial			Second Trial			Third Trial			r^2
	b	b'	Relative b'	b	b'	Relative b'	b	b'	Relative b'	Linear Regression
Clay content (log. %)	-61.1377	-2.8062	1.00	-61.1432	-2.8065	1.00	-41.2985	-1.8956	1.00	0.8783
Density (p.c.f.)	+ 0.5740	+2.2771	0.80	+ 0.5738	+2.2763	0.81	- 0.1340	-0.5316	0.28	0.5341
Montmorillonite content (log. %)	+40.2272	+1.5930	0.57	+40.2099	+1.5923	0.57	---	---	--	0.6082
Distance (log. miles)	- 0.0466	-0.0030	0	---	---	--	---	---	--	0.3202
a	- 2.3774			- 2.4205			+108.9470			
R^2	0.9506			0.9506			0.8895			

Independent Variable	First Trial			Second Trial			Third Trial			Fourth Trial			r^2
	b	b'	Relative b'	b	b'	Relative b'	b	b'	Relative b'	b	b'	Relative b'	Linear Regression
Clay content (log. %)	-14.5906	-0.3546	0.12	---	---	--	---	---	--	---	---	--	0.6786
Density (p.c.f.)	+ 1.4277	+3.0020	1.00	+ 1.2230	+2.5720	1.00	+ 1.6118	+3.3896	1.00	+ 1.7295	+3.6371	1.00	0.7550
Montmorillonite content (log. %)	-28.3672	-0.5957	0.20	-45.7095	-0.9599	0.37	- 5.0355	-0.1058	0.48	---	---	--	0.7891
Distance (log. miles)	+15.7317	+0.5365	0.18	+17.1769	+0.5857	0.23	-92.2099	-3.1444	0.93	-93.5339	-3.1895	0.88	0.6222
Organic content (%)	-33.9560	-0.4482	0.15	-34.7402	-0.4586	0.18	---	---	--	---	---	--	0.3080
a	-93.3994			-69.6734			+36.4071			+17.8202			
R^2	0.9142			0.9130			0.8813			0.8812			

The development of peak strength appears to be associated with the development of frictional resistance along the inclined surfaces of all irregularities. Patton (1966) investigated the contribution of irregularities on failure surfaces to strength development by studying the mode of failure of plaster of Paris specimens, which had irregularities molded on them. He concluded that the shear strength developed along such irregular surfaces is dependent upon the number, size, and shape of the irregularities, which unfortunately in natural rock specimens cannot be evaluated quantitatively. In a general manner, however, it may be assumed that the size and inclination of the irregularities increase as the grain size increases, if it is assumed that the failure plane does not cut across the coarser grains. The effective peak angles of shearing resistance therefore appear to be related to the clay contents or sand plus silt contents of the fine-grained rocks of central Alberta through the concept of strength development along irregular failure surfaces. Thus, concentrated clay seams, no matter what thickness, can control the peak strength of a fine-grained rock.

The direct relationship between shear resistance and density shown by the Alberta rocks is comparable to that reported for limestones and marls by Kowalski (1966). The increase in density of the Alberta rocks is associated with an increase in wet-dry cycle rating, or in other words, an increase in bond strength, which should result in an increase in the number and size of irregularities, thereby contributing to a strength increase.

Peak Cohesion

The other component of peak strength – cohesion – is interpreted as the intercept on the shear strength axis, C'_p. Peak cohesion is related to a number of other rock properties (Table 14), among which density and wet-dry cycle ratings (both related to "bond strength") are prominent (Fig. 22).

Multiple regression analysis of the relationship between C'_p in and other rock properties yields the following equation:

$$y = -93.3994 + 1.4277x_1 - 14.5906x_2 - 28.3672x_3 + 15.7317x_4 - 33.9560x_5$$

where $y = C'_p$ in lbs/cu ft

x_1 = density in lbs/cu ft

x_2 = log per cent clay content

x_3 = log per cent montmorillonite

x_4 = log distance in miles

x_5 = per cent organic matter.

Reference to the corresponding standard partial regression coefficients in table 15 (trial one) shows that density by far is the most efficient predictor of C'_P in relation to the other four variables. However, subsequent recalculations involving successive deletions of the least efficient variable in each case show that distance also contributes to the association with C'_P. Density and distance together "explain" 88 per cent of the variation in peak cohesion, as opposed to either 75 per cent for density or 62 per cent for distance alone. Because wet-dry cycle ratings are strongly related to density and distance, cohesion is influenced by all three factors. Unlike the inferences derived from multiple regression analyses of ϕ'_P and ϕ'_R, compositional effects appear to be subordinate factors in predicting the behavior of peak cohesion.

In the discussion of the scatter of peak strength results, it was noted that the CH6-54 sample series exhibits a constant angle of shearing resistance but the cohesion intercept, C'_P, varies within wide limits. This variation in C'_P is attributed in part to the presence of microcracks in the samples which resulted in a loss of bond linkages and a lower cohesion intercept. Thus, this sample series serves as an example of the effects of bond strength on cohesion.

Reduction of Peak to Residual Strength

The drop in shear resistance from peak to residual strength (as defined by Skempton, 1964) generally involves a complete loss of cohesion and in many cases a considerable decrease in the effective angle of shearing resistance. The drop in shearing resistance after the development of a peak value differs widely with the Alberta rocks, as illustrated by stress-ratio *versus* displacement plots (Fig. 24). These plots generally are comprised of three segments: an initial steep, "linear" positive rise to a peak point; an abrupt reversal of slope to a steep negative value; and a point of curvature followed by a curvilinear relationship. The compacted rocks from the eastern portion of the study area (e.g. CH1-39) exhibit relatively moderate strength drops immediately after peak, followed by a relatively large reduction in strength to the ultimate residual value. The immediate drop in strength after peak is much greater with rocks from the western portion of the area and is followed by a lesser reduction to the ultimate residual value, for example, CH8-74E (Fig. 24).

To compare the relative reductions in strength, a series of strength ratios D_1, D_2, and D_3 were established (Fig. 25).[11] The strength ratio, D_2, is of the same form as Bishop's brittleness index (Bishop, 1967). The two additional strength ratios, D_1 and D_3, were established to describe additional aspects of

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[11] Caution must be taken in evaluating parameters based on the shape of the load deformation curve for reasons outlined by Bishop (1967). However, the parameters appear to serve as a means of comparing material behavior where the materials have been subjected to the same test conditions.

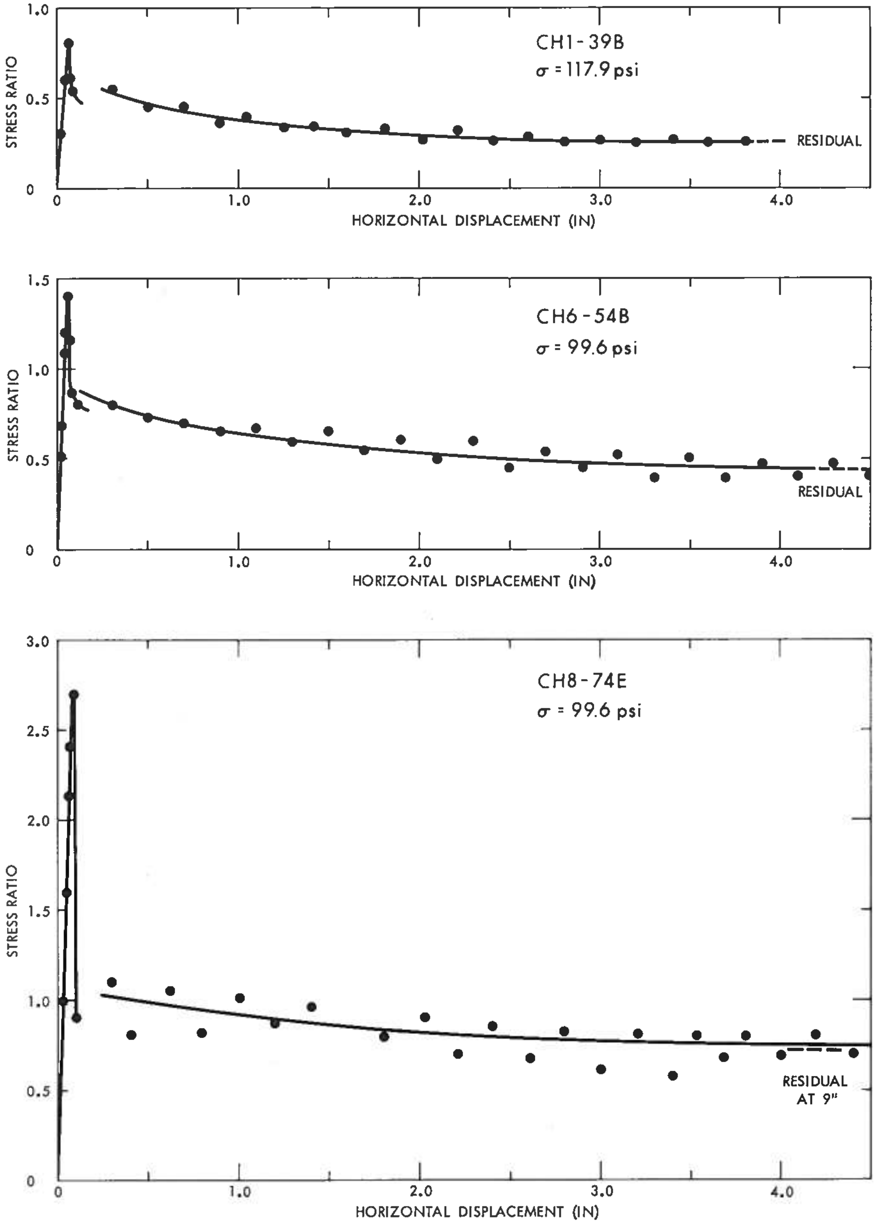
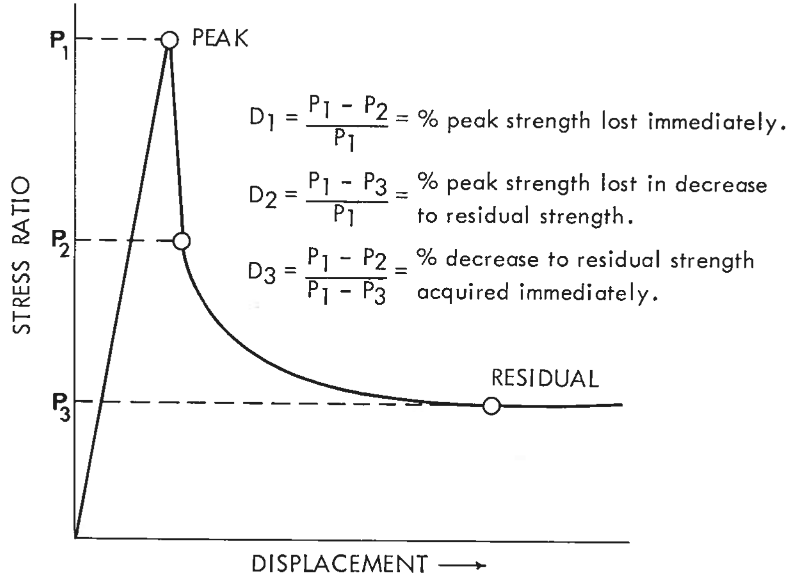


FIGURE 24. Relationship between stress ratio and horizontal displacement in selected corehole samples.



P_1 = peak stress ratio.

P_2 = stress ratio at point of curvature.

P_3 = residual stress ratio.

FIGURE 25. Hypothetical stress ratio versus *displacement curve to illustrate strength ratios.*

material behavior, namely, the degree of immediate strength loss after peak strength is exceeded (D_1) and the percentage of the strength decrease to residual strength acquired “immediately.” Table 16 lists the average strength ratio values and their ranges for each sample series studied. The range of D_1 values is attributable to the difficulty in selecting point P_2. The range in the strength ratios occurs owing to the scatter of the original shear strength data.

Despite the scatter, the D_1 values indicate a definite trend to a greater immediate loss of strength after the peak point with the more brittle, cemented rocks in the western portion of the study area as compared to the compacted rocks of the eastern portion. The D_3 values indicate how close the material is to the residual strength immediately following the loss of peak strength. For example, CH8-74 series has a D_3 equal to 89 per cent, which indicates that a further loss of only 11 per cent of its original strength is required to establish residual strength. However, CH1-39 with a D_3 equal to 33 per cent has to lose 67 per cent more of its original strength to establish residual strength. Thus, D_3 values illustrate that the cemented rocks in the western portion of the study area exhibit a shearing resistance nearly equal to residual strength almost immediately

Table 16. **Strength Ratios of Corehole Samples Subjected to Direct Shear Tests**

Sample Series	D_1 Mean	D_1 Range	D_2 Mean	D_2 Range	D_3 Mean	D_3 Range
CH1-39	23	20-25	70	68-78	33	28-37
CH1-53	10	0-23	58	55-62	17	0-37
CH6-54	42	32-55	68	64-71	61	48-79
CH6-69	63	56-67	79	75-82	80	75-81
CH8-45	53	44-59	68	78-55	76	72-81
CH8-74	67	65-68	74	65-80	89	84-100

after peak strength has been exceeded, whereas the compacted rocks to the east lose only approximately one-third of their competence immediately after the loss of peak strength.

This difference in the behavior of the three sets of samples appears to be attributable mainly to bond type and strength present in the rocks. Bonds are divided into two types by Goldstein and Ter-Stepanian (1957): *brittle bonds* formed over long periods of time which permit elastic deformation and then fail; and *viscous bonds* which form, break slowly under stress, and often reform readily. Cementation and recrystallization probably aid in developing the brittle bonds common to the rocks in the western portion of the study area, whereas electrical attractive forces such as van der Waals and Coulombic forces produce the viscous bonds common to the compacted rocks in the east. Such bond systems may explain the variation in the load-deformation characteristics of soft rocks from the Alberta Plains as they have for clays (Goldstein and Ter-Stepanian, 1957; Crawford, 1963).

Residual Strength from Undisturbed, Precut, and Remoulded Samples

Residual Angle of Shearing Resistance

The concept of residual strength can be resolved into two parameters: residual angle of effective shearing resistance (ϕ'_R) and residual cohesion (C'_R), both determined from the Mohr diagrams in figure 21. The residual angle, ϕ'_R (from undisturbed samples), is correlated with several rock properties, the multiple regression equation for the relationship being:

$$y = 44.6365 - 31.7280x_1 + 0.2366x_2 + 20.1518x_3 - 18.1352x_4$$

where $y = \phi'_R$ in degrees

x_1 = log per cent clay content

x_2 = density in lbs/cu ft

x_3 = log per cent montmorillonite

x_4 = log distance in miles.

The standard partial regression coefficients in table 17 (trial one) show that clay content is the most efficient predictor of the effective residual angle, although the other three independent variables appear to play a useful role in this respect. However, subsequent recalculation of the equation and the corresponding standard partial regression coefficients suggests that deletion of density (second trial) and then montmorillonite content (third trial) from the equation leads to only a minor loss in efficiency (about 4.5 per cent), distance and clay content together "explaining" 88 per cent of the variation in ϕ'_R. In fact, although the standard partial regression coefficients (third trial) suggest that distance is the more important of the two variables, the respective r^2 values for the linear regressions of clay content and distance show that clay content alone "explains" about 81 per cent of the variation in ϕ'_R whereas distance "explains" only 63 per cent. A study of the related data in table 11 shows that the same relation exists between clay content and ϕ'_R at specific coreholes, i.e. much of the variation in residual angle values can be attributed to local variation in clay content. Thus, in the case of both parameters ϕ'_P and ϕ'_R, clay content appears to be the dominant controlling factor.

A comparison of the effective residual angles of shearing resistance, ϕ'_R, as determined from undisturbed, precut, and remoulded samples, shows precut samples to have lower ϕ'_R values than undisturbed samples, but remoulded specimens to have ϕ'_R values both higher and lower than undisturbed samples (Fig. 21). The lower ϕ'_R values associated with precut failure planes presumably result from the fact that such failure planes contain only microscopic irregularities, whereas the higher values of ϕ'_R associated with undisturbed samples are in part due to irregular failure planes. According to Patton (1966), differences between the two sets of ϕ'_R values correspond to the weighted means of the angles of the irregularities on the failure planes, although this is not confirmed for the results described here.

Residual shear strength parameters for samples with cut planes were selected after a lamina of soil "mush" had formed between the two halves of the specimen. It was noted that the shear resistance along a freshly cut plane is greater than that which develops after the sample is reversed numerous times and a soil "mush" forms along the cut plane. The frictional resistance between freshly cut surfaces is augmented by microscopic irregularities which are worn off with deformation, the resulting soil "mush" reducing the shear resistance. A similar phenomena was observed by Patton (1966) with tests on plaster of Paris.

Table 17. Multiple Regression Analyses of Properties Associated with Effective Residual Cohesion (above) and Effective Residual Angle of Shearing Resistance (below)

Independent Variable	First Trial			Second Trial			r^2
	b	b'	Relative b'	b	b'	Relative b'	Linear Regression
Clay content (log. %)	+23.8007	+3.8986	0.54	+23.9983	-3.9309	0.52	0.0010
Density (p.c.f.)	- 0.5142	+7.2759	1.00	- 0.5358	+7.5816	1.00	0.2559
Montmorillonite content (log. %)	- 1.6730	-0.2366	0.03	---	---	--	0.0125
Distance (log. miles)	- 3.4157	-0.7832	0.12	---	---	--	0.0031
a	-98.8480			-96.8178			
R^2	0.7900			0.7825			

Independent Variable	First Trial			Second Trial			Third Trial			r^2
	b	b'	Relative b'	b	b'	Relative b'	b	b'	Relative b'	Linear Regression
Clay content (log. %)	-31.7280	-2.8048	1.00	-28.0953	-2.4836	1.00	-17.5453	-1.5510	0.82	0.8055
Density (p.c.f.)	- 0.2366	-1.8079	0.64	---	---	--	---	---	--	0.5018
Montmorillonite content (log. %)	+20.1518	-2.4928	0.89	- 8.8041	+0.6726	0.27	---	---	--	0.5961
Distance (log. miles)	-18.1352	-2.2433	0.80	-17.4500	-2.1586	0.87	-15.2228	-1.8831	1.00	0.6274
a	+44.6365			+82.2744			+72.8897			
R^2	0.9235			0.9122			0.8778			

The ϕ'_R value obtained from the remoulded specimen (ϕ'_R = 25.5°) is very similar to that found on the precut sample (ϕ'_R = 23.9°), for the CH8-74 sample series. Thus, in this instance the residual strength parameters obtained from tests on remolded specimens appear to be reliable estimates of the residual parameters of the undisturbed material, especially when the extremely variable composition and texture of this rock is considered. However, the ϕ'_R values from the remoulded specimens for the CH1-39 and CH6-54 series (20.0° and 26.8° respectively) are two to three times the values for undisturbed samples (6.5° and 13.0°, respectively). This discrepancy was noted by Hayley (1968) in tests on Upper Cretaceous marine shales from northern Alberta. Hayley postulated that the variation may be explained by:

(1) orientation of clay particles in undisturbed material compared with random structure in remoulded specimens;

(2) homogeneity of grain sizes in remoulded specimens compared with laminated structures in undisturbed samples;

(3) segregation of silt and clay particles in the remoulded material during shear.

A study of thin sections of undisturbed and remoulded samples shows that both exhibit negligible orientation of clay particles. No consistent variation in the silt content of the remoulded material in the failure zone of either sample type is present to indicate that segregation of the materials is a contributing factor to variation in strength. The major contributing factor appears to be the difference in the microstructure of the specimens, exemplified by subparallel lamination (sorting) of clay, silt, and organic (coaly) particles. In summary, it is difficult to estimate the effective residual strength parameters of complex materials such as the fine-grained rocks of central Alberta by means of tests on remoulded specimens.

Multiple regression analysis shows clay content to be the major factor contributing to variation in ϕ'_P, which fact is in keeping with the findings of Skempton (1964). Skempton also postulated that the drop in strength from peak to residual is due in part to the increase in water content along the failure plane and to the development of thin bands of oriented clay particles along the failure plane. He points out that silt or sand particles do not orient themselves; thus, they exhibit higher values of ϕ'_R and where coarse material is associated with clay, the ϕ'_R is greater than for clay alone because the coarser material inhibits the development of an oriented band.

With cemented rocks, the major factor causing the drop in strength from peak to residual is rupture of the brittle bonds; this occurrence is followed by a further reduction in strength due to the breakdown of irregularities on the failure surface. With compacted rocks, the loss of strength from peak is somewhat similar except that the bonds are viscous and their rupture does not involve such a drastic initial loss of strength. The effects of water content on the failure surfaces of the Alberta rocks are unknown (water contents could not be taken as the samples had to be kept intact for thin section studies). However, it is assumed that the major drop in shear strength, following the immediate loss after the peak point, of the compacted rocks is influenced by water content changes.

Thin section studies fail to reveal oriented clay bands, even in those samples which have a high clay content. This is probably due to the numerous irregularities on the failure surface which act as "mixers" during the shearing operation, thus preventing particle alignment. In many cases there was sufficient remoulded clayey material in the failure zone to orient unless some action such as mixing prevented it. Since particle orientation appears insignificant in the development of residual strengths in the Alberta rocks, the influence of clay content on $\phi_R^{\prime}$ must be of a different nature than that suggested by Skempton, i.e. it is believed to be associated with the contribution to shear resistance of irregularities on the failure plane. For example, the residual angle of shearing resistance on a precut plane will decrease as the microscopic irregularities decrease, i.e. as the particle size decreases or the clay content increases (compare values for CH2 and CH8-74). With relatively larger irregularities, found in the undisturbed samples, the increase in clay content is associated in the Alberta rocks with a decrease in density and interparticle bond strength, hence an increase in the number of fractured irregularities and a corresponding decrease in $\phi_R^{\prime}$.

Attempts also have been made to relate plasticity to residual strength (Sinclair and Brooker, 1967; Kenney, 1966). Kenney's work indicates that even for pure soil systems a unique relationship between plasticity and $\phi_R^{\prime}$ does not exist. His plot of plasticity index versus the tangent of $\phi_R^{\prime}$ shows a tendency for a decrease in residual strength with an increase in plasticity, but there is considerable scatter. Plots of liquid limit and plasticity index versus $\phi_R^{\prime}$ for the Alberta rocks (Fig. 23) indicate that $\phi_R^{\prime}$ decreases with increasing plasticity, but a definite relationship does not exist. Thus, despite the fact that such factors as clay content, mineralogy, and systems chemistry have been related to $\phi_R^{\prime}$ by various workers and the fact that each of these factors also affects plasticity, any relationship that may exist between plasticity and $\phi_R^{\prime}$ appears too weak to predict values of one property from values of the other.

Residual Cohesion

The fact that residual cohesion ($C_R^{\prime}$) shows generally low correlations with other rock properties in comparison with the other three strength parameters (Table 14) suggests that this parameter may be of a basically different nature, if indeed it has any real significance in terms of rock "strength." Multiple regression analysis throws some further light on these relationships, using C'_R (from undisturbed samples) as the dependent variable and those rock properties associated with other strength parameters as independent variables.

The multiple regression equation is:

$$y = -98.8480 + 23.8007x_1 + 0.5142x_2 - 1.6730x_3 + 3.4157x_4$$

where $y = C'_R$ in lbs/cu ft

x_1 = per cent clay content

x_2 = density in lbs/cu ft

x_3 = per cent montmorillonite

x_4 = distance in miles.

The four independent variables together "explain" about 79 per cent of the variation in C'_R (Table 17, first trial), which drops to only 78 per cent when the two least significant contributors (montmorillonite content and distance) are omitted (second trial). The situation is interesting, for neither clay content nor density alone are efficient predictors of variation in residual cohesion. In fact, the relationship of clay content with C'_R is contrary to the other strength relationships. Thus, a meaningful statistical interpretation of the "causal" factors associated with C'_R appears impractical on the strength of existing evidence.

The fact that an appreciable cohesion intercept was obtained in the residual strength determinations of undisturbed samples led to further testing with remoulded specimens and intact specimens with precut failure planes. Residual cohesion intercepts, C'_R, ranging from 3.0 to 17.5 psi, were found for undisturbed rock samples tested by the writer and C'_R values of 2.5 to 4.5 psi were found for other rock types in the study area (Fig. 21). In fact, the last-named results contain values of C'_R that exceed corresponding values of C'_P in some cases. The three rock specimens, CH8-74, CH1-53, and CH2-9A, tested with precut failure planes exhibited negligible or small cohesion intercepts; values ranged from 0.4 to 1.4 psi. (Only two rock types were tested with cut planes by the writer; insufficient sample material was available for the CH6 series, and test preference was given to samples required to establish the peak rupture line.) Residual rupture lines on remoulded specimens also show low C'_R values, i.e. less than 1.0 psi, except for CH8-74 which has a $C'_R = 5.0$ psi.

Skempton (1964) reported that the residual cohesion for London Clay and other overconsolidated clays is so small to be negligible. With these clays the increase in water content and orientation of the clay particles has reduced the inherent cohesion such that the material behaves much like a normally consolidated clay. The cohesion intercepts reported above for the remoulded specimens and samples with precut failure planes are generally small enough that they might be considered negligible. A search of the literature, however, reveals that residual cohesion intercepts can occur because of the influence of irregularities or projections on the failure plane (Goldstein *et al.*, 1966; Patton, 1966; Kenney, 1967).

A study of the failure planes in thin sections and by visual examination reveals that in most cases the failure planes which develop in the Alberta rocks have irregularities on both the microscopic and macroscopic scale (Table 13; Plates 13, 14). If the cohesion intercept is attributed to strength development along the irregularities of a failure plane, then it appears that it should not be considered cohesion *per se,* but rather as a form of "friction" which is dependent upon the normal stress applied and the weighted mean of the angles of inclination of the projections, in a manner similar to the findings of Patton (1966). The shear resistance developed is a measure of the work exerted by the horizontal thrust to lift and slide each projection past one another, against the effects of the normal load. During the development of the residual strength with displacement (large displacements are acquired by reversing the shearing direction), some projections which have a strength lower than the stress required to move relative to one another, rupture or break off. In this manner, the shearing resistance decreases with displacement until no further projections break off under the normal load applied, and the stress-ratio *versus* displacement curve levels off. Thus, for these materials the observed residual shearing resistance is in part dependent upon the normal load applied. A testing program that involves high normal loads might find a residual rupture line with slight downward curvature, reflecting a decrease in resistance with increase in normal load, as a result of the failure of an increasing number of projections. This type of envelope was not observed in the results discussed here, for the magnitude of the normal loads was such that very few projections were sheared off, as shown by thin section studies.

Summary

The relationships with respect to effective strength as outlined above can be more readily realized with the aid of a schematic diagram (Fig. 26). Arrows indicate the sequence of events or effects, and positive and negative signs represent direct and inverse relationships, respectively, as determined from tables 15 and 17. The diagram can be explained as follows: distance and clay content are assumed to be the primary "causal" factors in a complex variable system, whereas distance represents or measures the sum of the tectonic and overburden pressures to which the rocks have been subjected during their history, and clay content the basic compositional-textural properties. Density and montmorillonite are secondary factors which themselves are interrelated. All four factors affect "strength" (ϕ'_P, C'_P, ϕ'_R, C'_R) as discussed above.

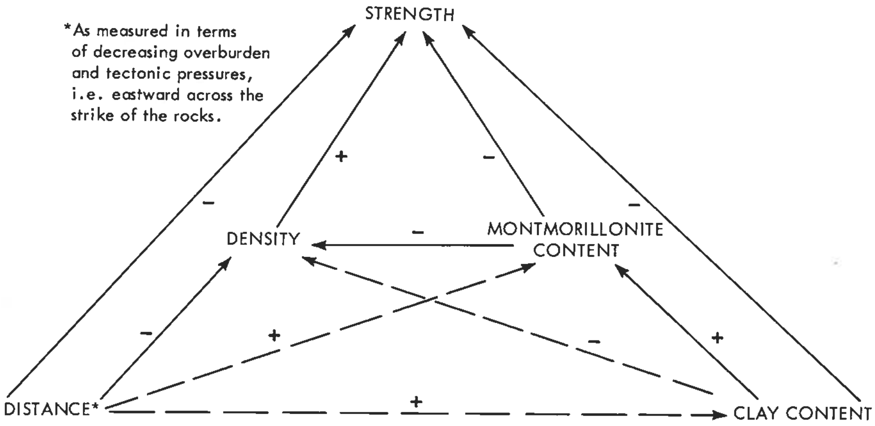


FIGURE 26. Schematic representation of interrelationships among rock properties affecting rock "strength".

For example, assume an increase in distance. This results in a direct drop in "strength," and a concomitant decrease in density. However, density is directly related to "strength," so that a decrease in density also results in a decrease in strength. Similarly, an increase in clay content results in a decrease in "strength" and a corresponding increase in montmorillonite content. The increase in montmorillonite content has two effects: a direct decrease in "strength" and a decrease in density, which is also associated with a decrease in strength.

Similar effects can be postulated if less well-developed relationships among distance, density, clay, and montmorillonite contents (shown in Fig. 26 as dashed lines) are considered. That is, an increase in either distance or clay content will directly or indirectly lead to a decrease in sample strength due to a high degree of intercorrelation among the variable pairs involved. This intercorrelation (in conjunction with the small number of samples tested) is the reason for the apparent failure of some of the independent variables to contribute to the precision of the multiple regression analysis of strength and cohesion parameters. One, or at the most two independent variables are sufficient to predict or "explain" approximately 80 per cent or more of the variation in the dependent variables summarized below.

Dependent Variable - Strength Parameter	Independent Variable Capable of Predicting Approximately 80% of the Variation in the Dependent Variable	Percentage Predicted
ϕ'_P	Clay content	87
C'_P	Density, distance	88
ϕ'_R	Clay content	81
C'_R	Density, clay content	78

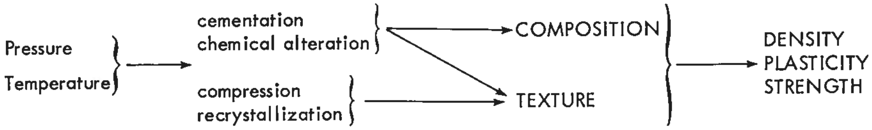
DISCUSSION OF RESULTS

Diagenesis

Causes and Effects

The agencies and processes associated with the phenomenon of diagenesis are outlined in a general way in a preceding section of the report. Broadly, these can be grouped as physical agencies or forces (pressure, temperature) operating on a regional scale within the sedimentary basin and those physical and chemical processes (compression, recrystallization, cementation, chemical alteration) at work on a local scale within the sediment mass (Fig. 2). Closely connected with these processes, and interacting with them to produce the final rock or soil type, are the compositional and textural features of the sediments and the physico-chemical properties of the surrounding pore fluids.

The complexity of diagenetic processes inhibits separating their effects into well-defined, measurable entities (Krumbein, 1942), but the sum or mass effects can be detected or inferred in many cases. In general, diagenetic processes and effects can be related in the manner shown schematically in the sketch below.



Basically, the relationship is such that an increase in the pressure-temperature gradient after deposition and burial leads to certain changes in the composition and textures of the unconsolidated sediment which involve:

(1) compression, reorientation, and possibly recrystallization of grains;

(2) expulsion of pore fluids;

(3) precipitation of chemical cements and replacement or alteration of existing mineral constituents.

These effects in turn lead to changes in the mass physical properties of the rocks, such as:

(1) reduction in porosity and permeability;

(2) increase in bulk density;

(3) increase in bond strength and related parameters.

The intensity of these processes and their effects also is a function of the initial composition and texture of the raw detritus and the physico-chemical properties (pH, Eh, ionic composition and concentration) of the pore fluids. During and immediately after deposition, the unconsolidated clastic material (soil) is subject to compositional changes that strive to attain equilibrium among the detritus, the surrounding pore fluids, and prevailing pressure-temperature conditions. Thus, sediments composed of inherently inert detritus, such as quartz, will exhibit minimal changes in composition and texture due to diagenesis, whereas those containing a high proportion of "unstable" constituents, such as volcanic glass and feldspars, are particularly prone to breakdown with the concomitant formation of new minerals stable at lower pressures and temperatures. Obviously, the initial chemical changes which take place in the unconsolidated sediment during and shortly after deposition will have considerable bearing on subsequent postburial (diagenetic) changes.

Indicators of Diagenetic Effects in Central Alberta Rocks

Some diagenetic effects – those concerned with composition and texture – can be directly observed from thin section studies, especially in coarser-grained clastic rocks. Others, including the bulk chemical and physical properties, can be related only indirectly to diagenetic processes, through prior knowledge of the depositional and stress histories of the rocks. With respect to the bedrock formations of central Alberta, it is assumed that the *intensity* of diagenetic effects increases in an east to west direction, across the regional strike of the strata towards the margin of the Foothills. This assumption is based on a knowledge of the stratigraphy and structure of the rocks, from which a model of the subsequent tectonic and erosional history of the region can be developed, as outlined in a preceding section. In this regard, it is of equal or greater interest to determine the value of regional changes in mass rock properties as indicators of the *degree* of diagenesis, as to determine or surmise the effect of discrete processes on individual sediment properties.

Composition and Texture

The degree of cementation and types of mineral cements in sandstones are useful indicators of the intensity or stage of diagenesis to which the nonmarine Cretaceous-Tertiary strata of Alberta have been subjected. Petrographic studies of sandstones associated with these rocks indicate that two series of compositional changes associated with diagenesis have taken place (Carrigy and Mellon, 1964):

(1) initial alteration of unstable volcanic detritus (glass, feldspars, micas) to form montmorillonite and kaolinite, which are found as cements in the sandstones of the Plains region; and

(2) subsequent alteration of montmorillonite and kaolinite to illite and chlorite under the influence of elevated temperatures and pressures within the folded Foothills region.

Similar compositional changes may be expected in the fine-grained rocks such as those described in this report. A few of the more bentonitic specimens exhibit relict shard structures (Plate 5), the original volcanic glass having altered to montmorillonite. Others contain irregular patches of montmorillonite or carbonate cement, although, in general, evidence of cementation and mineral alteration is difficult to obtain from thin sections owing to the fine particle sizes of the mineral constituents. Indirect evidence of regional changes in composition due to diagenesis, based on clay mineral analyses of the rocks (Table 3), are inconclusive, probably owing to the change in stratigraphic units in an east to west direction, and hence in the inherent clay composition of the rocks.

Local textural features due to compression and, less commonly, recrystallization can be observed in a number of rocks, although these phenomena are difficult to separate in many cases from inherited depositional features. Contortion of mica flakes and bedding features are common, both in samples from the eastern (Plains) area and from the folded Foothills. Similarly, grain orientation features (partly depositional in origin) are distributed randomly across the area, and their distribution yields no clue to regional variation in intensity of diagenesis. At the outcrop level, however, the presence or absence of such features may have some bearing on local variations in diagenetic processes which, in turn, may be related to strength parameters.

Bulk Density

Bulk density serves as an excellent indicator of the relative intensity of the compressional aspect of diagenesis for the fine-grained rocks of central Alberta, if some allowance is made for variations due to compositional and sampling ("random") factors. In particular, montmorillonite content shows a moderately high correlation with bulk density in both outcrop and corehole samples. Consequently, a high degree of variation is observed in bulk density measurements at most sampling localities, producing noticeable deviations from the regional trends shown in figure 12. However, if average values are used for each locality, a systematic east to west increase in density is observed, as the samples are traced from the Plains to the Foothills, which can be explained in terms of the depositional and stress history of the near-surface bedrock formations of central Alberta.

Density also serves as an indicator of the reverse process – weathering – in which the rock-forming bonds are destroyed rather than produced. Resistance to weathering increases in an east to west direction as shown by the systematic decrease in the difference between the average density of corehole and outcrop samples (Fig. 12). These trends are consistent with the concept that the degree of diagenesis in central Alberta increases towards the Foothills, in accordance with the general model of tectonic and depositional history developed by geologists.

Plasticity

The plasticity of fine-grained rocks or soils is affected mainly by those diagenetic processes which influence composition, i.e. chemical alteration and cementation. Certainly, the alteration of volcanic glass to montmorillonite is an outstanding example of the effects of diagenesis on plasticity, and changes in the ion-exchange system also may alter the plasticity of fine-grained rocks.

On a regional scale, sample plasticity values for fine-grained rocks from central Alberta show a low correlation with distance from the Foothills margin (Table 7), which is taken as a measure of the relative intensity of diagenetic processes. This is in large part due to compositional effects, especially local variation in the montmorillonite content of the rocks, which tend to mask any regional trends that may be present. Consequently, plasticity alone cannot be used to determine the degree or intensity of regional diagenesis, although it does serve to indicate certain compositional changes brought about by local diagenetic processes, e.g. the breakdown of volcanic glass to montmorillonite.

Bond Strength

The application of wet-dry cycle tests to the fine-grained rocks of central Alberta shows an apparent increase in the resistance of these materials to breakdown by simulated "weathering" processes in an east-west direction, towards the margin of the Foothills. This resistance can be attributed to the "bond strength" of the rocks, which in turn reflects the intensity of diagenetic processes to which the strata have been subjected.

Wet-dry cycle ratings also show a moderately high positive correlation with bulk density, which increases in a westerly direction towards the Foothills margin. However, local variations in clay content and mineral composition (montmorillonite and carbonate contents) affect both wet-dry cycle ratings and density values to some extent, partly masking the trends attributed to the effects of regional diagenetic processes. Nevertheless, wet-dry cycle tests are useful in obtaining a preliminary classification of the fine-grained bedrock strata of central Alberta which incorporates the concept of bond strength and which relates to the relative intensity of diagenetic processes involved in transforming "soils" to true "rocks."

Shear Strength

Natural slopes along bedrock river valleys in central Alberta commonly exhibit slumping and block movements, especially in the eastern part of the area underlain by the Belly River and Edmonton Formations. In the west, towards the Foothills margin, bedrock slumping appears to be less common, and it may be inferred from this observation that rock "strength" increases in a westerly direction, across the Alberta Plains, in response to the apparent regional increase in that direction of the relative intensity of diagenetic processes.

At first glance there is an apparent correlation between strength parameters (angles of shearing resistance and cohesion) and those chosen as indicators of the degree of diagenesis (density and distance from the Foothills margin) on the basis of data summarized in table 12. However, regional trends in strength attributes – especially those determined from angles of shearing resistance, ϕ'_P and ϕ'_R – are masked to a large extent by local variations in the clay content of the rocks, and subsequent analysis of the data shows that only peak cohesion (C'_P) can be directly related to density and distance factors. This interpretation is based on a small number of samples and must therefore be regarded with some caution, especially in view of the marked variation in composition of the samples tested for strength properties. Obviously, additional data from more closely spaced coreholes are required to determine the relationships between rock strength and composition (clay content) and those factors associated with diagenetic (i.e. bond-forming) processes in the near-surface bedrock formations of central Alberta.

Soil-Rock Transformation

The question has been posed in the introductory section of this report: At what point or stage following deposition does sediment mass cease behaving like a "soil" and take on the attributes of a true "rock"? Furthermore, how do the fine-grained "rocks" of the central Alberta Plains fit into a soil-rock classification scheme on the basis of existing data?

The answers to these questions are:

(1) There is no sharp distinction or boundary between true "soil" and true "rock"; rather, there exists a transitional area or zone characterized by materials with properties intermediate between those of soils and rocks.

(2) Most of the samples collected and analyzed for this study fall within the transitional zone between "soil" and "rock," they are, in fact, "soft rocks."

All of the shallow bedrock strata described in the preceding sections of the report have been subjected to various diagenetic processes since they were deposited as unconsolidated detrital sediments in late Cretaceous or Paleocene times. Volcanic ash has altered to montmorillonite, chemical cements have been deposited amongst the intergranular pores, and the entire succession of strata has been subjected to compression by the weight of overlying sediments. Consequently, none of the fine-grained rocks described here resembles the original soil-like sediment which existed during and immediately following deposition; all have been altered by physical and chemical processes which strive to attain equilibrium between the mineral particles and pore fluids, which together constitute a soil or rock, and the surrounding physico-chemical environment.

This is true even in the eastern Alberta Plains area, underlain by highly unstable bedrock formations (Edmonton and Belly River Formations) containing numerous bentonite or bentonitic claystone beds with soil-like properties, e.g. wet-dry cycle ratings of 5 or less. Nevertheless, these beds have undergone significant alteration from volcanic ash or glass particles to a weakly bonded clay-silt aggregate composed of montmorillonite. The strength properties of such beds are still comparable to those of a soft clay, even though the original composition and texture have changed substantially since deposition.

Despite the absence of a sharp boundary between "soil" and "rock" in the fine-grained strata of central Alberta, the evidence presented here suggests that some of the strata are more "rock-like" than "soil-like" in their physical and geotechnical properties, whereas others are more "soil-like" than "rock-like." The boundary between these two classes of materials is not defined by any one property, nor is it a hard-and-fast line which can be drawn unequivocally on a bedrock map of central Alberta. However, some consistent changes can be observed in the material behaviour of these strata which generally accord with the distinction between "compaction" and "cementation" rocks, defined by Philbrick (1950). These changes are:

(1) in wet-dry cycle ratings. "Cementation" rocks (ratings greater than 11) are confined to the western part of the Plains and Foothills, whereas "compaction" rocks (ratings of 11 or less) are more common in the eastern Plains of Alberta.

(2) in shear strength. "Cementation" rocks exhibit a large and rapid drop in shear resistance when peak strength is exceeded. Thus, they demonstrate a more brittle (rock-like) nature than "compaction" rocks, which show a more viscous (soil-like) behaviour.

(3) in cohesion. "Cementation" rocks exhibit large cohesion intercept values, which indicate high intrinsic strengths at zero normal stress.

(4) in large-scale slumping phenomena. Landslides are more common in the western part of the study area than in the east.

Again, local variations in composition, especially clay and montmorillonite contents, mask to varying degrees regional trends in the physical properties of the bedrock strata in central Alberta. Thus, highly bentonitic beds in the western part of the area, including the Foothills, will possess the attributes of "compaction" rocks, whereas hard carbonate-cemented (sideritic) strata were observed (but not tested) in the eastern Plains. However, these are exceptions rather than the rule, and their existence does not preclude drawing a general (or regional) distinction between soil-like "compaction" rocks and rock-like "cementation" rocks on the basis of criteria outlined above.

Practical Applications

Petrographic Studies

Thin section studies of soils and soft rocks have been recognized in recent years as a valuable tool in soil mechanics research (e.g. Mitchell, 1956; Morgenstern and Tchalenko, 1967a, b, c). The primary advantage of such studies is that they permit direct observation of microstructural and compositional heterogeneities in the material under investigation, an understanding of which is particularly important in the study of small specimens in the laboratory. An excellent example is provided by a thin section cut from a direct shear specimen of a fine-grained rock studied at the University of Alberta by Sinclair and Brooker (1967). If this sample had been cut so that the failure plane was imposed one-eighth of an inch lower, the direct shear test results would not fit the strength data from the test series, and the anomalous value would be difficult to explain. However, the thin section reveals a petrified wood fragment about one-eighth of an inch from the actual failure plane.

The amounts and distribution of montmorillonite are of particular interest because of the effect of this mineral on the shear strength of many fine-grained rocks and thus on bedrock slope stability in the Alberta Plains (Sinclair *et al.*, 1966; Sinclair and Brooker, 1967). Montmorillonite (bentonite) seams of variable lateral extent and thickness can be observed in both drillholes and outcrops of such rocks, and thin section studies reveal that similar "partings" of pure montmorillonite are present on a microscopic scale (Plates 2, 11). These observations are confirmed by the results of X-ray diffraction analyses, although the diffraction patterns do not indicate how the montmorillonite is distributed within the rocks. Thus, if montmorillonite is present but evenly disseminated throughout the rock, its effect on shear strength presumably will be less than if it forms discrete laminae or partings which constitute distinct planes of weakness. Thin section studies may reveal the presence of such laminae and thereby provide an explanation for anomalously low shearing resistance values in seemingly "hard" rocks. Meaningful explanations in such cases cannot be found from standard soil tests such as Atterberg limits tests.

These comments also apply to the distribution of organic matter in fine-grained rocks, especially at the hand specimen level used for laboratory tests. Thin coaly partings (Plate 11, Fig. 2) provide potential planes of weakness along which specimens may fail at loads substantially lower than would be observed in the surrounding material. Thin section studies provide a means for identifying these and similar microstructures which can provide some serious problems in interpreting the results of shear strength tests.

Classification of Fine-Grained Sedimentary Rocks

No universally acceptable classification system exists for fine-grained sedimentary rocks owing to the wide range in composition, texture, and structure of these materials. Pettijohn (1957) suggests that partial classification systems be employed, i.e. classification systems for related groups of materials such as those employed in this report for the fine-grained clastic rocks of central Alberta.

The main problem in such classification systems lies in the recognition of "fissility"; to be classed as a "clay-shale" or "shale," the material must be *readily fissile* (Spock, 1953; Pettijohn, 1957; Krumbein and Sloss, 1951). Many researchers, particularly in the field of soil mechanics, do not observe the above criteria, with the result that many so-called "shales" or "clay-shales" in the literature are actually claystones or even siltstones. The danger of such inconsistencies in descriptive terminology is that engineers working in localized areas develop their own concept of "shale" or "clay-shale", and comparisons with similarly named materials in other areas may be misleading. For example, the term "clay-shale" has found wide usage in Western Canada, but the connotation varies from one area to another. The writer advocates that this term should be restricted to fine-grained soft rocks, which are readily fissile and upon rebound and weathering revert to soil-like material that behaves like highly overconsolidated clays. In any case, indiscriminate use of the terms "shale" and "clay-shale" should be avoided, and the terms "siltstone" and "claystone" should be applied in their correct connotation.

The fine-grained rocks of central Alberta are mainly siltstones and claystones (Table 3). They have been classified on the basis of sand-silt-clay ratios following the criteria used by Shepard (1954). Shepard's classification (Fig. 27) is widely used by sedimentary petrologists and can be modified for engineering purposes by including descriptive terms denoting the degree of plasticity: materials with liquid limits greater than 50 are classed as highly plastic, and those less than 50 as moderately to non-plastic. Terms such as "compacted" or "cemented" and "organic" or "inorganic" also can be employed, according to the objectives of the investigator. Those Alberta rocks recognized as "bentonites" in the field are named such, although they also can be classed as highly plastic siltstones or claystones using the criteria suggested here.

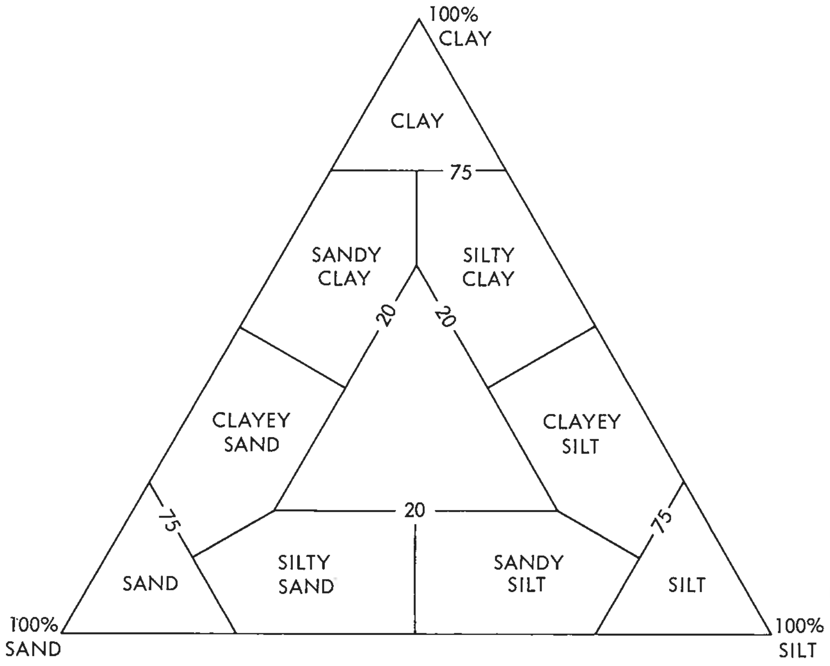


FIGURE 27. Textural classification of sedimentary rocks (after Shepard, 1954).

Shear Strength and Slope Stability

Interest in the shear resistance of bedrock formations of central Alberta has been confined until recently mainly to the Edmonton area, where there is a concentration of construction and design work. The Edmonton area also is underlain by highly bentonitic, incompetent rocks of the Edmonton Formation, as illustrated by numerous cases of instability along the banks of the North Saskatchewan River. Recently, however, interest in water control structures in central Alberta has increased greatly, and future dam sites are under consideration at several localities between Edmonton and the Foothills. In projects of this nature long-term shear resistance of the bedrock must be considered, and in the light of recent research by Skempton (1964) and Bjerrum (1967) and the risk factor involved in such projects, design considerations must take residual strength concepts into account.

Residual strength properties for bedrock materials of the Plains are summarized in table 12 for undisturbed samples, remoulded samples, and samples with precut failure planes, of which the results from undisturbed samples are considered to be most representative of shear conditions in the field. The higher residual strengths associated with undisturbed samples is suggested to be a direct manifestation of the irregularities on the failure surface. Studies of actual slip surfaces in the field show that irregularities and shear zones which contain numerous shear planes and shear lenses do exist in a variety of material types. For example, Morgenstern and Tchalenko (1967a) noted these phenomena in varved silt (Cod Beck), silty clay (Fiddlers Ferry), London Clay (Guildford), Oxford Clay (heavily overconsolidated, fissured clay, Peterborough) and Atherfield Clay (soft clay, Sevenoaks). Skempton (1966) also has presented an extensive discussion of tectonic shear zones in a compact clay at the Mangla Dam project and in a hard siltstone at Lough Fee in Ireland. Thus, despite the lack of studies on actual failure zones in the central Alberta rocks, it appears reasonable in the light of laboratory data and field observations from other localities to assume that failure surfaces of a comparable nature can develop in the Alberta rocks and that the residual strengths of undisturbed samples are representative of natural shear conditions.

Whether the residual cohesion intercept is applicable to field situations or not may be open to question. If it is a manifestation of an irregular failure surface, then it should be applicable to the field. However, as discussed in the section on shear strength, the value obtained for the cohesion intercept on the reported Mohr diagrams is susceptible to considerable variation inherent in the determination of the "best fit" rupture line from scattered data (Fig. 21). The design engineer confronted with similar data, therefore, may be reluctant to employ the "best fit" cohesion intercept in design but rather may select the lowest possible value for the intercept. In this connection, it may be noted that Pennell (1969) found that cohesion must be considered to exist along the failure plane in order to arrive at a factor of safety of unity with the application of residual strength concepts for slopes in the Edmonton area. Testing programs to evaluate the potential residual strength values should consider normal loads representative of field conditions, for the rupture line may curve at higher normal loads where more projections fail, as suggested in a preceding section of the report.

The steep river valleys in the western portion of the study area (from Edson west, Fig. 1) are a reflection of the high peak strengths of the bedrock strata; riverbank slopes and the effective peak angles of shear resistance are of comparable magnitude. In general, it may be stated that the rocks of this area are competent, but if a slope fails as a result of severe undercutting by river erosion, the movements are apt to be rapid, perhaps with no warning of failure, i.e. similar to a rock fall. This hypothesis is suggested in laboratory tests by the large and rapid drop in shear resistance after the loss of peak strength, as illustrated by the strength ratios summarized in figure 24.

In the Entwistle area between Edmonton and Edson (Fig. 1), the rocks exhibit peak strengths comparable to steep "stable" slopes of the river banks near corehole and outcrop sites, although there is evidence of some slope instability in this region (S. R. Sinclair, pers. comm.). The Entwistle region appears to be an area in which the rocks are changing from basically compacted materials to those of a cemented nature; therefore, some instability can be expected in this area, particularly within the compacted rocks. In this connection, detailed studies of bond strength (wet-dry cycle tests) and of the degree of fissuring on both macroscopic and microscopic scales may be quite useful in evaluating the competence of the rocks. The degree of fissuring, among other factors, will indicate the reliability of the peak cohesion intercepts as determined in the laboratory. For example, variation in peak cohesion values of the CH6-54 series of samples (with a relatively constant angle of shear resistance) can be attributed to the presence of microfissures in the rock.

The effective residual angles of shear resistance of the rocks in the western part of the study area are in the neighborhood of 20 to 32 degrees (with the exception of the CH6-54 series, which is transitional between cemented and compacted materials). With such high values of ϕ_R', even the most conservative designs using residual strength parameters provide quite steep slope values. In contrast, the compacted rocks of the Edmonton area are believed to lose strength with time and ultimately fail at a strength value close to or at residual strength (Sinclair, Brooker, and Thomson, 1966; Pennell, 1969). These rocks are believed to have bonds which are generally of a viscous nature and are very susceptible to weathering. Hence, a gradual loss of strength results in long-term movements of a slope to some attitude comparable to the effective residual angle of shearing resistance. In such situations the use of residual strength values for design results in very flat, somewhat costly, slopes.

CONCLUSIONS

The fine-grained near-surface bedrock strata of central Alberta display a wide variation in composition and other properties, although their gross lithologic attributes and inferred depositional environments are similar. This variability in properties is evident at all scales of investigation and, together with some obvious deficiencies in the sampling plan and procedures used for this investigation, presents some problems in determining regional trends in or interrelationships among these properties. Nevertheless, the existing data provide some basis for drawing certain general conclusions concerning the properties of the near-surface bedrock formations in central Alberta. These conclusions are summarized below.

(1) *Composition, texture, and structure:* Most of the fine-grained rocks of central Alberta are siltstones or silty claystones composed of fine sand- or silt-size particles of quartz, feldspars, rock fragments, and micas admixed with variable proportions of clay minerals, organic (coaly) matter, carbonates, and pyrite. Montmorillonite is the dominant clay mineral in most rocks and is especially common in the Upper Cretaceous (Edmonton and Belly River) strata of the eastern Plains. The rocks show extreme variability in texture and microstructures: most are laminated (bedded) to some degree, but relatively few are noticeably fissile or exhibit marked grain orientation.

(2) *Salt content and cation exchange capacity:* The soluble salt contents and cation exchange capacities of the rocks show some relationship to mineral composition but are less consistent with respect to areal distribution. Calcium and sodium are the most abundant adsorbed ions in that order, the amounts depending on the distributions of carbonate cement and montmorillonite, respectively. Seemingly "random" variations in the kinds and amounts of exchangeable cations may well be due to other factors such as groundwater composition and flow.

(3) *Plasticity:* The rocks show large variation in plasticity and related limits owing to the wide range in clay content and composition. One-half of the soft rocks are classed as inorganic clays of high plasticity, and most of the remainder are clays and silty clays of medium plasticity. The majority of samples from the eastern Plains (Edmonton and Belly River Formations) are normal to active rocks with high plasticity indices, whereas most from the western Plains and Foothills (Paskapoo Formation and Brazeau Group) are inactive to normal rocks with moderate plasticity indices. Multiple regression analysis shows that montmorillonite content is the dominant compositional factor associated with plasticity, although total clay and sodium ion contents also are highly correlated with plastic index values.

(4) *Bulk density:* The bulk density of the rocks increases systematically in an east to west direction, towards the Foothills margin, although this trend is masked to a considerable extent by local variations in composition, especially

montmorillonite content. Corehole (unweathered) samples have greater average densities than outcrop (weathered) samples in the eastern part of the area; this difference, presumably due to rebound effects, decreases towards the Foothills where the rocks show greater resistance to weathering processes.

(5) *Bond strength:* The resistance of the rocks to disaggregation by wet-dry cycle procedures (slaking) provides an approximate measure of relative bond strength, thus the related intensity of diagenesis. Wet-dry cycle ratings increase in an east to west direction, towards the Foothills margin, although local variations in carbonate content affect this regional trend. The tests also provide a basis for classifying the rocks into "compacted" and "cemented" types; the former tend to revert to overconsolidated clays upon exposure to the atmosphere, whereas the latter tend to maintain their indurated rock-like attributes.

(6) *Shear strength:* Drained direct shear tests on corehole samples from the Plains area show that three strength paramenters (peak and residual angles of shearing resistance, peak cohesion) exhibit similar correlation patterns with other rock properties. The correlations are especially high with clay and montmorillonite contents, bulk density, wet-dry ratings, and distance from the Foothills margin. The fourth parameter (residual cohesion) shows low or nonexistent correlations with the other rock properties; this suggests that residual cohesion is related to causal factors other than those studied.

Multiple regression analyses indicate that the major causal factors associated with strength parameters are:

Parameter	Factor
ϕ'_P	Clay content
C'_P	Density, distance
ϕ'_R	Clay content

The development of "strength" in the Alberta rocks is explained in terms of bond strength, friction, and irregularities on the failure surfaces. The magnitude of strength loss after peak strength is exceeded appears to depend on strength and type of bond.

It does not appear feasible to attempt to evaluate the residual strength of Alberta rocks from tests on remoulded samples.

(7) *Soil-rock transformation:* Most of the fine-grained Alberta rocks are characterized by properties intermediate between those of true "soil" and true "rock", i.e. they are "soft rocks". However, those from the eastern Plains (Edmonton and Belly River Formations) are more soil-like in their geotechnical

properties than those from the western Plains (Paskapoo Formation), reflecting regional differences in mineral composition, intensity of diagenesis, and stress history associated with the bedrock formations.

(8) *Diagenesis:* All of the rocks have been subjected to diagenetic processes of varying types and intensities since their deposition in Late Cretaceous and Paleocene times. The degree or intensity of bond-forming processes increases in an east to west direction, towards the Foothills margin, although partly masked by local variations in mineral composition. Consequently, rebound effects are more prominent in the eastern part of the Plains, characterized by "compaction" rocks of the Edmonton and Belly River Formations. These effects decrease in a westerly direction, concomitant with apparent increases in density, bond strength, and shearing strength in that direction.

(9) *Petrographic analysis:* The geotechnical engineer should employ petrographic analysis to determine the compositional, textural, and structural attributes of fine-grained soils and rocks. Thus, relevant petrographic details that normally are ignored in assessing geotechnical properties of fine-grained materials can be detected and studied.

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PLATE 1

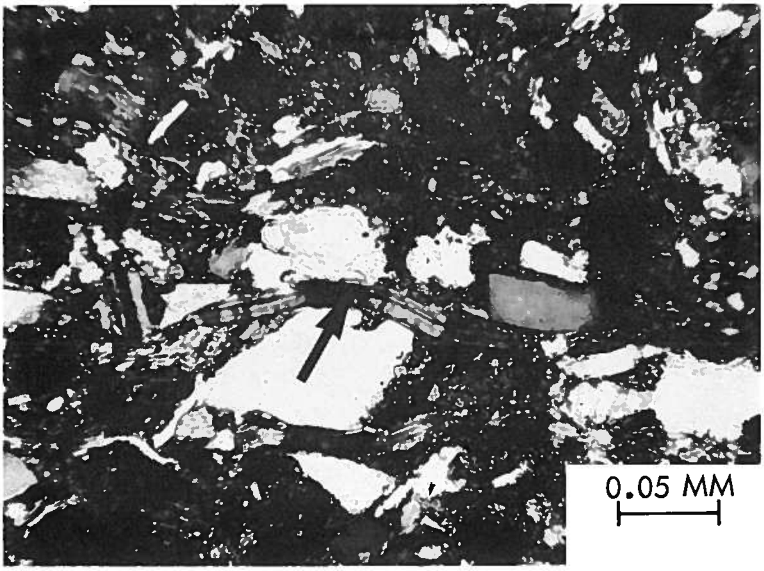

FIGURE 1. *Coarse-grained siltstone consisting of angular quartz, feldspars, rock fragments, and micas with micromicaceous "matrix". Note large distorted biotite plate (arrow). Sample MRL-9, crossed nicols.*

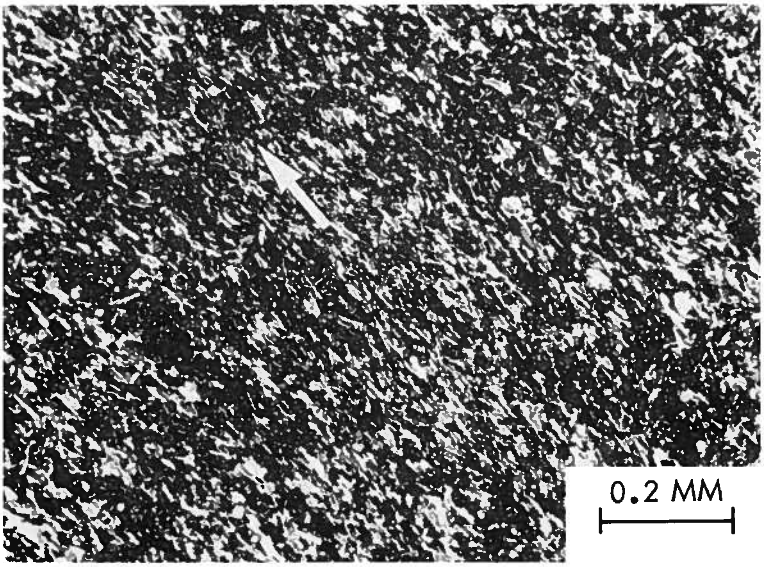

FIGURE 2. *Fine-grained clayey siltstone with oriented micromicaceous "matrix" shown by X-ray pattern to consist of montmorillonite. Arrow indicates inferred bedding plane direction. Sample CH7-1, crossed nicols.*

PLATE 2

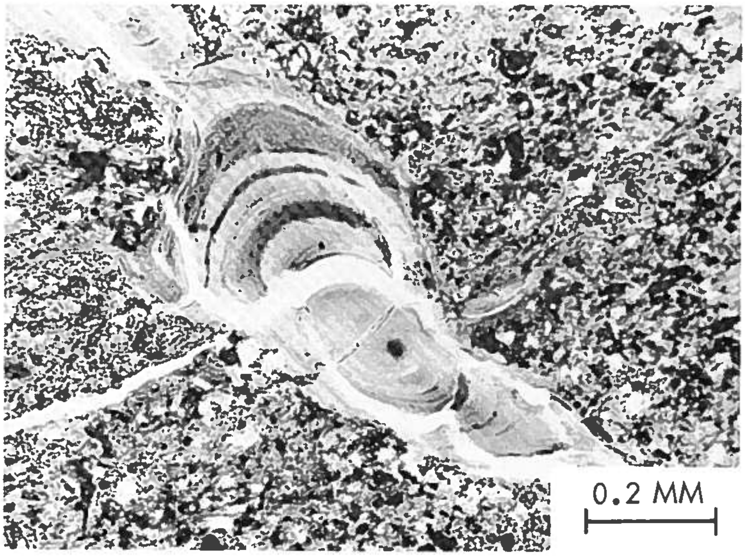

FIGURE 1. Montmorillonite-filled fracture in silty claystone. Ring-like structure indicates that montmorillonite formed from a colloidal gel. Sample CH5-7, plane polarized light.

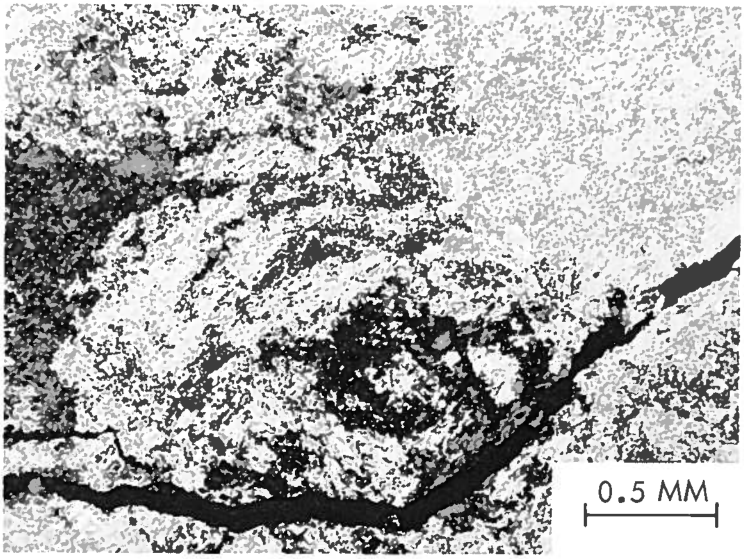

FIGURE 2. Claystone composed of very fine-grained micromicaceous montmorillonite showing irregular "swirly" structure. Dark streak in lower part of field is a crack in the thin section. Sample PEM-6, crossed nicols.

PLATE 3

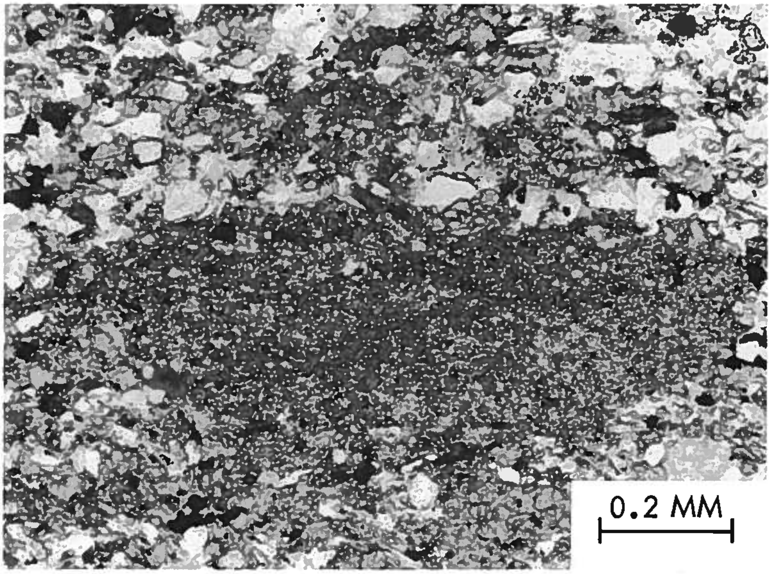

FIGURE 1. Sandy siltstone showing ovoid patch of finer-grained carbonate-cemented material (darker area in center of field). Sample CH5-2, plane polarized light.

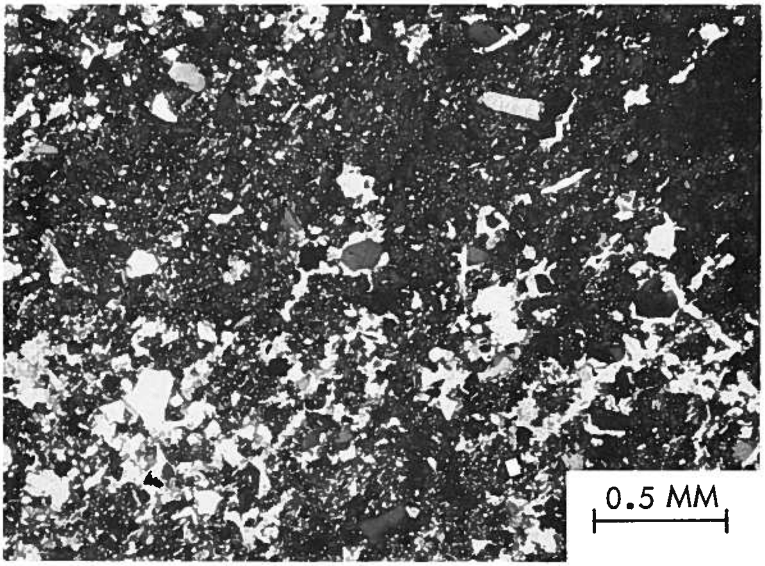

FIGURE 2. Clayey siltstone with dendritic patches of carbonate cement (white, irregularly shaped areas in lower half of field). Sample MYC-1, crossed nicols.

PLATE 4

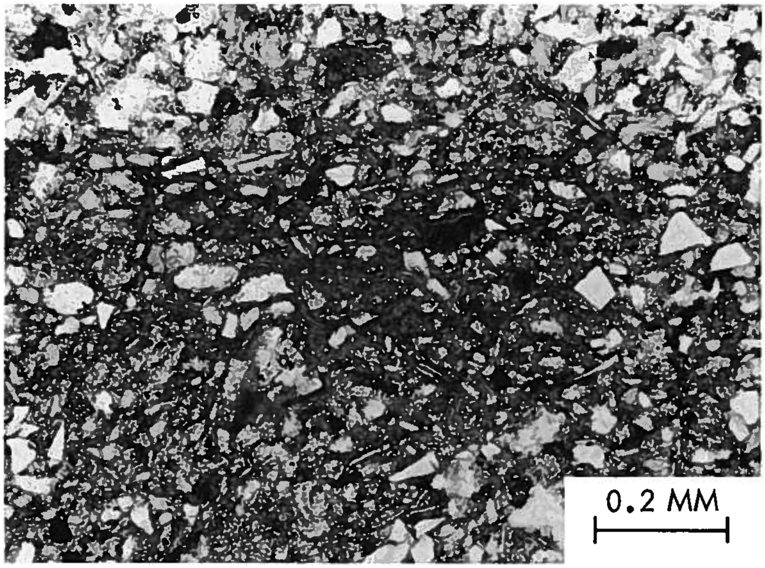

FIGURE 1. Poorly bedded clayey siltstone consisting of angular quartz, feldspars, and scattered mica grains in a cryptocrystalline matrix. Dark material is mainly coaly organic matter. Sample MRL-4, plane polarized light.

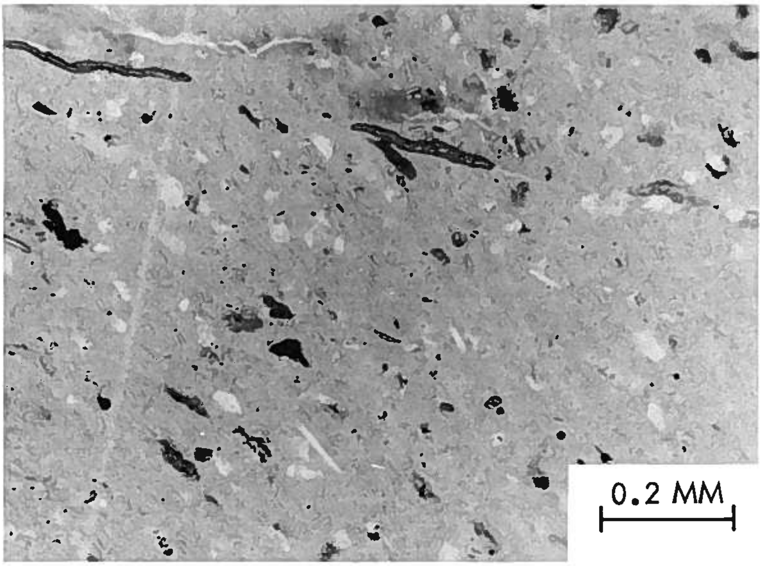

FIGURE 2. Bentonitic silty claystone composed of angular quartz and feldspar silt grains, and small coaly fragments in a cryptocrystalline montmorillonite "matrix" or groundmass. Sample CH2-1, plane polarized light.

PLATE 5

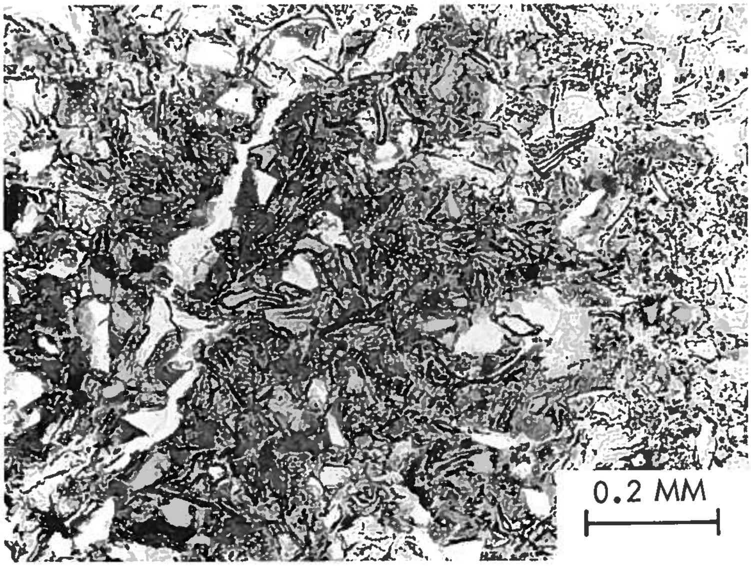

FIGURE 1. Relict shard texture in altered tuff (Kneehills-equivalent?, McLeod River near Mercoal). Quartz silt grains in pale brown montmorillonite groundmass. Sample MER-2, plane polarized light.

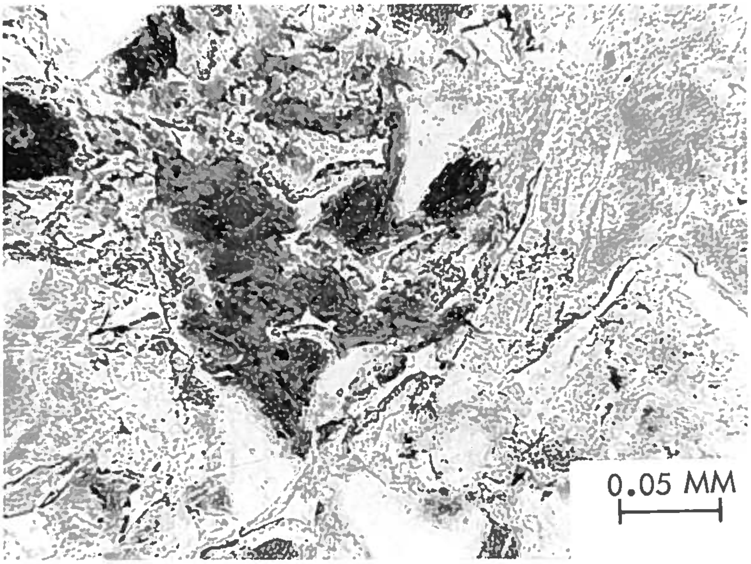

FIGURE 2. Same as figure 1, above. High magnification showing spicule-like outlines of altered glass shards. Plane polarized light.

PLATE 6

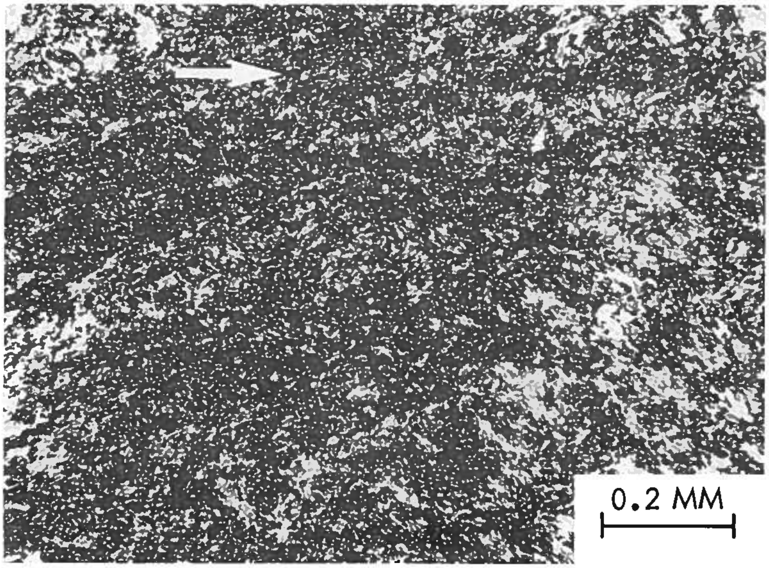

FIGURE 1. Claystone composed of oriented micromicaceous clay aggregates. Arrow indicates inferred bedding plane direction which is parallel to the c-axes of the majority of individual particles. Microscope stage in position of maximum extinction. Sample PEM-6, crossed nicols.

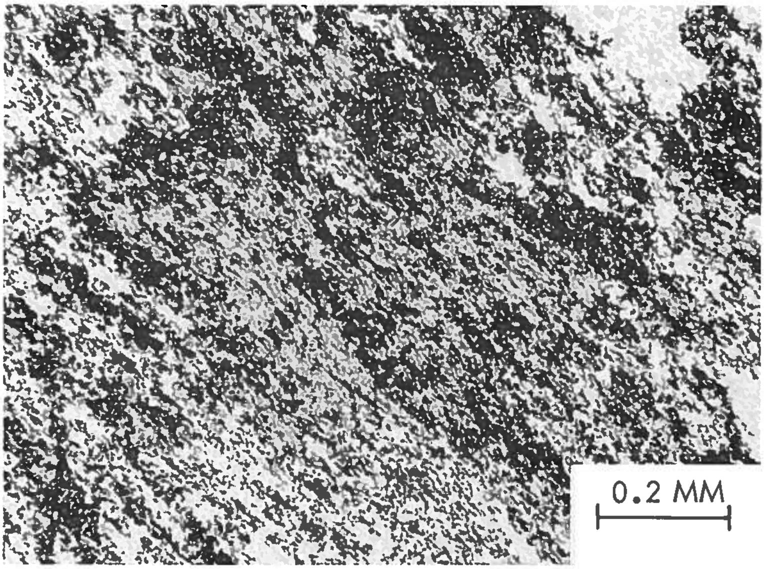

FIGURE 2. Same as figure 1, above. Microscope stage rotated to 45 degrees showing greatly increased aggregate birefringence of oriented clay particles.

PLATE 7

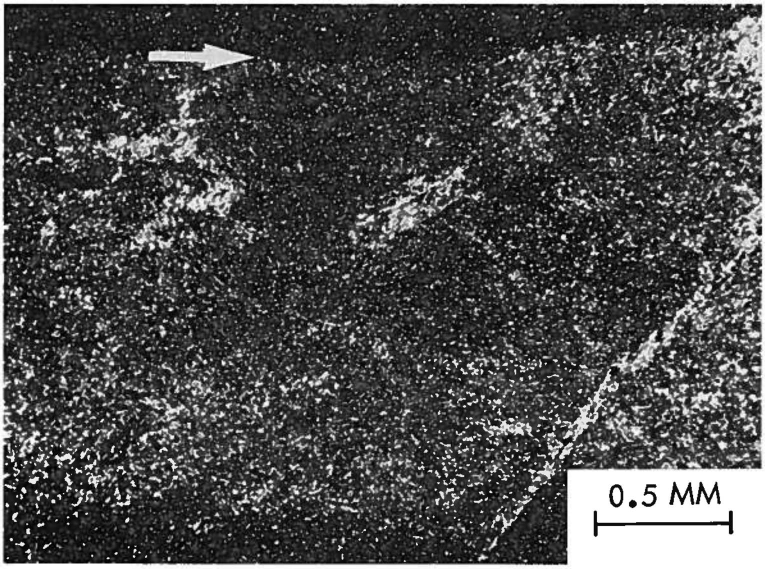

FIGURE 1. *Banded siltstone with oriented micromicaceous clay "matrix". Arrow indicates inferred bedding plane direction which is parallel to the c-axes of the majority of clay particles. Microscope stage in position of maximum extinction. Sample CH6-33, crossed nicols.*

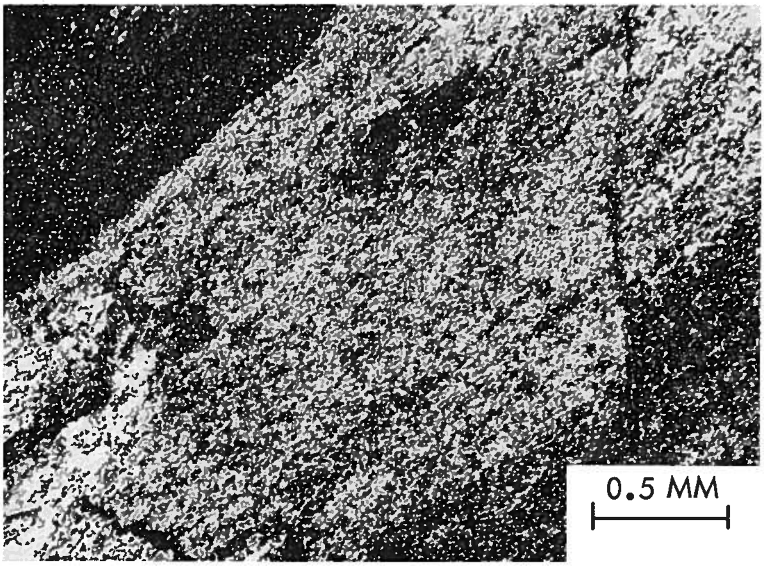

FIGURE 2. *Same as figure 1, above. Microscope stage rotated to 45 degrees showing greatly increased aggregate birefringence of oriented clay particles except in upper left corner of field. Note sharp boundary between oriented and non-oriented areas.*

PLATE 8

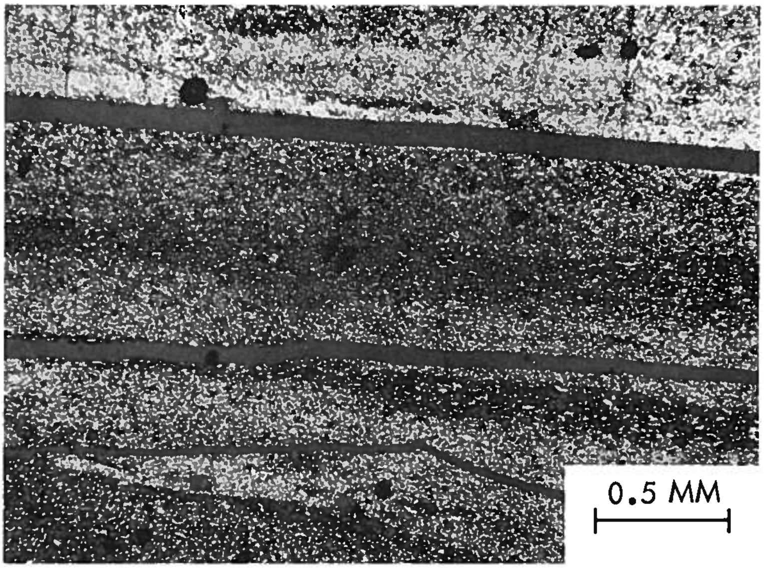

FIGURE 1. Laminated silty claystone showing primary bedding features caused by grain size variation. (Grey subparallel bands are cracks in slide). Sample CH7-4, crossed nicols.

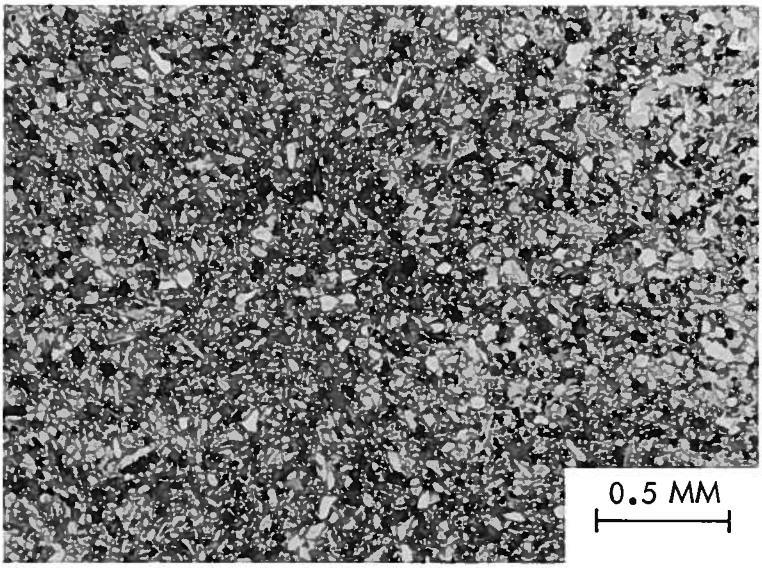

FIGURE 2. Homogeneous clayey siltstone composed of randomly oriented angular quartz and feldspar grains in a clayey "matrix". Sample MRL-4, plane polarized light.

PLATE 9

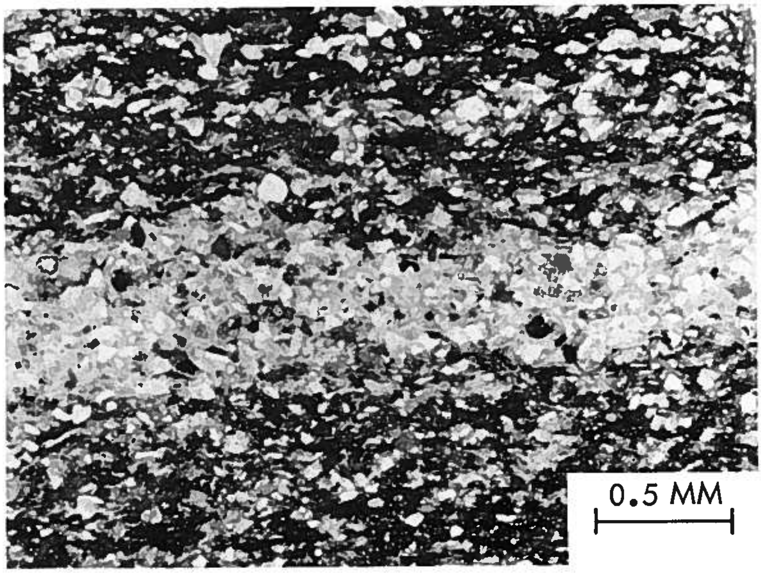

FIGURE 1. Laminated coarse-grained siltstone. Bedding structure is accentuated by abundant organic matter in upper and lower parts of field. Sample CH4-2, plane polarized light.

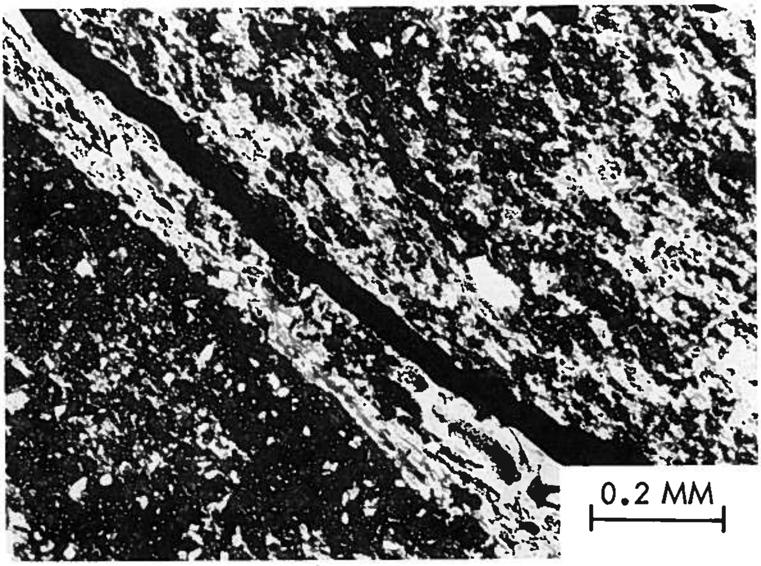

FIGURE 2. Laminated silty claystone. Bedding plane is accentuated by highly oriented montmorillonite aggregates rotated into position of maximum birefringence. Black band which cuts across field from upper left to lower right is a crack in the thin section. Sample CH5-7, crossed nicols.

PLATE 10

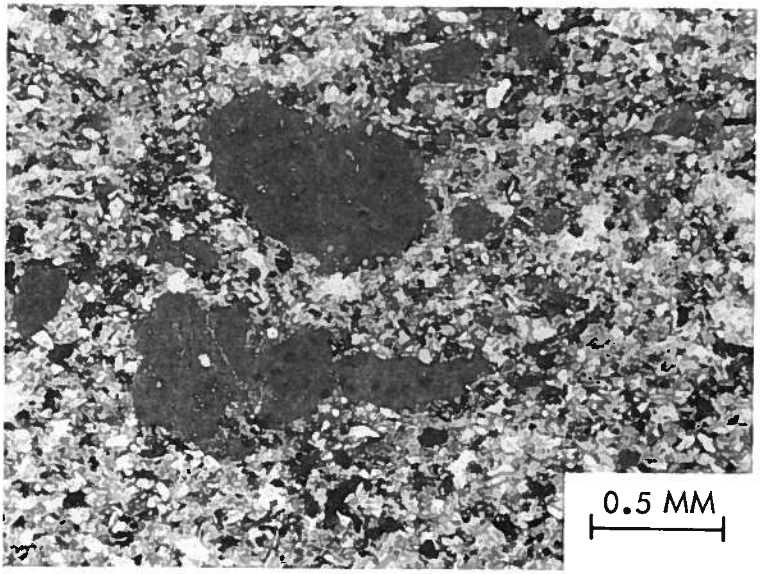

FIGURE 1. *Clayey siltstone showing large green mudstone pellets in randomly oriented silty groundmass. Sample CH5-1, plane polarized light.*

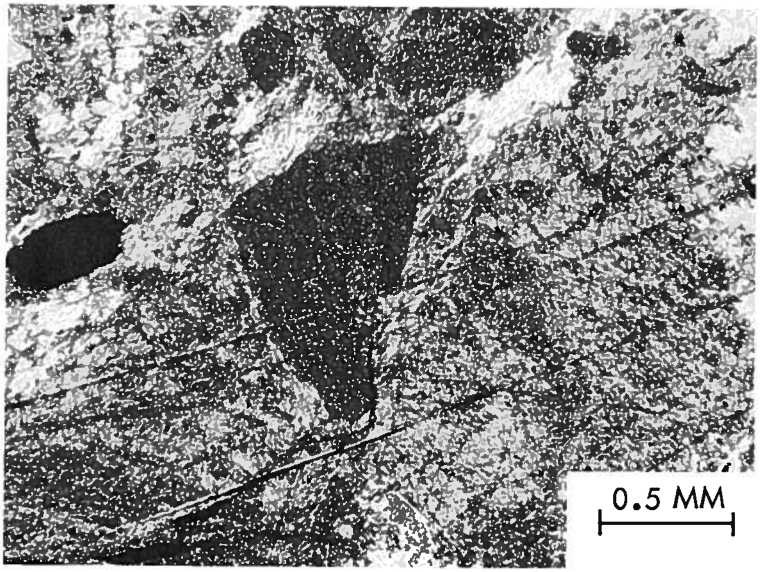

FIGURE 2. *Bentonitic claystone showing brecciated structure. Angular breccia fragments have same composition as highly oriented montmorillonitic groundmass.*

PLATE 11

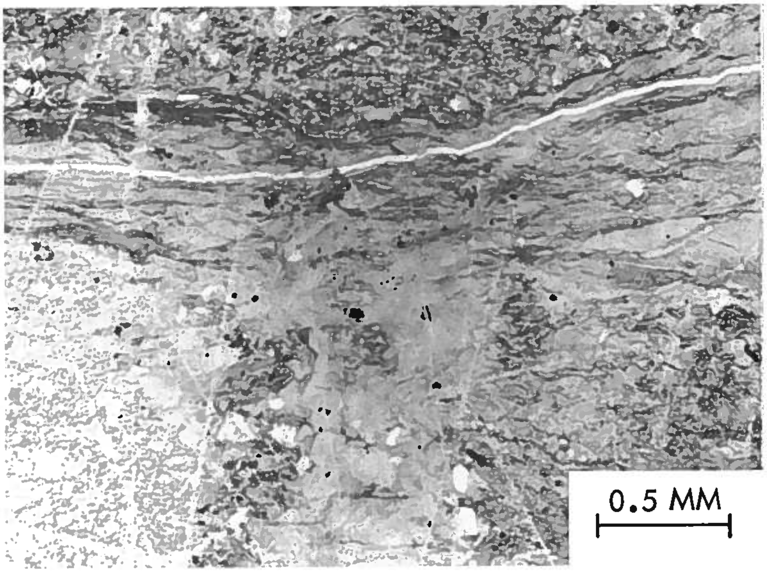

FIGURE 1. Bentonitic claystone showing two silty laminae separated by montmorillonite-rich band. The lower silty lamina is pierced by a "plug" or infilling of montmorillonite extending from the overlying band. Sample CH5-6, plane polarized light.

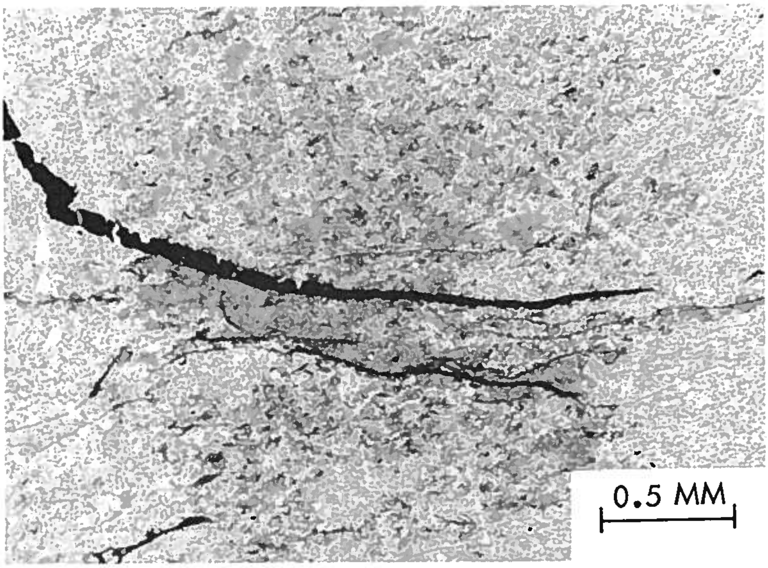

FIGURE 2. Silty claystone with crumpled subparallel partings of coaly organic matter. Sample CH5-8, plane polarized light.

PLATE 12

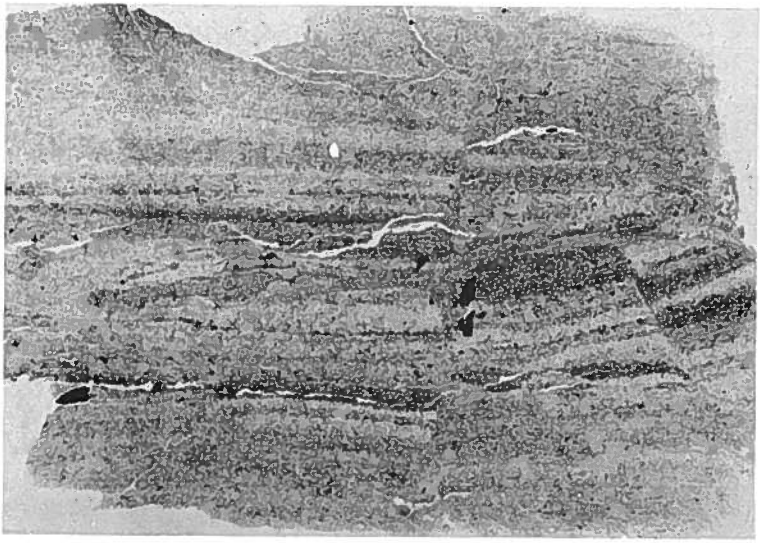

FIGURE 1. Laminated siltstone showing diagenetic slump (microfault) structures. (Dendritic white areas are cracks in the thin section.) Sample CH4-2, enlarged approximately 4 times.

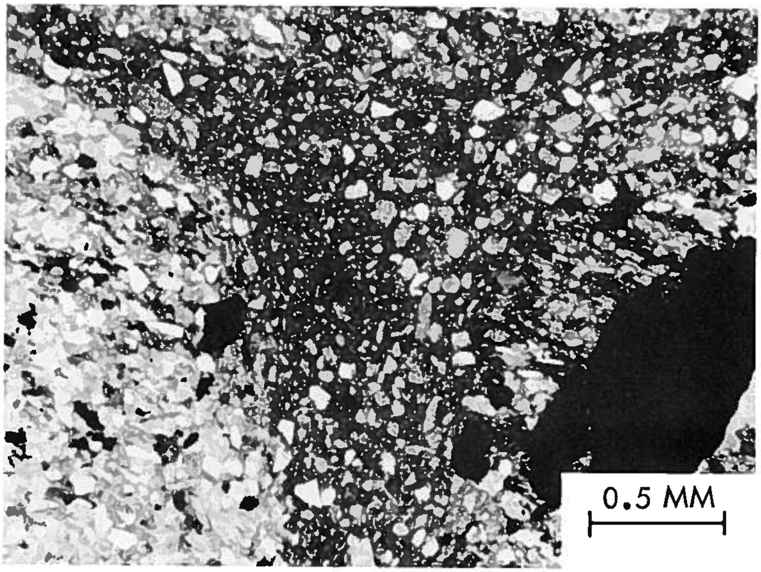

FIGURE 2. Enlargement from figure 1, above, showing disturbed structure along slump plane. Large dark area is authigenic pyrite. Sample CH4-2, plane polarized light.

PLATE 13

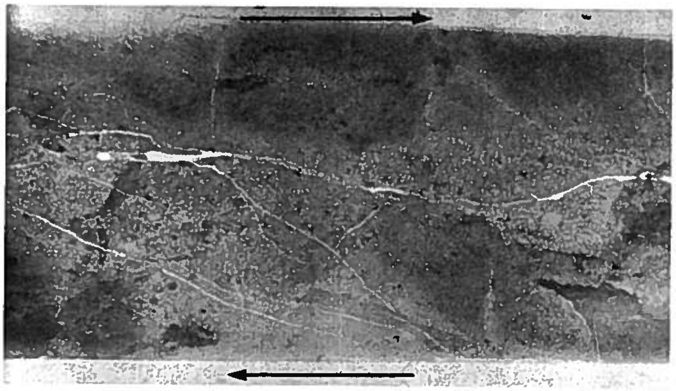

FIGURE 1. Type 1 cracking pattern. Sample CH8-74D.

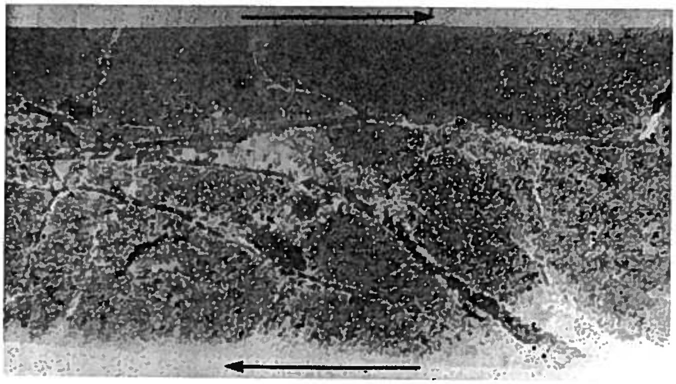

FIGURE 2. Type 1 cracking pattern. Sample CH8-45G.

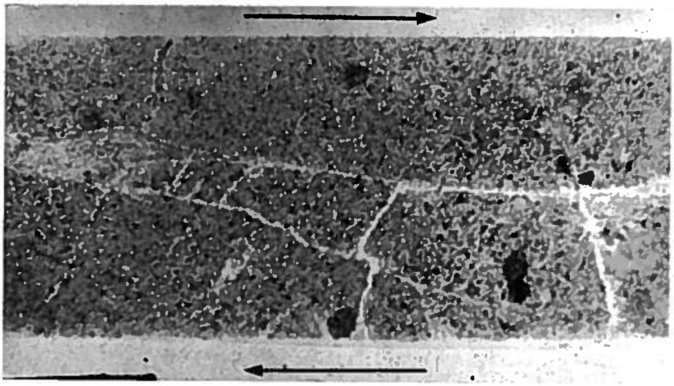

FIGURE 3. Type 1 cracking pattern. Sample CH8-45F.

PLATE 14

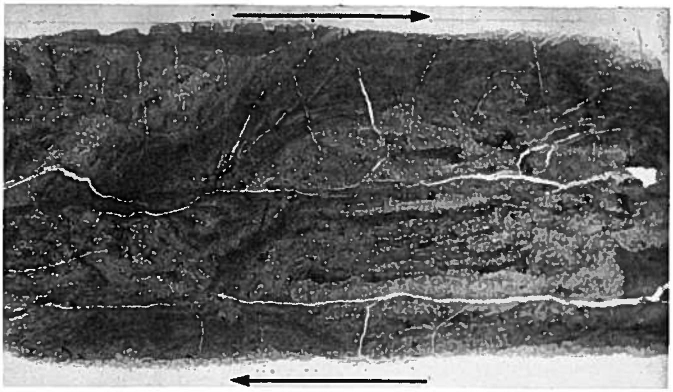

FIGURE 1. Type 2 cracking pattern. Sample CH1-39A.

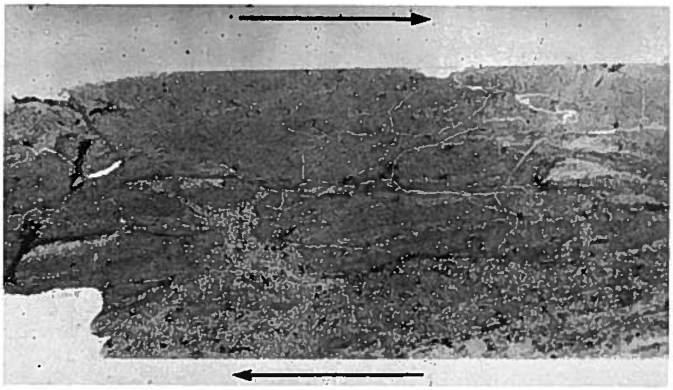

FIGURE 2. Type 2 cracking pattern. Sample CH1-39B.

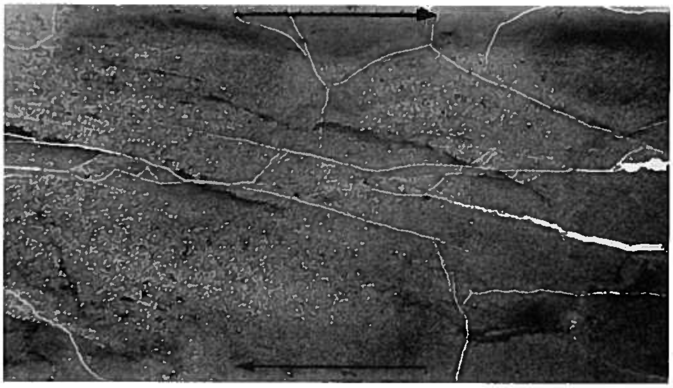

FIGURE 3. Types 1 and 2 cracking patterns. Sample CH6-54A.

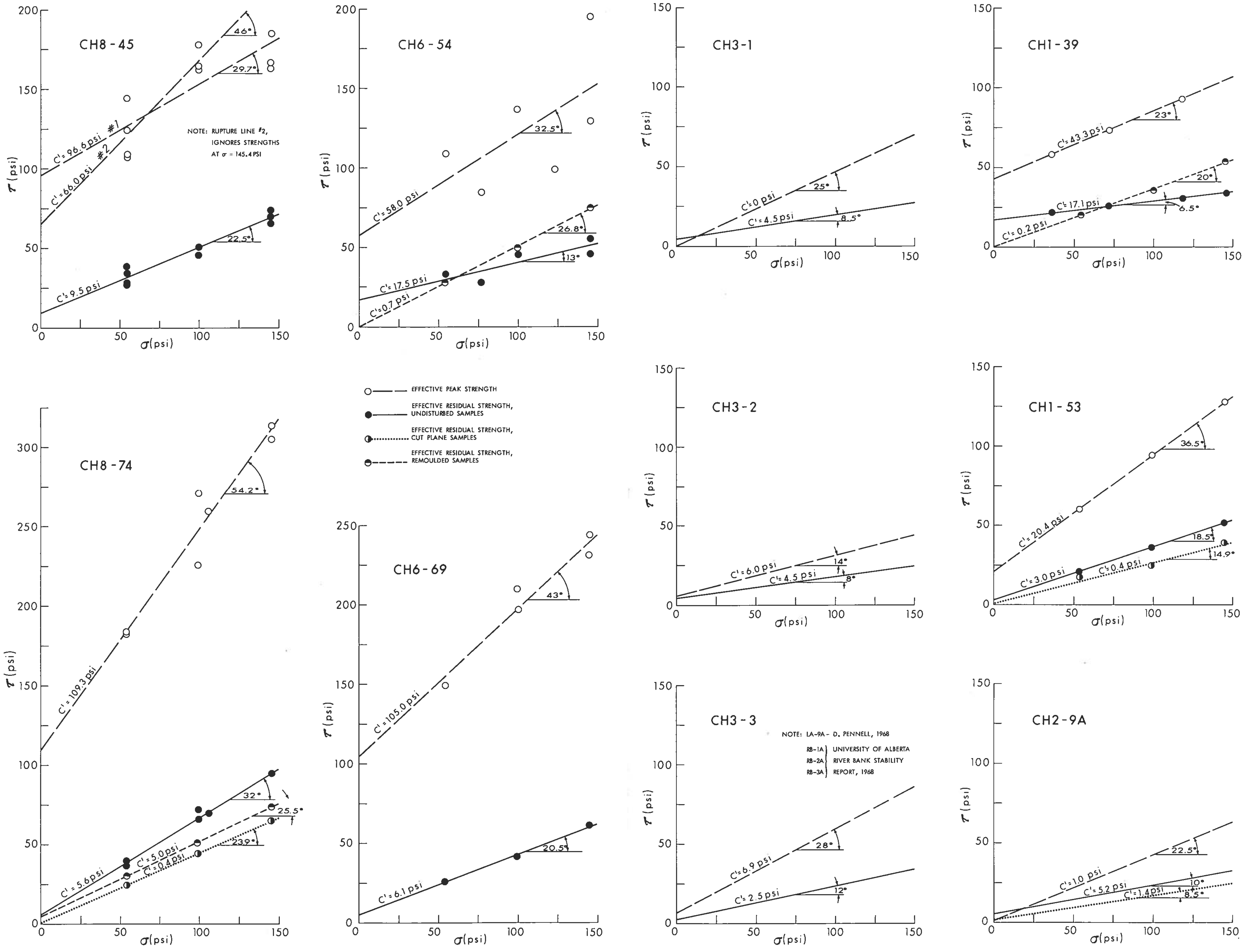

FIGURE 21. MOHR RUPTURE LINES FOR FINE-GRAINED ROCKS OF CENTRAL ALBERTA.

To accompany RCA Bulletin 30
by J. G. Locker

TABLE 3. TEXTURAL, COMPOSIONAL, AND BULK PHYSICAL PROPERTIES OF FINE-GRAINED ROCKS FROM CENTRAL ALBERTA

To accompany RCA B
by J.

Sample Number	Texture			Composition												Plasticity					Bulk Properties				Distance	Depth	Lithology
	Sand	Silt	Clay	Mont.	Ill.	Kaol.	Chl.	Org.	Carb.	PWS	Na$^+$	K$^+$	Ca^{++}	Mg^{++}	CEC	W_L	W_P	I_P	A	I_L	γ_t	e	W_N	WDR			
	%	%	%	%	%	%	%	%	%	meq	meq	meq	meq	meq	meq						pcf		%		mi	ft	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	
PAK - 1	12	48	40	28	6	6	0	0.8	0	6	4	1	20	7	25	56	19	37	0.94	0	123	.62	20	7	204	7	clayey siltstone
- 2	23	47	30	18	6	0	6	1.3	0	3	5	1	22	7	32	54	24	30	1.02	0	128	.64	23	7	204	11	sandy clayey sil
CH1 -39[1]	10	54	36	14	11	4	7	1.4	0	4	14	1	12	4	27	61	21	40	1.10	-0.18	136	.42	14	1	197	39	clayey siltstone
-52	12	48	40	26	6	0	8	1.6	0	7	19	1	16	4	33	100	26	74	1.86	-0.14	135	.43	16	NA	197	52	clayey siltstone
-53[1]	28	49	23	15	3	0	5	1.6	0	7	19	1	16	4	33	61	24	37	1.62	-0.27	132	.37	14	NA	197	53	sandy clayey sil
MYC - 1	8	52	40	20	10	4	6	0.7	0	7	14	1	17	6	30	90	23	67	1.66	-0.03	122	.71	21	7	196	22	clayey siltstone
- 2	16	52	32	16	8	2	6	0.5	0	8	12	1	13	4	22	91	20	71	2.22	-0.07	NA	NA	25	1	196	25	clayey siltstone
CH3 - 1	15	35	50	48	2	0	0	0.4	0	21	4	1	74	12	69	147	49	98	1.96	-0.09	112	NA	40	NA	150	113	silty claystone
- 2	28	15	57	57	0	0	0	0.5	0	43	2	1	71	40	71	182	51	131	2.30	-0.07	103	NA	60	NA	150	1	bentonite
- 3	33	45	22	17	4	0	1	1.0	0	10	3	1	38	9	41	62	31	31	1.41	-0.06	115	.67	29	NA	150	110	sandy clayey sil
CH2 - 9	4	24	72	61	11	0	0	0.5	0	19	34	1	30	3	50	192	42	150	2.07	-0.07	NA	NA	31	1	155	99	silty claystone
- 9A[1]	5	27	68	54	14	0	0	0.5	0	19	34	1	30	3	50	227	51	176	2.58	-0.09	112	.99	36	7	155	95	silty claystone
CH4 - 1	10	53	37	20	11	6	0	1.0	0	9	1	1	34	11	38	45	30	15	0.41	-0.53	129	.57	22	6	150	69	clayey siltstone
- 2	10	75	15	12	2	0	1	1.1	0	10	1	1	34	12	38	60	30	30	2.00	-0.50	140	.42	15	NA	150	85	siltstone
- 3	7	51	42	34	6	0	2	1.8	0	15	13	1	28	6	33	129	34	95	2.51	-0.17	135	.45	18	11	150	118	clayey siltstone
- 4	10	53	37	28	6	0	3	1.1	0	13	26	1	25	4	44	113	31	82	2.25	-0.17	137	.42	17	7	150	148	clayey siltstone
DEV - 1	41	40	19	10	7	0	2	1.3	0	3	1	1	24	12	34	42	29	13	0.67	-0.77	131	.52	19	6	135	8	sandy siltstone
- 2	25	48	27	19	5	0	3	1.4	0	11	1	1	28	16	34	46	27	19	0.72	-0.53	123	.53	17	6	135	12	sandy clayey sil
- 3	7	73	20	13	4	3	0	0.8	0	6	1	1	26	13	33	48	27	21	1.05	-0.43	130	.51	18	10	135	22	clayey siltstone
- 4	20	59	21	18	2	0	1	0.5	0	9	1	1	28	13	33	45	24	21	0.98	-0.14	126	.61	21	6	135	29	clayey siltstone
- 5	9	70	21	17	4	0	0	0.7	0	12	2	1	32	15	38	48	30	18	0.84	-0.50	129	.57	21	11	135	36	clayey siltstone
- 6	23	42	35	33	2	0	0	0.2	0	33	4	1	76	31	79	77	58	19.	0.52	0.21	NA	NA	62	NA	135	38	bentonite
CH5 - 1[2]	12	68	20	13	6	0	1	0.2	5.3	71	1	1	89	12	32	50	27	23	1.14						120	23	clayey siltstone
- 2	35	47	18	5	6	5	2	0.2	9.8	42	3	1	44	4	9	29	18	11	0.64						120	101	sandy siltstone
- 3	6	53	41	8	16	13	4	1.4	0	7	12	1	14	5	25	68	22	46	1.11						120	167	clayey siltstone
- 4	0	52	48	29	12	2	5	1.4	0	7	16	1	15	4	29	88	27	61	1.28						120	234	clayey siltstone
- 5	4	48	48	24	17	5	2	0.4	0	6	21	1	17	4	37	74	24	50	1.03						120	302	clayey siltstone
- 6	8	17	75	75	0	0	0	0.5	0.3	49	67	1	33	4	57	286	31	255	3.40						120	334	claystone
- 7	12	41	47	28	12	5	2	0.3	0	16	33	1	24	4	45	93	38	55	1.17						120	345	silty claystone
- 8	1	46	53	29	16	5	3	1.3	0	7	18	1	15	4	31	101	24	77	1.45						120	477	silty claystone
- 9	14	47	39	27	8	4	0	1.0	0	12	23	1	18	3	34	139	23	116	2.99						120	496	clayey siltstone
CH7 - 1	17	51	32	32	0	0	0	0.2	2.4	41	12	3	68	14	55	88	28	60	1.88						112	48	clayey siltstone
- 2	6	52	42	21	13	4	4	0.6	0	15	12	1	17	9	25	77	26	51	1.21						112	61	clayey siltstone
- 3	24	55	21	11	8	0	2	0.0	11.0	99	6	1	100	9	14	49	19	30	1.41						112	70	sandy clayey sil
- 4	2	48	50	8	30	10	2	1.0	0	8	12	1	14	4	23	79	24	55	1.09						112	171	silty claystone
- 5	5	45	50	10	30	5	5	1.6	0	16	13	1	18	9	25	74	24	50	1.00						112	184	silty claystone
- 6	11	65	24	20	2	0	2	0.5	2.3	27	11	1	33	5	22	63	21	42	2.09						112	114	clayey siltstone
PEM - 1	6	46	48	14	24	0	10	0.8	1.2	37	1	1	55	14	33	44	31	13	0.28	-1.08	136	.48	17	13	112	47	silty claystone
- 2	17	64	19	15	3	0	1	0.9	0	10	1	2	40	11	44	52	33	19	0.99	-0.53	126	.64	23	6	112	82	clayey siltstone
- 3	12	65	23	12	9	0	0	0.3	0	7	4	1	32	9	39	40	27	13	0.54	-0.92	135	.45	15	8	112	109	clayey siltstone
- 4	7	72	21	5	11	3	2	0.4	1.9	27	1	1	37	7	17	39	27	12	0.56	-1.08	140	.39	14	10	112	61	clayey siltstone
- 7	23	66	11	6	4	0	1	0.2	0	2	1	1	24	5	30	34	27	7	0.66	-1.71	138	.43	15	12	112	90	sandy siltstone
CH6 -33	23	57	20	10	7	0	3	0.3	0	2	1	2	36	11	47	52	23	29	1.44	-0.34	131	.60	13	8	112	33	sandy siltstone
-54[1]	0	70	30	10	12	3	5	0.5	1.5	28	1	1	38	5	16	45	26	19	0.63	-0.74	143	.33	12	11	112	54	clayey siltstone
-69[1]	18	65	17	8	7	0	2	0.3	0	2	1	1	33	5	37	46	27	19	1.10	-0.74	140	.37	13	14	112	69	sandy siltstone
-87	30	47	23	5	15	0	3	0.2	0	2	4	1	24	4	30	44	27	17	0.73	-0.88	142	.36	12	13	112	87	sandy clayey sil
-116	10	52	38	11	21	0	5	0.1	0	2	15	1	21	4	38	49	21	28	0.74	-0.36	146	.32	11	12	112	116	clayey siltstone
EDS - 1	4	61	35	5	21	5	4	0.8	1.7	33	1	1	39	12	19	36	26	10	0.29	-1.50	144	.32	11	14	77	61	clayey siltstone
- 2	30	49	21	12	8	0	1	0.4	0.5	21	1	2	50	30	62	57	39	18	0.88	-0.61	125	.77	28	6	77	67	sandy clayey sil
- 4	0	60	40	10	24	4	2	0.2	1.7	73	14	1	70	12	24	69	23	46	1.17	-0.39	NA	NA	41	NA	77	115	clayey siltstone
- 5	10	70	20	6	10	0	4	0.2	2.4	32	8	1	39	3	19	82	22	60	2.96	-0.18	145	.37	11	18	77	97	clayey siltstone
SHR - 1	7	53	40	8	26	0	6	0.3	0	1	1	1	23	6	31	55	22	33	0.81	-0.33	144	.35	11	13	76	1	clayey siltstone
MRL - 0	1	79	20	6	10	2	2	0.5	2.6	36	1	1	57	4	26	42	25	17	1.36	-0.71	144	.36	13	18	59	26	siltstone
- 1	14	46	40	6	24	4	6	0.9	0.3	14	1	1	35	6	28	50	24	26	0.66	-0.46	147	.32	12	15	59	34	clayey siltstone
- 2	12	70	18	8	7	0	3	0.3	0	6	1	1	26	8	28	38	21	17	0.98	-0.65	146	.30	10	15	59	41	clayey siltstone
- 3	14	61	25	5	13	3	4	0.3	1.8	34	1	1	49	5	23	42	26	16	0.67	-0.88	147	.34	12	18	59	45	clayey siltstone
- 4	12	72	16	6	7	0	3	0.2	0	4	1	1	20	9	25	32	21	11	0.70	-1.18	149	.25	8	17	59	48	clayey siltstone
- 9	15	68	17	7	8	1	2	0.4	2.6	26	1	1	38	5	19	37	21	16	0.93	-1.33	148	.26	9	20	59	127	clayey siltstone
-10	22	50	28	7	18	0	3	0.1	0	4	1	1	18	13	29	43	25	17	0.61	-1.24	146	.34	12	11	59	129	sandy clayey sil
CH8 -45[1]	38	43	19	5	12	1	1	0.3	0	4	1	1	21	9	27	43	23	20	0.60	-1.57	150	.22	7	15	59	45	clayey siltstone
-74[1]	10	82	8	5	2	0	1	0.1	2.4	29	2	1	38	7	19	57	24	33	4.14	-2.00	148	.28	9	17	59	74	siltstone
CSP - 1	10	76	14	4	6	3	1	0.8	2.2	24	1	1	34	10	20	31	23	8	0.54	-1.00	149	.23	8	17	37	NA	siltstone
- 2	12	57	31	6	20	3	2	0.4	0	5	1	1	19	19	24	31	22	9	0.29	-0.95	147	.19	10	11	37	NA	clayey siltstone
ROB - 1	27	50	23	11	9	0	2	2.8	0	5	1	1	29	13	38	0	0	0	0	0	128	.47	17	8	37	102	sandy clayey sil
- 2	15	52	32	5	21	3	3	0.7	0	3	1	1	19	4	21	43	22	21	0.65	-1.64	147	.26	9	14	37	112	clayey siltstone
- 3	15	55	30	24	5	0	1	0.5	0	20	29	1	28	3	41	94	33	61	2.05	-2.58	146	.25	9	NA	37	122	clayey siltstone
- 4	15	73	12	4	6	1	2	1.2	0	10	1	1	23	12	26	36	24	12	0.98	-0.96	139	.39	13	11	37	186	sandy siltstone
- 5	4	71	25	10	10	3	3	0.9	0	11	7	1	19	7	23	53	23	30	1.18	-1.70	138	.41	14	11	37	200	clayey siltstone
MER - 1	16	61	23	23	0	0	0	0.1	0	13	31	1	63	3	85	54	36	18	0.77	-0.86	127	.62	23	6	33	NA	bentonite
- 2	15	47	38	38	0	0	0	0.2	0	11	38	2	65	5	99	81	35	45	1.19	-1.14	107	NA	41	1	33	NA	bentonite
- 3	43	46	11	7	3	0	1	0.2	0	46	1	1	65	7	27	34	27	7	0.67	-1.00	152	.20	7	8	33	NA	sandy siltstone
CAD - 1																					160			20	20		shale
- 2				Only density measurements available for CAD samples																	160			19	20		shale
- 3																					160			20	20		shale

[1] Direct shear-tested samples. [2] Air-dried samples: density and wet-dry cycle rating data not available.

KEY – Cols. 5-8 (montmorillonite, illite, kaolinite, chlorite), Cols. 9, 10 (organic matter, carbonate content), Cols. 11-15 (pore water salt, sodium, potassium, calcium and magnesium ion concentrations in milliequivalents), Col. 16 (cation exchange capacity in milliequivalents), Cols. 17-21 (liquid limit, plastic limit, plasticity index, activity, liquidity index), Cols. 22-25 (bulk density in pounds per cubic foot, void ratio, natural water content, wet-dry cycle rating), Cols. 26, 27 (distance in miles across strike from western edge of Foothills, depth or distance in feet below surface or other datum).

TABLE 4. PETROGRAPHIC PROPERTIES OF FINE-GRAINED ROCKS FROM CENTRAL ALBERTA AS DETERMINED FROM THIN SECTIONS

To accompany RCA Bulletin 30
by J. G. Locker

Sample Number	Distance (miles)	> 20 Microns (%)[1]	Montmorillonite (%)[2]	Color	Structures						Textures			Composition						
					Primary			Secondary	Induced (Fractures)											
					Homo.	Lamin.	Pell.		Type	Stain.	% $>20\mu$	Silt size	Clay orient.	Q+F	RF	Micas	Mont.	Org.	Pyr.	Carb.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
PAK -1	204	25	28	Br-Gr	X				R		10	C	0	Ab	P		P	Ab		
-2	204	38	18	Gr		F			Pa, Pe	X	20	C	0	Ab	P	P		Ab	P	
MYC -1	196	24	20	Gr		F			R		15	C	1	Ab	P	P	P			Ab
CH2 -9	155	8	61	Gr		S			Pa, Pe	X	1	M	2	P		P	Ab	P		
-9A	155	8	54	Br-Gr	X				R		0	Sh	2			P	Ab		P	
CH3 -1	150	NA	48	Gr	X				R	X	0		2, NU				Ab		P	P
-2	150	NA	57	Gr	X			Brecc.	R	X	0		2, NU				Ab		P	P
-3	150	NA	17	Br-Gr		F	X				15	C	3	P	P		P		P	P
CH4 -1	150	25	20	Br	X			Brecc.	R		0		5, NU				P			
-2	150	30	12	Br-Gr		S		Slump	Pa		40	C	1, NU	Ab	P	P	P	P	P	P
-3	150	18	34	Br		S			Pa	X	25	C-M	1	Ab	P	P	Ab	P		Ab
-4	150	31	28	Br-Gr		S			R		20	C-M	2	Ab		P	Ab	P	P	
DEV -1	135	50	10	Br		F			Pa		10	M	1	P		P	P	P	P	P
-2	135	38	19	Gr		F			R	X	1	C	2	P			P	P		P
-3	135	27	13	Gr		F			Pa, Pe		10	C	1	Ab	P	Ab		P	P	Ab
-4	135	40	18	Gr-Br		F			Pa, Pe		1	M	1				P	Ab	P	Ab
-5	135	23	17	Gr		F	X		Pa, Pe	X	1	M	4, NU	P			P	P	P	P
CH5 -1	120	34	13	Gr			X		Pa	X	40	C	1, NU	P		P	P	P	P	P
-2	120	53	5	Br-Gr		S			Pa		55	C	0	Ab	P	P		P	P	Ab
-3	120	10	8	Gr		F					10	M	1			Ab		P	P	P
-4	120	3	29	Br		F	X				0		1			P	P	Ab	P	
-5	120	15	24	Br-Gr			X		Pa		10	M	2, NU	P		P	P	P	P	
-6	120	10	75	Br		F		Slump	Pa		1	C	3, NU	P		P	Ab			
-7	120	22	28	Br		F			Pa		5	M	4, NU	P			Ab		P	
-8	120	5	29	Gr		F			Pa		1		2, NU			P	P	P	P	
-9	120	31	27	Br-Gr		F					25	C	1	P	P	P	P	Ab	P	P
CH7 -1	112	34	32	Gn-Gr		F					10	M	4, NU	P		Ab	P			P
-2	112	7	21	Gr-Gn		S			Pa		5	M	5, NU	P		P	P	P	P	
-3	112	43	11	Gr		S	X		Pa		15	C	2, NU	P	P	P	P	P	P	Ab
-4	112	4	8	Gn-Gr		S			Pa		5	M	5			P	P	P		
-5	112	7	10	Br-Gr		S			Pa		1		1, NU	P		P		Ab	P	P
-6	112	30	20	Br-Gr		S		Slump	Pa		5	M	1	P		P	P	P	P	Ab
PEM -1	112	8	14	Br-Gr	X				Pa	X	0		4				P	Ab		P
-2	112	43	15	Gr		S			Pa, Pe	X	10	M	2, NU	P	P	Ab	P	P		P
-3	112	30	12	Gr-Gn	X			Brecc.	R		10	M	2, NU	P		P	P		P	
-4	112	20	5	Br-Gr			X		Pa		40	C	5, NU	P		Ab	P	P	P	
-6	112	NA	NA	Gn-Gr		F		Brecc.	R		0		5, NU				P		P	
-7	112	47	6	Gr-Gn		F	X		Pa		10	C	2, NU	P	P	Ab	P	P	P	
CH6 -33	112	38	10	Gn-Gr		F					0		2, NU			Ab				
-87	112	44	15	Gn-Gr		F	X		Pa	X	13	C	1, NU	P	P	P	P		P	
EDS -1	77	5	5	Br-Gr		F	X		Pa		10	M	1			P	P	P	P	Ab
-2	77	41	12	Gn		F			Pa	X	20	C	3	P		P	P	P	P	
-5	77	22	6	Gr		S		Slump	Pa, Pe		15	C-M	1, NU	P		P		P	P	Ab
SHR -1	76	15	8	Br-Gr			X				5	M	3, NU	P		Ab	P		P	
MRL -0	59	18	6	Gr-Br		S			Pa		25	C	1	P		P	P	P	P	P
-1	59	20	6	Br-Gr	X				Pa		0		2, NU				P	P	P	
-2	59	28	8	Br	X				Pa	X	13	C	2	P	P	Ab	P	P	P	
-3	59	25	5	Gr		F			R		10	M	1, NU	P		P	P	P	P	Ab
-4	59	55	6	Br			X		Pa	X	50	C	1, NU	Ab	P	P	P		P	P
-9	59	50	7	Gr-Br		F			Pa		55	C	0	Ab	P	P	P		P	P
-10	59	27	7	Br-Gr	X				R		0		2, NU				P	P	P	P
CSP -1	37	28	4	Br-Gr		S			Pa, Pe		10	M	1	P				Ab	P	Ab
ROB -1	37	45	11	Gr-Br		F			Pa, Pe		25	C	2, NU	P	P	P	P	Ab	P	
-2	37	22	5	Gn-Gr	X				Pa		0		1						P	
-4	37	37	4	Br-Gr		F			R	X	20	C	1	P	P	P		Ab	P	P
-5	37	15	10	Br-Gr		S			Pa, Pe		30	C-M	1	Ab	P	P	P	P	P	P
MER -1	33	42	23	Gr	X				R	X	5	Sh	1, NU	P		P	Ab		P	
-2	33	30	38	Br	X				R	X	13	Sh	1, NU	P	P	P	Ab	P		
-3	33	73	7	Gr		S		Slump	Pe	X	20	C	1, NU	Ab	P	P		Ab	P	P
-4	33	NA	NA	Gn-Gr			X		Pa		10	C	1, NU	Ab	P	P	P		P	

[1] From hydrometer analysis. [2] From grain-size and X-ray data.

KEY - Cols. 3, 4: NA = not available; Col. 5: Br = Brown, Gr = grey, Gn = green; Col. 6 (homogeneous): X = present; Col. 7 (laminated): F = faint, S = strong; Col. 8 (pelleted): X = present; Col. 9: Brecc. = brecciated; Col. 10: R = random, Pa = parallel to bedding, Pe = perpendicular to bedding; Col. 11 (staining): X = present; Col. 12: silt (>20 microns) content; Col. 13: M = medium, C = coarse, Sh = shard texture; Col. 14 (orientation): NU = nonuniform; Cols. 15-21 (quartz plus feldspars, rock fragments, micas, montmorillonite, organic matter, pyrite, carbonates): P = present, Ab = abundant.

TABLE 13. PETROGRAPHIC CHARACTERISTICS OF FAILURE ZONES IN DISTRICT SHEAR SPECIMENS

To accompany RCA Bulletin 30
by J.G. Locker

Sample Number	Macroscopic				Microscopic							Remarks
	Failure Plane Configuration				Failure Plane Face		Width of Failure Zone	Material in Failure Zone				
								Shear Lenses	Remoulded Material			
	Str.	Con.	Und.	Irr.	Sm.	Rou.	Mm		Silt content	Clay orient.	Silt orient.	
1	2	3	4	5	6	7	8	9	10	11	12	
CH1-39A			X			X		X	Same	Nil	Slight	
-39B			X		X		0.5-1.5	X	Same	Nil	Slight	
-39R[1]	X				NV		0.75		Same	10%	Slight	Silt orientation along secondary cracks; failure plane resealed.
CH1-53A	X					X	0.5	X	Same	Nil	Good	Sample badly fragmented.
-53B				X		X		X	Same	10%	Slight	
-53C		Dn			X		0.5-1.0		Same	10-20%	Good	
-53D		Dn			NV		1.0		Same	Nil	Nil	Failure zone filled with remoulded material.
CH6-54A			X		X		0.25-1.5	X	Same	10%	Good	25% of failure plane through clay.
-54D			X		X		0.25-0.75	X	Same	10%	Nil	
-54G	X				X		0.75	X	Same	10-20%	Nil	
-54R[1]			X		X		0.25	X	Same	10%	Nil	Failure plane resealed.
CH6-69A	X					X		X	Same	Nil	Nil	Sample badly fractured.
-69B		Dn			X		0.25-1.5	X	Less	Nil	Nil	
CH8-45A				X		X		X	Less	10%	Nil	Sample badly fractured.
-45B				X		X		X	Same	10%	Good	Sample badly fractured.
-45C				X		X		X		10-20%	Nil	2% of failure plane in carbonates; orientation of clay along border of failure plane.
-45D				X		X		X		(Not present)		Sample badly fractured; distinct failure plane not visible.
-45E		Dn				X		X	Same	Nil	Nil	Most of failure plane removed by thin section grinding.
-45F				X		X	0.5-1.5	X	Less	Nil	Good	
-45G		Dn				X		X		(Not present)		Sample badly fractured.
-45I				X		X		X		(Not present)		Sample badly fractured.
-45J				X		X		X	Less	10%	Nil	Sample badly fractured; 2% of failure plane in carbonates; orientation along border of failure alone.
CH8-74B			X			X	0.25-0.5	X	Same	Nil	Nil	
-74C				X		X		X	Less	10%	Slight	10% of failure plane in carbonates; sample badly fractured.
-74D				X		X	0.25-1.0	X		(Not present)		20% of failure plane in carbonates.
-74E		Up			X			X	Less	10%	Nil	
-74F			X		X		0.25-1.0	X	Less	10%	Nil	50% of failure zone in carbonates; orientation only in carbonate zone.
-74G			X			X	0.5-1.0	X	Same	10%	Good	25% of failure zone in carbonates.
-74R[1]	X						1.0	X		10%		

[1] R = remoulded samples.

KEY - Col. 2 (Straight): X = present; Col. 3 (Concave): Dn = down, Up = up; Col. 4 (Undulating): X = present; Col. 5 (Irregular): X = present; Col. 6 (Smooth): X = present, NV = not visible; Col. 7 (Rough): X = present, NV = not visible; Col. 8: width measured to nearest .25 mm unless zone is shattered; Col. 9: X = present; Col. 10: as compared with that of the ambient material; Col. 11 (Clay orientation); Col. 12 (Silt orientation).