MASTER

FINE-GRAINED SHEET SILICATE ROCKS

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PART I: CLASSIFICATION

Abstract

The boundary between clay and silt has been placed variously at grain size diameters of 2, 4, 5, and 20 μm . The terms claystone and siltstone are defined on the basis of texture. Mudstone is intermediate between claystone and siltstone in texture. The terms shale and argillite are applied to rocks containing various amounts of clay minerals. Most sheet silicate clay minerals are assumed to be clay-size. Structural criteria are assigned to most of these terms. The terms used to describe unindurated sediments are applied to indurated sediments. Siltstones are assumed to be composed largely of silt-size quartz, but many shales are composed predominantly of silt-size sheet silicate minerals. Fissility is largely determined by the amount of cement and the extent of weathering.

Based on chemical data, shale has been described as two parts silt and one part clay. X-ray analyses indicate that the average shale contains 61% sheet silicate minerals.

Shallow-buried recent and ancient marine sediments with a high content of clay minerals commonly contain 60 to 80% clay and 20 to 40% silt. Sheet silicate minerals are present in approximately the same amounts as the clay-size material. Recent deltaic fine-grained sediments contain about half this amount of clay and a slightly lesser amount of sheet silicate minerals. Sediments deposited in cold climates tend to have more feldspar and less sheet silicate minerals.

Many fine-grained sediments that have been relatively deeply buried commonly contain 30 to 40% clay; the sheet silicate content is in the range of 60 to 80%.

In some Paleozoic sediments, both the clay content and the sheet silicate content are in the 70 to 80% range.

Both Cenozoic and Paleozoic calcareous fine-grained sediments commonly have twice as much sheet silicate material as quartz. In unlithified, calcareous young sediments, the clay content is approximately 75%.

Regardless of the grain size, most fine-grained marine silicate sediments contain 60% or more sheet silicate minerals. The data also indicate that mineralogy does not have any fixed relation to grain size. The two parameters must be considered independently.

The slates have a mineral composition similar to shales. The quartz grains are similar in size to those in shales, but the sheet silicate minerals are coarser.

In most fine-grained sediments, as deposited, the majority of the material is in the clay size. With burial and diagenesis, much of the clay-size material grows to silt size. Thus, clays are converted to siltstones.

The term physil, an abbreviated form of phyllosilicate, is proposed to describe all sheet silicate minerals regardless of size. Physils are unconsolidated materials composed predominantly of sheet silicates. Physillites are indurated rocks composed predominantly of sheet silicates. The modifying adjective is physilic.

INTRODUCTION

Considerable interest has been shown in the possibility of using shales as repositories for radioactive waste and a variety of other waste products, and it appears that over the next few years much money and effort will be expended to investigate and test a wide variety of shales. If shales are to be studied in detail by a large number of investigators, it is important that all concerned have the same concept of what constitutes a shale.

The term shale and other terms for fine-grained rocks have been used for many years and have been continually redefined. Most definitions pre-date the development of modern instrumentation and are based on field observations and intuition; however, the main problem is the diversity of definitions. An attempt is made here to develop a simple, rational classification of fine-grained sediments, and it is hoped that this classification will eliminate some of the present ambiguity.

In order that the classification be pertinent, mineral composition and textural data were compiled and evaluated. The data on unconsolidated and consolidated sediments were contrasted and the effects of burial diagenesis assessed.

It was found necessary to introduce a new term, physil, to describe all sheet silicate minerals. In contrast to the term clay mineral, the term physil has no size connotation. A simple classification is proposed that is based on the percentage of physils and grain size.

In Part II the fine-grained physil rocks are classified on the basis of physil type, non physil minerals, and texture. Formations are listed which have the mineral and textural characteristics of the most important rock types volumetrically.

Selected rock types, and the formations in which they can be found, are recommended for laboratory study to determine their suitability for the storage of high-level radioactive waste.

NOMENCLATURE REVIEW

Despite the relative abundance of clay-rich rocks in the geologic section they have never been satisfactorily classified. Early attempts at classification were hindered by the lack of knowledge of the clay minerals. Although the mineralogy of fine-grained sediments is now fairly well understood, there is still relatively little information on the texture of these rocks. Another complicating factor is the dual meaning or connotation of the word clay.

As a textural term petrologists and others consider clay to be any material finer than $1/256$ mm ($3.9 \mu\text{m}$) (Wentworth, 1922). Others have placed the upper boundary at $2 \mu\text{m}$ (Atterberg - 1905), at $5 \mu\text{m}$ (U. S. Bureau Soils) and at $20 \mu\text{m}$ (Correns, 1969). Clay minerals are considered to be finely crystalline hydrous aluminum silicates. The upper limit of silt is generally agreed to be $1/16$ mm ($62.5 \mu\text{m}$).

A clay has been defined as a plastic earth composed of hydrous aluminum silicates and of fine grain size (Grim, 1968, and Pettijohn, 1975). The term, as used, has both a textural and mineralogical connotation which serves to cause confusion.

Twenhofel (1950) defined fine-grained clastics as including those particles $1/16$ mm and finer. The material between $1/16$ and $1/256$ mm is designated as silt; the finer material, as clay. Indurated clays are claystones and indurated silts are siltstones. "Clays and silts mingled with water form muds, and both claystones and siltstones have been termed mudstones.

If claystones and siltstones have cleavage parallel to bedding, the term shale should be applied." Claystones and siltstones retain considerable coherence on being wetted after drying. When dry clays and silts are wetted, they disintegrate into discrete particles. The definition is operational and characteristic of the methods used to classify fine-grained sediments. It is evident that Twenhofel was frustrated in his attempt to classify these rocks. This is further evidenced by his statement: "Classification of clays and silts and their indurated equivalents on almost any basis gives little satisfaction to other than the classifier and often not even to him."

Clark (1954) has presented a detailed review of shale nomenclature. Among other things, he notes that shales have a considerably smaller nomenclature than sandstones and limestones. He suggests that a classification should be both readily arrived and profitable used that it should be primarily descriptive and that incorporation of genetic data should be of secondary importance and that it should be based on field and binocular observations rather than being dependent on more sophisticated techniques. All of his suggestions have merit except the last. Petrographic study of thin sections is required for the classification of sandstones and limestones. Because of the fine-grained nature of shales, any classification should require, as a minimum, this level of observation. Clark concludes there is a fairly general agreement that 1/16 mm is the limit separating sand-sized particles from silt-sized particles. He notes that there is less agreement on a second limit separating the fine particles into silt and clay. He appears to favor the use of the term shale to include all fine-grained detrital sedimentary rocks even though most geologist's insist upon lamination as a primary requisite for shale.

Picard (1953) defines shale as a fine-grained rock containing 50 to 100% clay-size particles with clay minerals constituting at least 25% of the total rock volume. This is one of the few definitions that specifies the percentage of clay minerals. By this definition, a rock composed of 50% quartz silt, 25% clay-sized quartz, and 25% clay minerals would be a shale. Further, the clay minerals could be silt size, allowing the entire clay-sized fraction to be composed of quartz.

Pettijohn (1975) states that most workers divide the finer-grained materials into siltstone and claystone, with the boundary commonly being placed at $1/256$ mm. Krumbein and Sloss (1951) suggest that $1/100$ mm is a more desirable boundary because coarser sediments have the field characteristics of sandstone (cement, induration, and cross-lamination) and because finer sediments have the characteristics of shale (slaking, plasticity when wet, etc.).

Pettijohn and others define claystone as indurated clay; clay is composed of hydrous aluminum silicates and of fine grain size. If it possesses bedding fissibility, it is called shale. If the claystone is blocky or massive, it is called mudstone. Flawn (1953) defines claystone as being only weakly indurated (as compared to shale) and composed predominantly of "clay-sized" particles (less than $10\text{ }\mu\text{m}$). Flawn states that most geologists agree that a shale is a more indurated rock than claystone.

Pettijohn's diagrammatic classification (p. 262) does not allow for clay-rich rocks. Unconsolidated silt and clay are combined to make mud. Mud, in turn, is consolidated to form shale (laminated) and mudstone (non-laminated). Silt can form siltstone, but there is no rock equivalent for clay.

Ingram (1953) defines claystone as a massive rock in which clay predominates and he defines siltstone as a massive rock in which silt predominates. Mudrock is the general term including both of the above. Mudrock is defined as containing at least 50% silt and clay; thus, a mudrock can contain 50% sand or gravel. The correlative fissile rocks are clay shale, silt shale, and mud shale.

Folk in Picard (1971) classification a claystone contains more than 75% clay.

Folk (1961) defines claystone as containing two-thirds clay and siltstone as containing two-thirds silt. Rocks with subequal silt and clay are called mudstone. The equivalent fissile rocks are clay shale, silt shale, and mud shale.

Shrock (1948) calls mudstone a "partly indurated argillaceous rock which slakes readily to mud when repeatedly dried and wetted."

Twenhofel (1950) applies the term mudstone to the whole family of argillaceous rocks. The definition of argillaceous rocks is not specified. Pettijohn restricts the term to rocks with the grain size and composition of shale (two-thirds silt and one-third clay) but lacking its laminations or fissility.

Shepard (1954) has reviewed the various triangular classifications of sand-silt-clay, and after discussion and correspondence with 40 sedimentationists concluded the term mud should be dropped. He recommended adoption of the triangular classification shown in Figure 1. Pettijohn (1975) suggested that since most sediments are mixtures of two textural components rather than three the triangular classifications are unnecessarily complex.

The terms mud and mudstone are used to describe sediments or rocks that contain a mixture of clay-sized and silt-sized particles. Mixtures of silt and sand and pebbles are not given specific names and there is no reason a mixture of clay and silt should be given a specific name. The terms silty clay and clayey silt or silty claystone and clayey siltstone are more accurate.

An argillite is defined by Twenhöfel (1950) as a siltstone or shale that has undergone a higher degree of induration than is usually present in those rocks. Plawn (1953) defines argillite as an indurated argillaceous rock without visible parting, cleavage, or foliation and in which less than half the micaceous paste and clay minerals have been reconstituted. Most of the reconstituted clay minerals are silt-sized. An Argillite is considered to be composed entirely of clay minerals. Grim (1968) considers argillite to be equivalent to shale but massive rather than laminated. Dunbar and Rodges (1957) and Pettijohn (1975) classifies it as a metamorphosed mudstone or shale with no cleavage. If secondary cleavage is present, the rock is classed as slate. The French consider argillite to be equivalent to the English term claystone. It is defined as a common rock composed, for the most part, of one or several clay minerals and without any notable bedding (Millot, 1970). However, claystone is defined in terms of grain size rather than mineralogy.

There is no common term that is used to describe a rock composed predominantly of sheet silicate minerals and which has no connotation of grain size. The words claystone, mudstone, lutite, pelite are defined on the basis of grain size rather than mineralogy, though the rocks are categorized on the basis of their clay mineral content.

Fig. 1. Classification system for unconsolidated sediments.
After Shepard (1954).

The term argillaceous is widely used but seldom defined. According to Millot (1970) the French term argile can be translated as claystone or mudstone. Both these English terms are textural terms. Millot defines argillite as being composed "for the most part" of clay minerals.

In the report of the Committee on Sedimentation (Twenhofel, 1936), argillaceous is defined as "An adjective descriptive of a rock containing appreciable clay." The term clay mineral, rather than clay, would be more specific.

As will be shown, much confusion is caused by applying the terminology of unindurated sediments (clays, muds etc.) to indurated and diagenetically altered sediments. Thus, the term argillaceous implies clay. Clay, in turn, contains clay minerals of clay size. However, in consolidated rocks many of the sheet silicate minerals are silt-sized. Actually, argillaceous might be more accurately defined as an adjective describing a rock which contains appreciable silt-sized sheet silicates. A clayey rock would be one containing appreciable clay-sized sheet silicate minerals of clay-size.

Silt has been referred to as material 1/16 to 1/256 mm, 0.05 to 0.005 mm, and 0.1 to 0.01 mm, in diameter (Pettijohn, 1975). Pettijohn notes that siltstones are not as common as sandstones (10-20% sedimentary rocks). Siltstones occur as thin flags or as thin seams interbedded with shales. Siltstones (quartz predominant) rarely form beds of any considerable thickness. Field geologists normally consider a siltstone to be composed to two-thirds, or more, of silt particles larger than 0.01 mm in diameter. Most of the silt is presumed to be quartz. Siltstones are cemented with mineral cements and bonded by recrystallized clay minerals (Pettijohn, 1976). Siltstones seldom occur as thick units and are of no interest for waste disposal; however, many shales contain sufficient silt-sized silicate minerals to be classed as siltstones.

A typical siltstones from the Upper Devonian Chemung Formation of Pennsylvania is composed of 40 to 45% quartz, 2-10% rock fragments, 15 to 25% mica flakes (silt-sized) and 30 to 35% clay paste. In contrast, the shales contain 10% quartz, 10% mica and 80% clay paste (Krynine, 1940).

The present discussion is not concerned with the structure of fine-grained sedimentary rocks but the concept of fissility will be briefly reviewed. Fissility is the tendency of a rock to split along relatively smooth surfaces parallel to the bedding (Pettijohn 1975). Fissility is caused by the parallel orientation of the sheet minerals and organic material (Ingram, 1953; Gipson, 1965; O'Brien, 1970; Pettijohn, 1975 and many others). Fissility is decreased when calcareous and siliceous material are present. As the amount of cement increases and as orientation becomes more random the size of the fracture blocks increases. Grim, et al. (1957) note that in shales with a high content of clay minerals, the clay minerals should be 5 mm or larger for fissility to develop. Ailing (1945), Ingram (1953) and McKee and Weir (1953) have proposed classifications based on the splitting properties of layered rocks.

Fissility is a derived property and in addition to being a function of particle orientation is affected by weathering, pressure and water content. All fine-grained rocks with orientated sheet minerals are massive when under overburden pressure. As the overburden is removed or a sample is removed from beneath the overburden, exfoliation occurs in some rocks and parallel cleavage develops. Other rocks require considerable weathering (water penetration?) before cleavage develops. Rocks containing swelling clay commonly do not develop fissility until they have lost an appreciable amount of their water by dehydration.

Thus, a rock may be a shale (fissile) or a mudstone (non-fissile) depending on how much it has been weathered. Grain orientation and degree of cementation are apparently the two basic factors which determine the cleavage-potential of a rock. Shales should not be defined as fissile claystones or siltstones but as claystones and siltstones that have a high degree of particle orientation and a minor amount of cement. These rocks will commonly become fissile when they are released from confining pressure and weathered.

Pettijohn estimates, on the basis of some very limited chemical data, that the average shale is composed of two parts silt and one part clay. Thus, most shales should be siltstones. Two-thirds of the twelve samples used to calculate his typical silt and clay were glacial and recent clays (Grout - 1925). All samples are from Minnesota. It is unlikely that the group of samples are "typical". The only true shale (Ordovician, Decora Shale) in the group consists of equal parts silt-sized and clay-sized material. Total quartz content is 17%.

He uses the term silt and clay strictly in a textural context. The calculated mineral compositions of his two end members are shown in Table 1.

Table 1. Calculated Mineral Composition (Simplified)

	Silt	Clay
Quartz	37	13
Feldspar	13	7
Clay Minerals	35	60
Iron Oxides	3	8
Carbonates	10	6
Titanite & Rutile	2	2
Organic Matter	0.2	0.6

His "two parts silt - one part clay" shale would have the composition shown in Table 2 under the Pettijohn column.

Table 2. Average Shale

	Pettijohn (1975)	Yaalon (1962)	Shaw & Weaver (1965)
Quartz	29	20	31
Feldspar	11	8	4
Clay Minerals	43	59	61
Iron Oxides	5	3	0.5
Carbonates	9	7	4
Other Minerals	2	3	2
Organic Matter	0.3	--	1

Thus, Pettijohn's average shale contains 29% quartz, and 11 feldspar and 43% clay minerals. Grout's (1925) method of calculation would tend to over emphasize the feldspar and iron oxides at the expense of the clay minerals.

Also shown in Table 2 are two other estimates of the mineral composition of the average shale. Yaalon's (1962) data are based on normative calculations using the chemical composition of the average shale, compiled by Clark (1924). The data of Shaw and Weaver (1965) are based on direct mineral analysis (x-ray diffraction of 400 shale samples. Appendix 1 list the mineral composition of most of the shale samples analysed by Shaw and Weaver (1965). Figure 2 shows the cumulative and frequency distribution plots for the quartz and sheet silicates in these shales. Both have a near normal distribution. Quartz averages 31%, feldspar 4%, carbonates 4%, and sheet silicates 61%. Tertiary and Mesozoic shales average 26% quartz, 6% feldspar, 3.5% carbonates, and 64.5% sheet silicates; the Paleozoic shales average 38% quartz, 3% feldspar, 7% carbonate and 52% sheet silicates. The Paleozoic average includes some silicious shales and the quartz value is a little high and the clay value low; however, the differences between the two groups appear to be real.

Figure 2. Frequency curves showing the distribution of quartz and sheet silicate minerals (clay) in 300 shale samples. After Shaw and Weaver (1956).

Shaw and Weaver examined only "pure" shales (claystones) and excluded sandy shales, silty shales and siltstones. The similarity of their results to those obtained by normative calculations from chemical analyses suggest most of the shales used for the chemical analyses were "pure" shales rather than silty shales and siltstones.

Evans and Adams (1975) calculated from 10 chemical analyses of Paleozoic mudrock from Wales that the content of free silica was 32.2%.

Blatt and Schultz (1976) used a chemical solution technique to determine the amount of quartz in 16 mudrocks. The amount of quartz plus chert averaged 28% of which 96% was quartz. These results are close to those of Shaw and Weaver (1965). The sand-silt-clay percentages for the size distribution of quartz plus chert was 12, 73 and 15% respectively.

Pettijohn (1975) states that common shales are a mixture of clay-sized material, mainly clay minerals, and silt, mainly quartz. Yet the data he presents earlier indicates that the silt fraction only averages 37% quartz. Analyses of Paleozoic shales (Scotford, 1965) indicate that the quartz content of the silt fraction is only 24%. Grout's (1925) data on two shales shows that one has approximately 40% of the clay minerals in the silt size. Scotfield's (1965) data from 105 Ordovician shale samples indicates over half of the clay minerals are silt-sized. It is a mistake to assume that silt-sized material is largely quartz and that clay minerals are largely clay-sized.

Does a clayey sand or clay-rich sandstone or limestone contain some clay minerals or some clay-sized minerals? The former is usually assumed but the latter is the correct definition. The term argillaceous implies clay minerals, but not exclusively so, and is a more accurate description of a rock containing clay minerals.

Petrologists have tended to use textural data from unconsolidated sediments to classify the clay-rich rocks. Among other things, they assume that the grain size of unconsolidated material is the same as that of buried sediments and ignore the diagenetic processes which change the mineralogical and textural properties of clay-rich rocks.

TEXTURAL AND MINERAL DATA

Deltaic Sediments

Analyses by Russell (1939) show that the Mississippi Delta sediments consist of 60% silt-sized material and only 11% clay-sized material, yet siltstones are relatively rare in the geologic record. These data are based on samples from the surface of the Mississippi Delta and may not be representatives of the whole delta section. Potter et al., (1975) reported that Mississippi River Basin muds (177 samples) contain an average of 32% less than 2 μm material (probably close to 40% less than 4 μm material). The less than 10 μm fraction contained an average of 80% sheet silicates. Ho and Coleman (1969) found that samples from a 30 m core of swamp sediments near the mouth of the Mississippi River had an average clay content of 60% (range 40 to 80%). Shaw and Weaver's (1965) x-ray analyses indicate the Mississippi River muds contain approximately 54% quartz and 14% feldspar; the Mississippi Delta shelf muds contain 30% quartz; slope muds contain 20% quartz and deep muds 18% quartz (Fig. 3). The clay mineral content, and probably the clay-sized material, increases seaward from 30% to approximately 70%.

Textural studies by Shepard (1950) show that a large portion of the subaqueous muds that fringe the Mississippi Delta (delta-front, platform, pro-delta slope, bottom-set beds) contain 50 to 70% clay-size material ($<4\mu\text{m}$).

The other 30 to 50% is largely silt-sized. Farther west, in offshore Texas, most of the bay, delta and outer shelf sediments contain more than 50% clay size material (Shepard and Moore, 1955).

The silt content of the continental portions of the delta may be relatively high but the marine and marine fringe sediments have a high content of clay.

Offshore Marine Sediments

Chemical analyses of Pliocene and Miocene pro-delta and delta-front muds from the Mississippi Delta area (Weaver and Beck, 1971) indicate that they contain from 23 to 43% quartz (average 37%), 3% feldspar, 2% dolomite, and 58% clay minerals. The quartz content is smallest in the benthonic clays and largest in the pro-delta clays. Quantative x-ray analyses of Miocene muds from offshore Texas indicate they contain an average of 25% quartz, 4% feldspar and 71% clay minerals.

A search was made of the Initial Reports of the Deep Sea Drilling Project (DSDP) in order to obtain some textural information on deep sea clay sediments. Most of the fine-grained sediments contain a large content of silicious or calcareous microfossils; however, terrigenous silt and clay facies are present in some moderate-to-deep-ocean areas.

Terrigenous sediments (38 samples) of Upper Cretaceous and Eocene age from the Indian Ocean and Tasman Sea (Andrews and Owenshine, 1974) have a clay (less than 3.9 μm) content ranging from 33 to 86% with an average of 57.5% silt ranges from 13 to 79% and average 40.8%; sand ranges from 0 to 8.5% and averages 1.7%. The clay content increased approximately 10% from near shore to more seaward areas, x-ray analyses of a few samples indicate they contain approximately 35% quartz, 7% feldspar, 3% calcite, 2% pyrite and 52% clay minerals (minor clinoptilolite).

Figure 3. Composition of muds in the Mississippi Delta area. After Shaw and Weaver (1956).

Cretaceous, abyssal plain terrestrial sediments (36 samples), originally deposited in deep water, off the west coast of Australia contains from 50 to 95%, average 79%, clay; silt range from 4 to 50% and averages 20%; sand ranges from 0 to 10% and averages 1%. The average grain size is $1.0 \mu\text{m}$ (Thayer et al., 1974). The samples are composed of approximately 30% quartz, 10% cristobalite, 6% feldspar and 54% clay minerals. A significant portion of the quartz is diagenetic chert.

Late Tertiary, near shore glacial sediments from the Ross Sea, Antarctica, contain approximately 50% clay, 35% silt and 15% sand (Barrett, 1975). The glacial origin suggested by the mineralogy. The sediment is composed of approximately 45% quartz and cristobalite, 35% feldspar and 20% clay minerals (Cook et al., 1975).

Pliocene - Pleistocene sections (5) off the northwest coast of the United States and Canada have fine-grained sediments that contain an average of approximately 57% clay (range 45 to 70%), 42% silt and 1% sand (Bode, 1973). The bulk samples contain an average of 27% quartz, 26% feldspar, 3% carbonate and 44% clay minerals. The less than $2 \mu\text{m}$ fraction contains an average of 15% quartz, 15% feldspar and 70% clay minerals (Zemmelis and Cook, 1973). Though these sediments are not classed as glacial, the high feldspar content and the relatively low content of clay minerals indicates there has been relatively little weathering in the source area.

Lower Cretaceous muds (22) from the Blake-Bahama Outer Ridge contain approximately 70% clay and 30% silt. The average mineral composition is 24% quartz, 2% feldspar, 9% carbonate, 2% pyrite and 63% clay minerals. Late Tertiary samples (14) from the Lower Continental Rise east of Virginia also contains 70% clay and 30% silt. The average mineral composition is 24% quartz, 4% carbonate and 72% clay minerals (Boyce, 1972).

Late Cenezoic sediments (7 wells) from the Gulf of Mexico which contain from 10% to 50% carbonate (average approximately 23%) commonly contain 65 to 80% clay (average approximately 74%) and 1% sand (Ewing, 1968 and Boyce, 1973). The quartz content is approximately 21% and feldspar 9%. The average content of clay minerals is approximately 47%. The less than 2 μ m fraction contains 18% quartz, 6% feldspar and no carbonate (Rex, 1968, Cook and Zemmels, 1973). The clay mineral/quartz plus feldspar ratio is similar to that found in calcareous shales.

Shales

Scotford (1965) made detailed analyses of 158 Ordovician shale samples (Cincinnati series) from Ohio, Kentucky and Indiana. The rocks are described as being massive when dry but show good fissility when wet. This further demonstrates the limits of fissility as a basic criteria for classification. Scotford states that the term mudstone can not be applied to these rocks as silt is more abundant than clay, yet most authors (Pettijohn, 1975 and Picard, 1953) consider shale and mudstone to be identical in grain size and composition with the latter lacking fissility. Scotford chose to call his samples shales.

The mean size distribution of the shale samples is 3% sand, 59% silt and 38% clay. The mean mineralogy of the 158 shale samples and the range of the average value of four subunits of the shale section are shown in Table 3.

The quartz and feldspar comprises approximately one-quarter of the shale by weight and the clay minerals 61%. The carbonate content is 14% which is four times as much as for the average shale of Shaw and Weaver (1965). The relatively high carbonate content probably accounts for the low fissility of the rock. The rock is texturally a siltstone, yet contains 61% clay minerals. The silt fraction of these shales contains 28% quartz,

Table 3. Mineral Composition Ordovician Shale

	<u>Mean</u>	<u>Range</u>
Quartz	24.0	17.3 - 29.4
Calcite	6.2	3.4 - 8.5
Dolomite	6.7	0 - 18.0
Illite	47.0	37.7 - 51.1
Mixed-layer illite	4.4	2.2 - 10.9
Chlorite	7.7	3.8 - 11.1
Mixed-layer chlorite	1.7	0.8 - 4.6
Kaolinite	Tr	
Feldspar	Tr	
Pyrite	Tr	
Total Clay Min.	60.8	
Quartz & Fld.	24.0	
Carbonates	13.9	

55% clay minerals and 17% carbonate minerals. The quartz content would appear to be considerably lower than that of a "real" siltstone.

Scotford plotted the lateral distribution of the data obtained from a study of one of the shale units (Clarksville member). Over a distance of 150 miles the silt content decreases from approximately 65% to 45%, sand from 15 to 0% and calcite 10 to 1%. Conversely the clay content increases from approximately 20% to 55%. The rock unit would appear to be a siltstone at one extreme (shoreward) and to approach the texture of a clay-stone at the other extreme. Farther seaward true claystones should be encountered.

Size analysis of eleven Pennsylvanian shales from Kansas (McMillian, 1959) show an average of 68% of the material is coarser than $3.9\text{ }\mu\text{m}$. Five to ten percent of the coarse material is sand size. These shales lie below underclays and probably were deposited in relatively high energy fluvial-deltaic environments. Size analyses of 80 Pennsylvanian underclays from Illinois (Odom and Parham, 1968) indicate they are siltstones. The silt content ranges from 32 to 87% and average 62.8%. Clay (less than $1/256\text{ mm}$) ranges from 3 to 57% and averages 28.1%. The sand content ranges from 0 to 38% and averages 8.9%. The coarse texture of these sediments are due to the fluvial-deltaic origin of these Pennsylvanian clays. Kaolinite and illite are the dominant clay minerals.

Hower et al., (1963) made mineral and size analyses of an Upper Ordovician Sylvan shale sample from Oklahoma. This shale is probably typical of Paleozoic clay-rich shales and contrast with the silt-rich shales described previously. The shale contains 61% less than $2\text{ }\mu\text{m}$ material. Approximately 67% of the shale is finer than $4\text{ }\mu\text{m}$. Quartz comprises 23.8% of the total sample; clay minerals, largely illite, comprise the other 76.2%. The coarser than $2\text{ }\mu\text{m}$

fraction contains 46.0% quartz and 53.2% clay minerals. The less than 2 μ m fractions contains 9% quartz and 91% clay minerals. This appears to be a clay shale similar to the type analysed by Weaver and Shaw (1965) to establish the average mineral composition of shales. It should be noted that even though one-third of the material is silt size more than half of the silt-size material is clay minerals.

K-Ar analyses of the Sylvan shale indicates most of the silt-sized and some of the clay-sized illite is detrital and was presumably was derived from a shale, schist or gneiss. Though the nature of the source material is less a factor in determining the grain size of a shale than it is a sandstone, it is a factor. The maximum grain size of the clay minerals in most shales is controlled by source (detrital effect) but the average and minimum grain sizes are effected both by source and diagenetic mineral alterations. A genetic classification should take into account these two factors.

Figure 4 contains a series of frequency curves showing the size distribution and mineral composition of the Cretaceous Eagle Ford shale from near Dallas, Texas. The sample appears to have slightly more silt than clay. Only minimum agitation was used to disaggregate the sample. This is demonstrated by the fact that montmorillonite occurs in the 20 mm size fraction.

X-ray and size analyses of Ordovician K-bentonite beds indicate they contain more than 95% clay minerals but only 30 to 70% of the material is clay size. The amount of clay-sized material increases as the intensity of weathering increases and as dispersion time is increased (Weaver, 1953).

The results of textural analyses of rocks containing clay minerals commonly reflect the efficiency of the dispersion technique rather than the true grain size.

Figure 4. Particle size distribution and mineral composition of the Eagle Ford shale, near Dallas, Texas. After Mielenz and King (1955).

Tourtelot (1962) made a detailed study of the montmorillonitic Upper Cretaceous Pierre shale of the Great Plains region. The term shale is used to indicate the general class of fine-grained sedimentary rocks. Size analyses of 38 shale samples indicate they contain an average of about 70% finer than 1/256 mm (about 4 μ m); values range from 35 to 90%. Nearly 50% of the material is finer than 1 μ m. The shales in Wyoming and Montana, nearest the source area, contain an average of 60% clay size material. Farther east, in the Dakotas, the average is 75%. Marlstone increases to the east.

Ruby (1930) made size analyses of nine shale and mudstone samples from the Upper Cretaceous of the Black Hills Region., including the Pierre Shale. He reported subequal amounts of clay and silt in his samples. His low clay values may in part be due to the fact that the rocks were allowed to dry for three to four years. This makes dispersion much more difficult. Further, Ruby devised his own method for calculating grain-size from settling velocities and his data is not directly comparable with other data.

Size analyses of montmorillonitic Oligocene-Miocene clays and claystones (1,250 m to 5500 m) from the Gulf Coast (Hower et al, 1975) show that 50 to 71% of the material is finer than 2 μ m. Eighteen Miocene samples (390 m to 3588 m) from the Gulf Coast (Cooke, 1977) contain from 55 to 78% less than 4 μ m material, averaging approximately 65%.

These Cretaceous and Tertiary sediments contain an abundance of montmorillonite and mixed-layer illite-montmorillonite which can be easily dispersed to clay size. Thus, the textural analyses and the mineral analyses gives similar results. In contrast, much of the illite and chlorite in Paleozoic shales does not disperse to clay size and there is a marked contrast between the textural analyses and the mineral analyses. The type of clay mineral present can determine if a rock is a claystone or a siltstone.

X-ray analyses of 7 Precambrian Belt argillite samples show they contain 23.6% quartz (range 20 to 27%); 63% clay minerals (range 48 to 70), largely illite, 9.2% feldspar, 2.3% calcite and 6.4% dolomite (Eslinger and Savin, 1973). They point out that though some of these rocks have been exposed to temperatures of 300°C, resulting in considerable mineral and chemical alteration, there is no visual evidence of metamorphism. There is no information on the grain size of the clay minerals in the Belt argillite. Flawn (1953) states that the reconstituted material in argillite ranges from 10 to 50 μm .

Bates and Strahl (1957a) reported on the bulk mineralogy of a number of black shales (fig. 5). Organic carbon ranges from approximately 2 to 16%. Much of the material listed under kaolinite is actually chlorite.

Aside from the relatively high organic (4%) and pyrite (5%) content, the Ohio shale has a composition similar to that of typical Paleozoic shales: approximately 22% quartz, 5% carbonate, 2% iron oxide and 50% illite and chlorite. Some feldspar is probably present. In contrast, the Chattanooga shales contains 22% quartz, 9% feldspar, trace of carbonate, 11% pyrite, 2% iron oxides, 15% organic carbon (22% organic matter) and 33% illite and chlorite (Bates and Strahl, 1957b). Microscopic study indicates 45% of a sample is fine-grained matrix. The quartz and feldspar content is typical of Paleozoic shales but the clay mineral content is low. The organic matter and clay minerals total 55% which is similar to the average value for Paleozoic shales. Much of the organic material is detrital and may have assumed the role of clay minerals during weathering and transportation.

The mineral composition of the Devonian-Mississippian Besa River Formation black shale in British Columbia (300 to 2000 m thick) changes laterally from approximately 30% quartz, 66% illite >> chlorite, and 4% carbonate to 53% quartz,

Figure 5. Composition of organic-rich shales.
After Bates and Strahl (1957a).

43% illite >> chlorite and 4% carbonate. The quartz occurs as sponge spicules, radiolarian and chaledonic lenses. No detrital quartz was observed. The organic content is apparently on the order of 5% (Pelzer, 1966).

One of the few thin studies of a series of shales is that of Grim et al., (1957). They estimated the mineral composition and measured the maximum grain diameter of 45 Paleozoic shales ranging in age from Pennsylvanian to Ordovician, but mostly of Pennsylvanian age. All samples were from Illinois. Most of the samples were described as being laminated or having partings (even, uneven, wavy). Only one was described as fissile, so perhaps they are not "typical" shales; fissil shales are relatively uncommon in Pennsylvanian age sediments. Their definition of shale is an indurated, argillaceous sedimentary rock which is layered or laminated parallel to the bedding. Basically, the samples were all described as shales by field geologist.

X-ray analyses indicate illite is the dominant clay mineral in most of these shales. Chlorite and kaolinite are present in varying proportions. The clay fraction ($<2\text{ }\mu\text{m}$) of most samples contain 5 to 10% quartz. No quartz was detected in approximately one-quarter of the samples.

The following discussion of the textural characteristics is quoted directly from Grim et al. (1957). Observations are based on microscopic examination. The data on individual samples is listed in Appendix 2.

"The clay mineral content of the shales studied varies from substantially 100 percent to 40 percent or less. In those samples with very high clay mineral contents. The clay mineral particles are all very small (maximum size less than 5-10 microns and mostly less than 2 microns) and they show uniform aggregate orientations parallel to the lamination. The maximum divergence from perfect parallelism is about 20° . There is no positive evidence of secondary growth of the clay mineral particles.

In the very pure clay mineral shales, the maximum size of the nonclay minerals is 10 microns or less. As the amount of nonclay minerals increases their maximum size also increases. Thus, in shales with 10 percent nonclay minerals, their maximum size is likely to about 10 microns; with 30 percent nonclay minerals, the maximum size is about 50 microns; and with 50 percent nonclay minerals, it is likely to be as much as 100 microns. (Weaver and Beck's, (1977) study of the Miocene marine clays of the southeast indicates there is an excellent positive linear relation between the amount of quartz and the size of the quartz grains.

As the amount of nonclay minerals increases, the particle size of the clay minerals also increases. In shales with 50 percent or more nonclay minerals, the maximum size of the micaceous minerals may reach 150 microns. Muscovite, biotite and chloritic types of mica can be identified among these large flakes. The various types of mica are present in distinct books; that is each book is homogeneous and apparently mono-mineralic.

The large mica flakes in the shales with large percentages of nonclay minerals show a general tendency towards uniform orientation parallel to the lamination. It is not perfect as many of the flakes are bent around quartz grains and some few are actually perpendicular to the lamination. The boundaries between the large flakes of mica and the very small clay mineral particles is distinct. Frequently the books of mica show split or frayed ends.

In most of the shales with large amounts of nonclay minerals the nonclay minerals are scattered through the clay minerals; that is, there is no tendency to concentrate the nonclay minerals and clay minerals in distinct layers, and the shale is composed of a heterogeneous assemblage of clay and nonclay minerals

of all sizes. In some shales there is an occasional slight concentration of nonclay minerals in small lenses or layers, and in a few samples studied there is a distinct layering of clay minerals and nonclay minerals. The very largest flakes of mica are found in the shales having a layering of components and in the layers composed of the nonclay minerals.

The specific nature of the types of mica, the characteristics of the flakes themselves, and the association of large flakes with large and abundant nonclay minerals indicate that they have been deposited as such. There is no evidence of substantial secondary growth of the large flakes of the micas. The unsorted characters of many of the shales suggest fairly rapid accumulations of the shales showing this particular characteristic.

All the shales contain carbonaceous organic material varying in amount from a trace to about 5 percent. In most of the shales studied, organic material makes up 1 percent or less of the total sample, and in general the amount is least in shales with the highest clay mineral content. The organic matter is present in pigmentary material (that is, as particles too small to be recognized individually), in black opaque particles many of which are about 10 microns in diameter, and very rarely in waxy, yellow, translucent rounded or lenticular particles 10-30 microns in cross-section. The pigmentary material is most common in the purer clay mineral shales, and indeed is the only type of organic matter in many such shales. Very frequently the pigmentary organic matter is concentrated in streaks parallel to the lamination. Also the larger discrete organic particles are very often concentrated in elongate patches parallel to the lamination.

Quartz in rounded to angular grains is the most abundant nonclay mineral and frequently the only one that can be identified readily. Many of the larger grains show secondary growth and mutually accommodating boundaries when they

are concentrated in layers and lenses. In shales containing quartz in grains 30 microns or more in diameter and in abundance greater than about 30 percent, angular to rounded grains of feldspar can be identified easily. The abundance of the feldspar is probably less than one percent. Both plagioclase and orthoclase can be found. There is no indication that the feldspar is not depositional.

A few of the shales studied are calcareous. In almost all cases the carbonate particles are fossil fragments. Frequently the fossil fragments have been broken and are strung out parallel to the lamination.

The major and in many shales the sole, cause of the lamination is the aggregate parallel orientation of the clay mineral particles. Additional causes of the lamination are the concentration of organic material in streaks and the concentration of the quartz grains in distinct layers. In shales with appreciable amounts of organic matter the shale splits preferentially where the organic material is concentrated.

Lamination is least well developed in the pure clay mineral shales with very small amounts of organic matter where the sole cause of lamination is the parallel orientation of the clay minerals. In many such shales there is a tendency to a blocky fracture across the direction of parallel orientation of the clay mineral flake surface as well as parallel to the clay mineral surfaces. In such purer clay mineral shales, the clay mineral particles are very small. It seems that the clay mineral particles should be larger than about 5 microns before their parallel orientation alone is likely to cause distinct fissility."

The 43 samples contain an average of 66.3 clay minerals, 25.3% quartz, 2.7% carbonates and minor amounts of feldspar and organic material. An appreciable portion of the clay minerals are silt-sized and larger. Ten

of these samples were analyzed by the quantitative x-ray method of Shaw and Weaver (1965). The average quartz content based on microscopic examination is 29.5% and by x-ray analysis 36.6%. The difference is surprisingly small and most of the difference can be assigned to the 5 to 10% of quartz that is present in the less than 2 μ m fraction. Only trace amounts of feldspar were observed though the x-ray analyses indicate an average of 9% was present. Neither techniques detected any appreciable amount of carbonate. Because of their fine grain size, the quartz and feldspar content tends to be underestimated by microscopic observation.

Most of the shales, largely Pennsylvanian, were probably deposited in a fluviatile - deltaic - lacustrine complex of environments and would be expected to have a relatively high content of silt-sized minerals. Finer grained and more fissile shales are commonly deposited under marine conditions.

Krynine (1950) reported that the red shales associated with the Triassic arkosic rocks of Connecticut became fissile when weathered and contain 15 to 20% grains and 80 to 85% ferruginous clay matrix. Dark shales typically contain organic matter, 30% quartz and 27% feldspar. Most of the other minerals are sheet silicates with about half of them being relatively large, oriented micaceous flakes. Red silt-stones contain 15 to 75% quartz and feldspar grains (3:2) in a paste of ferruginous clay.

A thin section study of the Silurian by Folk (1960) showed the clay shales in the marine Rose Hill shale contained 5% visible quartz-silt (.005 to .030 mm, average 0.015 mm) and 95% clay (presumably clay minerals). Carbonate grains and organic material are rare or absent. The quartz grains are randomly scattered throughout the clay. The few mica flakes present average 0.05 mm long and are distinctly coarser than the clay flakes which average

5 μ m in length. These shales are probably typical marine shales which characteristically contain less silt-size material than the fluvial-deltaic shales.

In the less common mud-shales, silt (quartz?) comprises 30 to 50% of the rock and averages 0.020 to 0.040 mm. The typical siltstone is a very fine, sandy silt-stone containing only 3% clay. Two-thirds of the grains are between 0.035 to 0.07 mm in diameter.

Calcareous Shales and Marls

Pettijohn (1975) states the average shale contains about 6% calcite. Shaw and Weaver (1965) found the average shale contained 3.6% carbonate minerals. As the carbonate content increases the rocks become less fissile and should be called calcareous shales. Pettijohn defines marls and marlstones as containing 35 to 65% (in 1948 his limits were 25 to 75%) carbonates, with the remaining material being largely clays. They have a blocky, subconchoidal fracture.

There is little data on the relative quartz-clay mineral content of calcareous rocks. Shaw and Weaver's (1965) data shows that the clay mineral/quartz ratio of shales containing from 0 to 3% carbonate minerals averages 1.8, those which 3 to 10% average 1.6 and those containing 10 to 55%, average 2.2. For shales with more than 10% carbonate, the clay mineral/quartz ratio increases linearly. Shales containing 50% carbonate have a ratio of approximately 4.

The trend is what might be expected. Samples with a small carbonate content have a clay mineral/quartz ratio similar to that for non-calcareous shales. Environments in which abundant carbonates and clay-sized material accumulate are low energy environments which would tend to receive a relative small amount of silt (quartz).

An excellent example of a calcareous shale is the Devonian Ireton Formation which is associated with the Ledux Reefs of Alberta (Weaver, 1968 and Campbell and Oliver, 1968). The carbonate content increases from 10 to 30% as the reefs are approached. The carbonate content (both calcite and dolomite) of the shaley portion of the Ireton averages 27%, quartz averages 23%, and clay minerals 50% (illite greater than chlorite).

There appears to be little textural data on fine-grained sediments that have an appreciable carbonate content. The clay mineral/quartz is similar to that in shales and it is likely the textures are also similar.

Summary

Shallow buried, recent and ancient marine sediments with a high content of clay minerals commonly contain 60 to 80 clay and 20 to 40% silt. Sheet silicate minerals are present in approximately the same amounts as the clay-sized material. Recent, deltaic fine sediments contain about half this amount of clay and a slightly lesser amount of sheet silicate minerals. Sediments deposited in cold climates tend to contain more feldspar and less sheet silicate minerals.

Many fine sediments that have been relatively deeply buried contain 30 to 40% clay (limited data); the sheet silicate content is in the range of 60 to 80%. Some Paleozoic sediments exist which have both the clay content and the sheet silicate content in the 70 to 80% range.

Both Cenezoic and Paleozoic calcareous fine-grained sediments commonly have twice as much sheet silicate material as quartz. In unlithified younger sediments the clay content averages approximately 75%. In older sediments the average clay content is slightly lower.

Thus, regardless of the grain size, it appears that most fine-grained marine silicate sediments contain 60% or more sheet silicate minerals. The data confirms the x-ray analyses of Weaver and Beck (1965) that indicated the average shale contained 61% sheet silicates. The data also indicates mineralogy does not have any fixed relation to grain-size. The two parameters must be considered independently.

Slates

On the basis of semiquantitative x-ray data of 19 slates from Pennsylvania, Virginia and Vermont, Bates (1947) obtained the data shown in Table 4.

Table 4. Mineral Composition of Slates

	Average	Range
Quartz	44.6	32.1 - 53.2
Feldspar	9.6	6.7 - 13.1
Calcite	10.9	5.7 - 20.2
Dolomite	6.1	1.7 - 10.8
Pyrite	4.2	1.5 - 11.3
Chlorite	5.1	2.9 - 6.5
Sericite	24.8	15.2 - 31.7

The sheet mineral content is surprisingly low and the carbonate and quartz content is high, if the precursor rock was a normal Paleozoic shale. Chemical analyses suggest the quartz is probably overestimated by approximately 20% and the sheet silicates underestimated by 20%. However, these slates may not be a typical as they are similar in composition to low-grade metamorphic rocks in the Alpine region (Frey, 1970).

Thin section studies by Bates (1947) showed that the maximum size of the quartz grains in the slate samples ranged from 13 to 60 μm and averaged 35 μm . This suggests the original rock had the texture of a shale. In contrast, the maximum size of the chlorite flakes ranged from 180 to 360 μm and average 270 μm . This is in contrast to an average maximum flake size of 64 μm for chlorite and mica in Paleozoic shales (Grim, et al., 1957). Presumably there has been considerable recrystallization and growth of the sheet silicates.

The quartz has presumably maintained its original size but the sheet silicates have increased in size during diagenesis and metamorphism. With increased temperature and pressure a clay-rock can be converted to a sand-rock.

Dale (1914) listed a large number of chemical analyses of slates from United States and Europe. Al_2O_3 ranged from 11 to 23%, with most samples being closer to the high number. If all the Al_2O_3 is assigned to phyllosilicate minerals and feldspars, the slates would contain approximately 40 to 90% of these minerals. Most would be phyllosilicates. Most of the CaO values are less than 2% indicating the carbonate content is relatively low.

The range in mineral composition of slates is similar to that for shales. The quartz grains appear to be similar in size to those in shales but the sheet silicate minerals are generally coarser.

Mineralogic Classification

Krynine (1948) attempted to relate the clay mineral composition of shales to the principal sandstone types. He believed shales associated with graywacke were chloritic, those with arkoses, kaolinitic and those with quartzites, illitic. There is some validity to this suggestion but exceptions are numerous (Weaver, 1958).

Krumbein and Sloss (1951) classify shales on the basis of the silt minerals which they believe correspond in mineral composition, to the four main types of sandstone. They suggest that very fine shales that contain few silt minerals should be classified on the basis of chemical analysis. Essentially, they are saying that the siltstones have the same mineral composition as the sandstones and that they do not know what to do with the clay shales.

They classify silt shales as follows: (1) Quartzose shale - composed dominantly of rounded quartz grains in the silt sizes. (2) Feldspathic shale (kaolinitic shale) - has a feldspar content greater than 10% in the silt-size and a finer matrix of kaolinitic clay minerals. (3) Chloritic shale - contains a variety of minerals in the silt-size. Chlorite may be abundant in the finer matrix. Chloritic shale is associated with graywacke and represents accumulation of relatively fine detritus under conditions of rapid deposition. (4) Micaceous shale - has abundant muscovite flakes and finer grained sericite in the clay matrix. Silt minerals include abundant quartz and minor feldspar. It is associated with quartz wacke.

The classification of Krumbein and Sloss (1951) like that of Krynine (1948) is based on limited data and the assumption that the shales are essentially fine-grained sandstones. There is some truth to the analogy but it holds more for the nonclay minerals than the clay minerals.

Although some generalizations can be made, there is not always a direct and obvious relation between the clay mineral composition of shales and the mineral composition of associated sandstones. The clay minerals derived from a given source rock are often determined more by climate, drainage, and topography than by composition of the source rock. Further, clay minerals are more easily segregated in the depositional environments than are sand-sized

minerals; and clay minerals are more susceptible to diagenesis than sand-size minerals. Thus, only a very vague or complex relation exist between shale composition and sandstone composition.

A collection of clay-rich shales with known sandstone association were analysed by Shaw and Weaver (1965) to determine mineralogic associations. The shales were divided into three groups: (1) Shales associated with moderately mature sublithic sandstone (89-95 per cent quartz, trace to 5 per cent feldspar, trace to 10 per cent matrix) have a quartz/feldspar ratio of 15. (2) Shales associated with immature lithic sandstone (50-75% quartz, 10 per cent feldspar, 25-35 percent matrix) have a quartz/feldspar ratio of 9.0. (3) Shales associated with immature arkosic sandstone (approximately equal abundance of quartz and feldspar, 25-35 percent matrix) have a quartz/feldspar ratio of 1.0.

The 27 shales in the first group average 31 percent quartz, 3.5 percent feldspar, 60 percent clay, and a trace to 1 percent carbonate; the quartz/feldspar ratio is 8.6. The 50 shales in the second group average 32 percent quartz, 4.3 percent feldspar, 63 percent clay, and a trace to 1 percent carbonate; the quartz/feldspar ratio is 7.5. The 19 shales in the third group average 23 percent quartz, 19 percent feldspar, 57 percent clay, and a trace to 1 percent carbonate, the quartz/feldspar ratio is 1.2. Only a few samples of shales associated with mature quartz sandstones were examined, but the results of these analyses suggest that the quartz/feldspar ratio is approximately 30.

This relation is better seen when sediments from a single province are examined. In southern Oklahoma, the Stanley (high-rank graywacke) shales have an average quartz/feldspar ratio of 6.8; the Atoka and Morrow (low-rank graywacke to quartzose graywacke) shales have a ratio of 12; and the Springer (orthoquartzite to quartzose graywacke) shales, a ratio of 27. Thus, the relative quartz and feldspar content of shales with a high content of clay minerals is related to that of the associated sandstones. The relation in coarser

shales is probably more pronounced. The clay mineral suite has only a vague relation to sandstone type. The relation would probably be closer if the clay suite was not modified by diagenesis.

EFFECTS OF DIAGENESIS ON TEXTURE

It is virtually impossible to analyze a shale and obtain any meaningful information about the size of the clay mineral particles at the time of deposition. The clay minerals are deposited as isolated flakes, books, floccules, pellets, clast, rock fragments, etc. The grain size of clay minerals and aggregates of clay minerals changes during burial; most become larger but some become smaller. Unconsolidated clays commonly become silt-stones when buried deep enough to be exposed to temperatures higher than approximately 150° to 200° C.

The majority of the clay minerals in unconsolidated clays, recent marine muds, and clay mineral-rich rocks that have not been deeply buried, are finer than $4\text{ }\mu\text{m}$. With burial the temperature and pressure increases and the average grain size of the clay mineral suite systematically increases and many of the clay minerals and clay mineral aggregates (tactoids) increase in size and eventually become silt-sized.

In the thick Tertiary mud sections of the Gulf Coast calcite is dissolved during shallow burial and most of it appears to be lost before burial temperatures exceed 90°C (Weaver and Beck, 1971 and Hower, et al., 1975).

Hower et al. (1975) indicate silt-sized K-feldspar is dissolved (disappears) relatively abruptly at a temperature of approximately 80°C ; however, in a similar but younger section (Upper Miocene) Weaver and Wampler (1970) found K-feldspar systematically decreasing with depth but still present at depths where the temperatures were 119°C . Thus, time is a factor. Roughly, it may take 20 to 25 m.y. for K-feldspar to be destroyed at temperatures below 100°C .

The K is adsorbed by the montmorillonite. It is not known what happens to the Si and Al. Hower et al. (1975) suggests the Si is converted to quartz. Weaver and Beck (1971) suggested the Al combines with montmorillonite to form dioctahedral chlorite.

At burial temperatures as low as 80°C (commonly 2,000 to 4,000 m) montmorillonite starts to convert to mixed-layer illite-montmorillonite and increases in size. The increase in size is probably continuous with increasing temperature, up to and through the metamorphic stage, as the montmorillonite is converted to illite (~200°C) and then phengite. This is probably true but has not been definitely established. Weaver (1960) and Kubler (1964) have demonstrated that during advanced diagenesis and early metamorphism the "sharpness" of the 10°A illite peak (crystallinity) increases. It seems likely that a flake-size also increases. Si may be released from the tetrahedral sheet during this conversion and form fine quartz. This would decrease the average particle size. However, if the Si precipitates on pre-existing quartz grains the grain size would increase.

Kaolinite can be destroyed at temperatures as low as 80°C but can persist to temperatures as high as 190°C (Dunoyer De Segonzac, 1970 and Weaver and Beck, 1971), depending on age, porosity, organic content, K^+/H^+ , etc. It is not clear what happens to the Si and Al. It has been suggested that it alters to illite (Dunoyer Der Segonzac, 1970) and dioctahedral chlorite (Weaver and Beck, 1971). It is unlikely that there is enough K available in most shales to accommodate the conversion of appreciable kaolinite to illite, though such a conversion can occur in porous sandstones (Millot, 1970).

The size of detrital, high temperature illite (2M) and chlorite (11b) is probably little effected by diagenesis unless they have been fairly extensively

weathered. The story for low-temperature chlorites is complex and not well understood. Chlorites can form at surface temperatures in environments in which sandstones and limestones are abundant. In hydrothermal areas, chloritic material starts forming at temperatures less than 100°C (Steiner, 1967). Hower et al. (1975) reported that in a thick clay section chlorite increased abruptly from zero to 10% at a depth where the temperatures was to approximately 70°C . There was no further increase with increased depth and temperature. In a slightly younger Gulf Coast section Weaver and Beck (1971) observed no change in the chlorite content with depth; however, in Pennsylvanian age shales that had been subjected to temperatures in the 150° to 200°C range they found an increase in chlorite and a decrease in kaolinite.

The chlorite formed during the early stages of diagenesis is probably clay-sized and may cause a decrease in the silt/clay ratio. Grain size increases during the more advanced stages of diagenesis and some of the chlorite becomes silt-sized. In general it appears that during diagenesis, illite becomes coarser than chlorite.

The dissolution of K-feldspar and kaolinite during burial causes a decrease in grain size. This effect is commonly more than offset by the increase in grain size of the other clay minerals, particularly during the late stages of diagenesis; however, the process is probably not linear when measured in terms of the silt/clay ratio.

In some instances K-feldspar is lost from the silt fraction before there is any appreciable change in the clay suite (Hower et al., 1975). This would cause a decrease in the silt/clay ratio. With increased burial the silt/clay ratio should increase. Hower's et al. (1975) data indicate the clay mineral content of the greater than $2\text{ }\mu\text{m}$ fraction increases from approximately

20% to 50% between 2,000 m and 4,000 m, then remains constant to 5,500 m. The total amount of material coarser than 2 μm increases by approximately 20% (27% to 45%) over this same interval. The amount of material finer than 0.5 μm decreases from 29% to 11% with depth. Thus, most of the size increase is due to an increase in the size of clay minerals and/or clay mineral aggregates. A temperature of 174°C was reported for the bottom of the well. Deeper in the section the silt content should become dominant and the original clay mud will have been converted to a siltstone.

Though this depth-size relation is probably most pronounced for montmorillonite-rich sediments, a similar textural change should occur in all sediments containing a major content of clay minerals. Most other clay minerals would require higher temperatures to produce equivalent textural changes. Conversely, if the clay minerals are never exposed to burial temperatures significantly higher than 80°C for montmorillonites and 200°C for illites the flake size is not likely to increase though the aggregate size may. The details remain to be worked-out, particularly the effects of time.

NEW NOMENCLATURE

There is need for a term equivalent to feldspars and carbonates that includes the whole family of sheet silicates and has no connotation of grain size. I am proposing that the term physil be used as an abbreviated form of the term phyllosilicate. Physils would include all hydrous aluminum-magnesium-iron silicates with a sheet structure and would include the palygorskites and sepiolites which can be considered to have a sheet structure with limited width in one direction. The term has no size implications and includes both the clay minerals and the coarser micas and chlorites. Thus, various classifications can be constructed using the terms quartz, feldspar, carbonate and

physil. The term clay minerals and, to some extent, the word clay have been used as synonyms for the term phyllosilicates but with the added connotation of fine grain size. The preceeding discussion has shown that many of the physils in fine-grained rocks are silt-sized or larger. The term clay should be used only in the textural sense, preferably to describe the material finer than $1/256$ mm ($4 \mu\text{m}$).

The terms physil clay, physil silt, physil silty clay, etc. can be used to refer to unconsolidated material containing more than 50% physils. Clay minerals would be all minerals finer than $4 \mu\text{m}$. Calcareous physillic clay, etc. can be used to describe unconsolidated sediments containing less than 50% physils (Table 5).

Consolidated or lithified rocks containing more than 50% physils would be called physilites. Physilites would include most rocks classed as shales, claystones, mudstones, siltstones, slates, schist and gneiss among others. The term physilite should be restricted to sediments. Metamorphic rocks should be referred to as metamorphic physilites. If the physil content is larger than 50%, the rocks can be described as clay physilites, silt physilites, calcareous clay physilites, etc. If the physil content is less than 50%, the terms physilic claystone, physilic silt-stone, etc. are applicable.

Sedimentary rock names should not have a structural connotation. Structural terms would serve as prefixes. Thus, rocks should be described as fissil physilites, fissil clay physilites, laminated clay physilites, massive silt physilites, massive physilitic siltstones, etc. The two and three word descriptions are not as succinct as single words but the ambiguity is considerably reduced. The proposed terminology is flexible and will allow the clay rocks to be described more accurately. In time this will lead to a better understanding of the genetic implications of the various rock types.

For example, it will probably be established that most fissile clay physilites are marine in origin and have only suffered mild burial diagenesis (low temperature) fissile silt physilites probably are indicative of rock that have gone through advanced diagenesis (high temperature); laminated physilic siltstones are probably indicative of fluvial-deltaic sediments that have been exposed to moderate diagenesis; etc. A genetic interpretation is not only concerned with tectonic background, environment of deposition and source but, particularly in physilites, diagenesis.

The physil sediments have the potential to provide more information than all other rock types combined, hopefully one new word will help.

Table 5. Classification of Fine-Grained Rocks Containing Sheet Silicate Minerals

Texture	COMPOSITION			
	Unindurated		Indurated	
	>50% Physils	<50% Physil	>50% Physils	<50% Physils
> 50 silt 1/256 - 1/16 mm	physil silt	physilic silt	silt physilite	physilic siltstone
> 50 clay < 1/256 mm	physil clay	physilic clay	clay physilite	physilic claystone

REFERENCES

- Alling, H. L. (1945) Use of microlithologies as illustrated by some New York sedimentary rocks, *Geol. Soc. Amer. Bull.*, 56, 737-755.
- Andrews, P. B. and A. T. Owenshine (1974) Terrigenous silt and clay facies: deposits of the early phase of ocean basin evolution, DSDP Leg 29. in Kennett, J. P., Houtz, R. E., et al., *Initial Reports of the Deep Sea Drilling Project*, Vol. 19, Wash. (U.S. Gov. Printing Office) 1049-1063).
- Atterberg, A. (1905) Die rationelle klassifikation der sande und kiese. *Chem. Zeitschr.*, Vol. 28, 195-198.
- Barrett, P. J. (1975) Textural characteristics of Cenozoic preglacial and glacial sediments at size 270, Ross Sea, Antarctica. In Hayes, D. E. Frakes, L. A., et al. *Initial Reports of the Deep Sea Drilling Project*, Vol. 28, Wash. (U.S. Gov. Printing Office), 757-773.
- Bates, T. F. (1947) Properties and New Uses of Pennsylvania slate. Penn. State College, Miner. Indus. Exp. Station, Bull. 47, 168p.
- Bates, T. F. and E. O. Strahl (1957a) Mineralogy and chemistry of uranium-bearing black shales. 2nd UN Geneva Conf., Pergamon Press, London, 407-411.
- Bates, T. F. and E. O. Strahl (1957b) Mineralogy; petrography, and radioactivity of representative samples of Chattanooga shale. *Bull. Geol. Soc. Amer.*, Vol. 68, 1306-1314.
- Blatt, H. and D. J. Schultz (1976) Size distribution of quartz in mudrocks, *Sedimentology*, 23, 857-866.
- Bode, G. W. (1973) Grain size analyses, Leg 18, In Kulm, L. D., von Huene, R., et al., 1973. *Initial Reports of the Deep Sea Drilling Project*, Vol. 18, Wash. (U.S. Gov. Printing Office) 1061-1067.
- Boyce, R. E. (1972) Leg 11 grain size analyses In Hollister, C. D., Ewing, J. I. et al. 1972, *Initial Reports of the Deep Sea Drilling Project*, Vol. XI. Wash. (U.S. Gov. Printing Office) 1047-1057.
- Boyce, R. E. (1973) Grain size analyses In Worzel, J. L. Bryant, W., et al. 1973, *Initial Reports of the Deep Sea Drilling Project*, Vol. X, Wash. (U.S. Gov. Printing Office) 637-640.
- Campbell, F. A. and T. A. Oliver (1968) Mineralogic and chemical composition of Ireton and Duvernay formations Central Alberta. *Bull. Canadian Petroleum Geol.*, Vol. 16, 40-63.
- Clark, F. W. (1924) Data of geochemistry. *Bull. U.S. Geol. Surv.*, No. 770, 841 p.

- Clark, T. H. (1954) Shale: A study in nomenclature. Trans. Royal Soc. Canada, Vol. XLVIII, Senes III, 1-7.
- Cooke, Gary E. (1977) Pore Water Constituents of Deeply Buried Pelagic Gulf Coast Muds as Indicators of Diagenetic alteration, M. S. Thesis, Ga. Inst. Technology.
- Cook, H. E. and I. Zemmels (1973) X-ray mineralogy studies of Leg 10 cores in the Gulf of Mexico; in Worzel, J. L. Bryant, W. et al., 1973, Initial Report of the Deep Sea Drilling Project, Vol. X, Wash. (U.S. Gov. Printing Office) 337-374.
- Cook, H. E., I. Zemesl and J. C. Matti (1975) X-ray mineralogy data. In Hayes, D. E. Frakes, L. A. et al. Initial Reports of the Deep Sea Drilling Project, Vol. 28, Wash. (U.S. Gov. Printing Office), 981-998.
- Correns, C. W. (1969) Introduction to Mineralogy. Springer-Verlag, N.Y. 484 p.
- Dale, T. N. (1914) Slate in the U.S., U. S. Geol. Surv. Bull., Vol. 586, 220 p.
- Dunbar, C. O. and J. Rodgers (1957) Principles of Stratigraphy, John Wiley and Sons, Inc., New York, 356 p.
- Dunoyer De Segonzac, G. (1970) The transformation of clay minerals during diagenesis and low-grade metamorphism: a review. Sedimentology, Vol. 15, 281-346.
- Evans, L. J. and W. A. Adams (1975) Chlorite and illite in some lower Paleozoic mudstones of mid-Wales Clay Miner., 10, 387-397.
- Eslinger, E. V. and S. M. Savin (1973) Oxygen isotope geothermometry of the burial metamorphic rocks of the Precambrian Belt supergroup, Glacier National Park, Montana. Geol. Soc. Amer. Bull., Vo. 84, 2549-2560.
- Ewing, M. E. (1968) Grain size analyses; in Ewing, M., and Worzel, J. L., et al. Initial Reports of the Deep Sea Drilling Project, Vol. 1, Wash. (U.S. Gov. Printing Office) 325-357.
- Flawn, P. T. (1953) Petrographic classification of argillaceous sedimentary and low-grade metamorphic rocks in subsurface. Bull. Amer. Assoc. Petrol. Geol. Vol. 37, 560-565.
- Folk, R. L. (1960) Petrography and origin of the Tuscarora, Rose Hill, and Keefer Formation, Lower and Middle Silurian of eastern west Virginia. J. Sedimentary Petrology. Vol. 30 1-58.

- Folk R. L. (1961) Petrology of sedimentary rocks. Austin, Texas. Hemphill's, 154 p.
- Frey, M. (1970) The step from diagenesis to metamorphism in pelitic rocks during Alpine orogenesis. *Sedimentology*, Vol. 15, 261-279.
- Gipson, Mack, Jr. (1965) Application of the electron microscope to the study of particle orientation and fissility in shale, *J. Sedimentary Petrology*, 35, 408-414.
- Grim, R. E. (1968) Clay mineralogy, 2nd ed., New York: McGraw-Hill, 596 p.
- Grim, R. E., W. F. Bradley and W. A. White (1957) Petrology of the Paleozoic shales of Illinois. Ill. State Geol. Surv., Rept. of Investigations, Vol. 203, 35 p.
- Grout, F. F. (1925) Relation of texture and composition of clays. *Bull. Geol. Soc. Amer.*, Vol. 36, 393-416.
- Ho, C. and J. M. Coleman (1969) Consolidation and cementation of Recent sediments in the Atchafalaya Basin. *Geol. Soc. Amer. Bull.*, Vol. 80, 183-192.
- Hower, J., P. M. Hurley, W. H. Pinson and H. W. Fairbairn (1963) The dependence of K-Ar age on the mineralogy of various particle size ranges in a shale. *Geochim. et Cosmochim. Acta.*, Vol. 27, p. 405-410.
- Hower, J., E. V. Eslinger, M. E. Hower and E. A. Perry (1975) Mechanism of burial metamorphism of argillaceous sediment: 1. Mineralogical and chemical evidence, *Geol. Soc. Amer. Bull.*, Vol. 87, 727-757.
- Ingram, R. L. (1953) Fissility of mudrocks. *Bull. Geol. Soc. Amer.*, Vol. 64, 869-878.
- Krumbein, W. C. and L. L. Sloss (1951) Stratigraphy and Sedimentation. 1st ed. San Francisco, Freeman, 497 p.
- Krynine, P. D. (1940) Petrology and genesis of the Third Bradford Sand. Pennsylvania State College, Miner. Indus. Exp. Station Bull. 29, 134 p.
- Krynine, P. D. (1948) The megascopic study and field classification of sedimentary rocks, *J. Geol.* 56, 130-165.
- Krynine, P. D. (1950) Petrology, stratigraphy, and origin of the Triassic sedimentary rock of Connecticut. *Conn. Geol. and Nat. Hist. Survey Bull.*, 73, 247 p.
- Kubler, B. (1964) Les argiles de metamorphisme. *Rev. Inst. Franc., Petrole*, 19, 1093-1112.

- McKee, E. D. and G. W. Weir (1953) Terminology for stratification and cross-stratification in sedimentary rocks, *Geol. Soc. Amer. Bull.*, 64, 381-389.
- Mielenz, R. C. and M. E. King (1955) Physical-chemical properties and engineering performances of clays. *Clays and Clay Tech.*, California Dep. Nat. Res. Bull., 196-254.
- Millot, G. (1970) Geology of Clays. Springer-Verlag, New York, 429 p.
- O'Brien, N. R. (1970) The fabric of shale-an electron microscope study. *Sedimentology*, 15, 229-246.
- Odom, I. E. and W. E. Parham (1968) Petrology of Pennsylvanian underclays in Illinois and their Application to Some Mineral Industries. *Ill. State Geol. Survey, Cir.* 429, 36 p.
- Pelzer, E. E. (1966) Mineralogy, geochemistry and stratigraphy of the Besa River Shale, British Columbia. *Bull. Canadian Petroleum Geol.*, 14, 273-321.
- Pettijohn, F. J. (1975) Sedimentary Rocks. 3rd ed. New York, Harper and Row, 628 p.
- Picard, M. D. (1953) Marlstrone-a misnomer as used in the Uinta Basin, Utah. *Bull. Amer. Assoc. Geol.*, 37, 1075-1077.
- Picard, M. D. (1971) Classification of fine-grained sedimentary rocks, *J. Sedimentary Petrology*, 41, 179-195.
- Potter, P. E., Ditterling, N. F. Shimp and W. Van Wie (1975) Clay mineralogy of modern alluvial muds of the Mississippi River Basin. *Bull. Centre Rech. Pau-SNPA*, 9, 353-389.
- Rex, I.R.W. (1968) X-ray mineralogy studies; in Ewing, M. and Worzel, J. L., et al., Initial reports of the Deep Sea Drilling Project, Vol. 1, Wash. (U.S. Gov. Printing Office), 354-367.
- Rubey, W. W. (1930) Lithologic studies of fine-grained Upper Cretaceous sedimentary rocks of the Black Hills Region. *U.S. Geol. Survey Prof. Paper* 165-A, 54 p.
- Russell, R. J. and R. D. Russell (1939) Mississippi River delta sedimentation, in recent marine sediments. (Trask, P.D., ed.): Tulsa Okla., Amer. Assoc. Petrol. Geol. 153-177.
- Shaw, D. B. and C. E. Weaver (1965) The mineralogical composition of shales. *J. Sedimentary Petrology*, 35, 213-222.
- Shepard, F. P. (1950) Marginal sediments of Mississippi Delta. *Bull. Amer. Assoc. Petroleum Geol.*, 40, 2537-2623.
- Shepard, R. R. (1954) Nomenclature based on sand-silt-clay ratio. *J. Sed. Petrology*, 24, 151-158.

- Shepard, F. P. and D. G. Moore (1955) Central Texas coast sedimentation: Characteristics of sedimentary environment, recent history and diagenesis. *Bull. Amer. Assoc. Petroleum Geol.*, 39, 1463-1593.
- Shrock, R. R. (1948) A Classification of Sedimentary Rocks. *J. Geology*, 56, 118-129.
- Steiner, A. (1967) Clay minerals in hydrothermally altered rocks at Wairakei, New Zealand, (Abstr.) *Clays Clay Miner.*, 16th Conf. p. 31-33.
- Thayer, P. A., J. Hostettler, and S. Smith (1974) Grain-size distribution of sediments from the Eastern Indian Ocean; In Veevers, J. J. Heirtzler, J. R., et al. *Initial Reports of the Deep Sea Drilling Project*, Vol. 27, Wash. (U.S. Govn. Printing Office) 507-522.
- Tourtelot, H. A. (1962) Preliminary Investigation of the Geologic setting and Chemical Composition of the Pierre Shale Great Plains Region. *U. S. Geol. Survey Prof. Paper*, 390, 74 p.
- Twenhofel, W. H. (1937) Terminology of the fine-grained mechanical sediments: Exhibit F - report of Committee on Sedimentation 1936-1937: *Nat. Res. Coun., Div. Geol. Geog.*, 81-104.
- Twenhofel, W. H. (1950) Principles of sedimentation. McGraw-Hill Company, New York, 673 p.
- Weaver, C. E. (1953) Mineralogy and petrology some Ordovician K-bentonites and related limestones. *Geol. Soc. Amer. Bull*, 64, 921-943.
- Weaver, C. E. (1958) The clay petrology of sediments. *Clays Clay Miner. Proc.* 6th Nat. Conf., 154-187.
- Weaver, C. E. (1960) Possible uses of clay minerals in search for oil. *Bull. Am. Assoc. Petrol. Geol.* 44, 1505-1518.
- Weaver, C. E. (1968) Geochemical study of a reef complex. *Am Assoc. Petrol. Geo.*, 52, 2153-2169.
- Weaver, C. E. and K. C. Beck (1971) Clay water diagenesis during burial: How mud becomes genesis., *Geol. Soc. Amer.*, Spec. Paper 134, 93 p.
- Weaver, C. E. and K. C. Beck (1976) Miocene of the S.E. United States; A model for chemical sedimentation in a peri-marine environment. *Sedimentology* 21, 200 p.
- Wentworth, C. K. (1922) A scale of grade and class terms of clastic sediments. *J. Geol.*, 30, 277-392.
- Yaalon, D. H. (1962) Mineral composition of the average shale. *Clay Min. Bull.*, 5, 31-36 p.
- Zemmels, I. and H. E. Cook (1973) X-ray mineralogy of sediments from the north-east Pacific and Gulf of Alaska-Leg 18., in Kulm, L. D., von Huene, R., et al., 1973 *Initial Reports of the Deep Sea Drilling Project*, Vol. 18, Wash. (U. S. Govn. Printing Office) 1015-1060.

APPENDIX I

LIST OF SAMPLES AND ANALYSES

Sample	Age	Nonclay (+ 10%)			Estimated % Clay
		Quartz	Feldspar	Carbonate	
<u>Texas Gulf Coast Subsurface</u>					
N-1	Pliocene	24	2	T	74
N-2	Pliocene	30	2	T	68
N-3	Pliocene	19	7	1	73
N-4	Pliocene	37	7	-	56
N-5	Pliocene	29.5	5	T	65.5
N-6	Pliocene	18	2	T	80
N-7	Miocene	22	10	3	65
N-8	Miocene	18.5	T	T	81.5
N-9	Miocene	30.5	4	1	64.5
N-10	Miocene	22	3	3	72
N-11	Miocene	22	5	3	70
C-1	Oligocene	25	5	15	55
C-2	Oligocene	22	5	17	56
C-3	Oligocene	17	5	8	70
C-4	Oligocene	29	6	4	61
C-5	Oligocene	24.5	12	9	54.5
D-1	Eocene	27.5	12	1	59.5
D-2	Eocene	33.5	10	3	53.5
D-3	Eocene	38.5	5	-	56.5
D-4	Eocene	30	7	T	63
D-5	Eocene	37.5	7	-	55.5

Sample	Age	Nonclay (+ 10%)			Estimated % Clay
		Quartz	Feldspar	Carbonate	
<u>Marathon Uplift, Brewster Co., Texas</u>					
M-16	L. Haymond	37.5	8	-	54.5
M-17	L. Haymond	31	5	-	64
M-12	U. Dimple	31.5	T	30	38.5
M-14	U. Dimple	48.5	9	30	12.5
M-4	L. Dimple	24.5	T	-	75.5
M-5	L. Dimple	29	T	-	71
M-1	U. Tesnus	36	2	-	62
M-34	U. Tesnus	32.5	7	-	60.5
M-36	U. Tesnus	62	T	-	38
M-38	U. Tesnus	53	1	-	46
M-30	M. Tesnus	37.5	1	-	61.5
M-31	M. Tesnus	34.5	2	-	63.5
M-32	M. Tesnus	44.5	5	T	50.5
M-21	L. Tesnus	46.5	2	T	51.5
M-24	L. Tesnus	44	1	T	55
M-25	L. Tesnus	31.5	2	-	66.5
M-18	U. Caballos	62.5	T	T	37.5
M-19	U. Caballos	65	-	-	35
M-20	U. Caballos	77	T	-	23
M-48	Woods Hollow	35	1	-	64
M-49	Woods Hollow	46	2	-	52
M-50	Woods Hollow	71.5	T	T	28.5
M-51	Pt. Pena	52.5	T	-	47.5
M-52	Pt. Pena	75	T	-	25

Sample	Age	Nonclay ($\pm$ 10%)			Estimated % Clay
		Quartz	Feldspar	Carbonate	
<u>Marathon Uplift (Contd.)</u>					
M-60	Marathon	54.5	T	4	41.5
M-61	Marathon	56.5	1	-	42.5
M-62	Dagger Flat	59.5	2	T	38.5
<u>West Flank of Bend Arch, N. Central Texas</u>					
BA-2	Wolfcamp	59	2	2	37
BA-3	Wolfcamp	63	7	-	30
BA-4	Wolfcamp	35	T	T	65
BA-5	Wolfcamp	26	T	T	74
BA-7	Virgil	28.5	T	-	71.5
BA-9	Virgil	28	T	-	72
BA-10	Missouri	34.5	-	-	65.5
BA-11	Missouri	38	1	-	61
BA-12	Missouri	61	20	-	19
BA-13	Missouri	27	T	1	72
BA-14	Missouri	34	-	-	66
BA-15	Missouri	52.5	5	-	42.5
BA-16	Missouri	56	7	-	37
BA-17	Missouri	31.5	4	4	60.5
BA-18	Des Moines	34	3	0	63
BA-19	Des Moines	47	3	-	50
BA-20	Des Moines	39	5	-	56
BA-22	Des Moines	51.5	7	-	41.5
BA-23	Atoka	55	-	5	40

Sample	Age	Nonclay ($\pm$ 10%)			Estimated % Clay
		Quartz	Feldspar	Carbonate	
<u>Bend Arch (Contd.)</u>					
BA-25	Atoka	14	-	43	43
BA-26	Atoka	34	2	6	58
BA-27	Barnett	39.5	2	1	57.5
BA-28	Barnett	41	2	1	56
BA-29	Barnett	41	2	10	47
BA-30	Barnett	33.5	T	-	66.5
BA-32	Barnett	42	T	-	58
BA-33	Barnett	46	2	-	50
BA-34	Woodford	25	2	25	50
<u>Ft. Worth Basin, North-Central Texas</u>					
Osborne Comp. (5 sple)	Atoka	31	8	-	61
Purcell Comp. (5 sple)	Atoka	40	10	-	50
<u>Arbuckle Mt., Ardmore Basin, McAlester Basin, Oklahoma</u>					
Sycamore Creek 21	Atoka	44	5	-	51
Turner Comp. (8 sple)	Atoka	26	3	-	71
Jones Comp. (5 sple)	Atoka	18.5	3	-	78.5
Sycamore Creek 15	Morrow	26	T	2	72
Sycamore Creek 16	Morrow	29.5	T	T	70.5
Sycamore Creek 18	Morrow	33	1	-	66
Sycamore Creek 19	Morrow	29	T	2	69

Sample	Age	Quartz	Nonclay (+ 10%) Feldspar	Carbonate	Estimated % Clay
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Arbuckle, Ardmore, McAlester (Contd.)

Sycamore Creek (4 sple)	Springer	42.5	T	1	56.5
Boyd (13 sple)	Springer	22	T	-	78
Phariss (23 sple)	Springer	24	T	-	76
Patton (6 sple)	Springer	11	T	-	79

Ouachita Mountains (Transitional Facies)

Hoehman Comp. (6 sple)	Atoka	28	5	-	67
T-44	Atoka	26	3	-	71
T-55	Atoka	20.5	5	-	74.5
T-38	Morrow	9	1	-	90
T-39	Morrow	27	18	-	55
T-80	Morrow	23	3	-	74
T-1	Springer	34.5	T	-	65.5
T-2	Springer	22	-	-	78
T-51	Springer	66	-	-	34
T-52	Springer	39.5	T	-	60.5

Ouachita Mountains (Ouachita facies)

O-68	Atoka	21.5	1	-	77.5
O-69	Atoka	29	1	-	70
O-70	Jackfork	32.5	2	-	65.5
O-72	Jackfork	33.5	1	-	65.5
O-73	Jackfork	24	1	-	75

Sample	Age	Nonclay ($\pm$ 10%)			Estimated % Clay
		Quartz	Feldspar	Carbonate	
<u>Ouachita Mountains (Ouachita facies) Contd.)</u>					
O-65	Stanley	35	1	-	65
O-66	Stanley	25	T	-	75
O-67	Stanley	36	T	-	64
Stanley Comp. (5 sple)	Stanley	34	5	-	61
<u>Middle Cambrian-Roane Co., Tenn.</u>					
T-5-5	Conesuega	20.5	1	-	78.5
<u>Upper Ordovician - Giles Co., Virginia</u>					
T-6-5A	Martinsburg	22	5	1	72
<u>Paleozoic - Vicinity of University Park, Pennsylvania</u>					
Pa 14-15 (comp)	U. Devonian (Chemung)	37	10	-	53
Pa 20-22-23 (comp)	(Catskill)	27	8	-	65
Pa 28	L. Devonian (Onondago)	47.5	T	12	40.5
Pa 75-76 (comp)	U. Silurian (Bloomsburg)	19	3	1	77
Pa 77-78 (comp)	(Wills Creek)	16.5	T	29	54.5
Pa 84	(Tonoloway)	7	-	56	37
Pa 85	M. Silurian (Rose Hill)	24	3	-	73
Pa 87	M. Ordovician (Rodman)	12	1	35	52
Pa 88-89 (comp)	(Salona)	40	8	8	44
Pa 65	L. Ordovician (Bellefonte)	7	2	55	36

Sample	Age	Nonclay (+ 10%)			Estimated % Clay
		Quartz	Feldspar	Carbonate	
<u>Pennsylvanian Cyclothem - Southeast Kansas</u>					
Heebner shale	Penn.	28.5	3	-	68.5
Underclay	Penn.	41	3	-	56
Gray shale	Penn.	41	4	5	50
Red Shale	Penn.	17	2	3	78
<u>Denver Basin - Mesozoic</u>					
LK 2 comp (3 sple)	Benton	25	9'	22	44
C. 2	Pierre	39	10	10	41
Dakota comp (12 sple)	Dakota	34	3	-	63
Muddy comp (9 sple)	Muddy	33	5	-	62
LK 2 comp (2 sple)	Niobrara	4	T	30	66
<u>North Flank Williston Basin, Alberta, Canada - Mesozoic</u>					
West comp (3 sple)	Blackstone	36	4	7	53
OW comp (2 sple)	Dakota	46.5	3	-	50.5
Bergen comp (2 sple)	Ostracod sh	33	1	3	63
OW comp (2 sple)	Rierdon	29	5	3	63
C&L comp (2 sple)	Fernie	32	T	3	65
<u>Big Horn Basin - Mesozoic</u>					
Sheep	Churwater	15.5	10	2	72.5

Sample	Age	Nonclay ($\pm$ 10%)			Estimated % Clay
		Quartz	Feldspar	Carbonate	
<u>Caliente Trough - Tertiary</u>					
Hubbard Hill ss. comp (5 sple)	Miocene	18	31	-	51
Soda Lake sh. comp (7 sple)	Miocene	17	19	1	63
Soda Lake ss. comp (3 sple)	Miocene	28	12	1	59
Simmler Red Bed comp (4 sple)	Miocene	31	14	T	55
<u>Eastern Gulf of Mexico</u>					
Miss. River comp (6 sple)	Recent	54	14	2	30
Miss. Delta comp (6 sple)	Recent	29.5	3	1	66.5
East Gulf Bay comp (5 sple)	Recent	53	T	1	46
East Gulf Slope comp (7 sple)	Recent	18.5	1	6	74.5
East Gulf Deep comp (7 sple)	Recent	17.5	2	16	64.5
<u>Argillaceous Limestone Composites</u>					
Quachita (3 sple)	Paleozoic	56.5	-	29	14.5
Marathon (5 sple)	Paleozoic	31	T	34	35
Pz (2 sple)	Paleozoic	11.5	4	63	21.5
Bishop (7 sple)	Paleozoic	T	T	41	50

APPENDIX II

SUMMARY OF DATA OBTAINED FROM THIN SECTION STUDIES

Sample Number	Clay minerals				Nonclay minerals ¹				Organic material			Texture ⁴
	Abundance in percent	Maximum size in microns	Orientation ²	Miscellaneous ³	Kind	Abundance in percent	Maximum size in microns	Miscellaneous ³	Abundance ⁴	Maximum size in microns	Miscellaneous ³	
262	60	80	pr 30°	Muscovite C ¹ Chlorite C	Quartz Carbonate	30 5	30 5	D L	A	20	L	Pcm, Pca, Pom
278	90	10	p 20		Quartz	5	5	D	T	<1	L	Pcm
264	60	100	pr	Muscovite C Chlorite C	Quartz Feldspar	35 T ¹	40	Sorted 25-40μ, secondary growth L	A	20	L	Pqt
229	75	20	p 20	Muscovite C Chlorite C	Quartz Limonite	20 <1	15 T	D	T	<1	irregular masses	Pcm
281	80	20	p 20	Muscovite T Chlorite T	Quartz Carbonate Feldspar	15 C T	100 100	D Fossil fragments	T	10	L	Pcm, Pom
280	80	25	p 20	Muscovite T Chlorite T	Quartz	15	20	D	T	10	D	Pcm
279	35	150	r	Muscovite C Chlorite C	Quartz Carbonate	50 5	100 10	D Fossil fragments	T	<1	D and L	Only faint lamination due to Pqt and Pcm
243	60	80	r	Muscovite C Chlorite C	Quartz	35	50	D and L	C	10	D	Only faint lamination due to Pcm and Pqt
238	60	80	pr	Muscovite C Chlorite C	Quartz Carbonate Feldspar	30 T T	50	D secondary growth	C	20	D and L	Pcm, Pqt, Pom
270	60	100	pr	Muscovite C Chlorite C	Quartz	35	50	D and L, secondary growth	C	20	L	Pcm, Pqt, Pom
239	80	20	p 20	Muscovite C	Quartz	15	20	D	C	10	L	Pcm, Pom
202	60	100	pr	Muscovite C Chlorite C Biotite C	Quartz Feldspar	35 T	75	D and L, secondary growth	T	10	D	Pcm, Pqt
237	85	20	p 20		Quartz	10	15	D	T	10	D	Pcm

APPENDIX - (continued)

Sample Number	Clay minerals				Nonclay minerals ¹				Organic material			Texture ²
	Abundance in percent	Maximum size in microns	Orientation ³	Miscellaneous ⁴	Kind	Abundance in percent	Maximum size in microns	Miscellaneous ⁴	Abundance ¹	Maximum size in microns	Miscellaneous ⁴	
227	60	80	pr	Muscovite C Chlorite C	Quartz	35	40	D	C	10	L	Pcm, Pom
285	80	40	pr	Muscovite C	Quartz	15	30	D and L	C	10	L	Pcm, Pom
269	40	150	pr	Muscovite C Chlorite C	Quartz	55	60	L	C	10	L	Pcm, Pom, Pqt
272	90	20	p 20		Quartz	5	15	D	T	5	L	Pcm
231	60	150	pr	Muscovite C Chlorite C	Quartz Feldspar	35	60	D	C	10	L	Pcm, Pom
254	95	10	p 10		Quartz	T	10	D	T	<1	L	Pcm
224	50	120	pr	Muscovite C Chlorite C Biotite C	Quartz Feldspar	45	100	D, secondary growth	C	10	L	Pcm
217	85	20	p 20		Quartz	10	15	D	T	<1	L	Pcm
215	70	40	pr		Quartz	20	30	D	C	<1	L	Pcm, Pom
242	60	150	pr	Muscovite C Chlorite C Biotite C	Quartz	35	80	D and L, secondary growth	A	15	L	Pcm, Pom, Pqt
240	60	150	pr	Muscovite C Chlorite C	Quartz	35	80	D, secondary growth	A	15	L	Pcm, Pom
275	50	150	pr	Muscovite C Chlorite C	Quartz Feldspar	45	100	D and L	A	15	L	Pcm, Pom, Pqt
241	95	10	p 20		Quartz		5	D	T	<1	S	Pcm
204	70	50	r	Muscovite C	Quartz	25	30	D	C	10	D	Scant lamination
213	60	80	pr	Muscovite C	Quartz	35	40	D and L, secondary growth	C	10	D and L	Pcm, Pqt
268	25	60	pr	Muscovite C Chlorite C	Quartz Feldspar	70	40	D and L, secondary growth	T	<1	L	Pcm, Pqt

577A	60	70	p 30	Muscovite C	Quartz	35	40	D	C	10	D	Pcm
579B	85	10	p 10		Quartz	10	15	D	T	<1		Pcm
					Carbonate	T	5	D				
576	45	10	pr		Quartz	5	10	D				Pcm, Pca
					Pyrite	T		fossil fragments				
					Carbonate	45						
575B	80	20	p 20		Quartz	15	20	D and L				Pcm
575A	85	20	p 20		Quartz	10	15	D and L				Pcm
DS38	85	10	p 30		Quartz	10	20	D and L	T	5		Pcm
DS51	35	30	r		Quartz	60	30	D and L,				Pqt
					Carbonate	T		secondary growth				
DS45	15	25	r		Quartz	60	25	L				Pqt, Pca
					Carbonate	20	25	L				
546	85	15	pr		Quartz	10	20	D	T	8	L	Pcm, Pom
1093	80	25	p 10		Quartz	15	20	D and L	C	10	L	Pcm, Pom
547	80	50	p 20		Quartz	15	30	D and L	C	<1	L	Pcm, Pom
					Carbonate	T	10				Spores	
DS7	45	50	pr		Quartz	45	25	D and L				Pcm, Pqt
					Carbonate	5	10					
DS8	55	50			Quartz	20	25	D				Pcm
					Carbonate	20	25					
580	80	20	p 20		Quartz	15	20	D	C	10	D and L	Pcm, Pom

*Minerals present in very small amounts are not considered.

*p indicates parallel orientation; r random orientation; pr partial parallel orientation; the degree value indicates the divergence from parallel.

*The mica determinations are based on optical properties; they are listed as clay minerals because of their small size.

*A=abundant; C=common; T=trace.

*D=disseminated; L=concentrated in streaks or lenses.

*Pcm=lamination due to parallel orientational clay minerals.

*Pca=lamination due to concentration of carbonate in thin beds or lenses.

*Pom=lamination due to concentration of organic material in thin beds or lenses.

*Pqt=lamination due to concentration of quartz in thin beds or lenses.

PART II: ROCK TYPES RECOMMENDED FOR TESTING

Abstract

The water content, porosity, permeability and mineralogy of fine-grained sediments must be evaluated when considering them as repositories for high level radioactive waste. The three major groups of phylsils are smectite, mixed-layer illite-smectite, and illite-chlorite. The interlay water and pore water decrease as the proportion of smectite decreases. The effect of quartz, feldspar, carbonate and organic material must also be considered. Grain size, predominantly silt or clay, must also be taken into account.

The phylsilites can be classified into 18 types. Only 4 of these types are volumetrically important. There are 6 basic varieties of calcareous phylsilitic rocks, of which only 2 occur in abundance. The feldspathic phylsilitic rocks can be narrowed down to 2 or 3 basic types. The quartzose phylsilitic rocks can be classified into 24 types. Only 4 of these types are important. Only 1 organic-rich rock type need be considered.

Fourty formations are listed that contain the rock types that have the various mineralogic requirements should be tested. The 13 most abundant rock types could be collected from 5 to 6 formations.

INTRODUCTION

The important parameters of fine-grained sediments which must be considered when they are to be used for the isolation of high level waste are water content, porosity and permeability, and mineralogy. Grain size is not particularly important, except as it effects porosity and permeability. Thermal conductivity should increase as the content of quartz and carbonate minerals increase. The homogeneity of the rock is probably a significant factor. Interbeds of siltstone, sandstone, and limestone should increase the thermal conductivity of fine-grained rocks.

The physilites and physilic claystones and siltstones can be divided into three broad groups on the basis of the composition of the physils. One group includes those rocks composed largely of illite and chlorite (largely pre-Mississippian in age); another group includes those containing an abundance of mixed-layer illite-smectite (largely Mississippian to Cretaceous); the third group are the rocks composed largely of smectites (Cretaceous and younger). The geologic age ranges are assigned on the basis of those rock types expected to be encountered at depths less than 900 m. Thick rock units with abundant kaolinite and chlorite are relatively rare.

The sequence smectite → illite-smectite → illite and chlorite represents a systematic decrease in the amount of interlayer water and in most instances pore water. This decrease in water is generally accompanied by a decrease in porosity and probably permeability. Thus, the three physil groups can be considered to represent porosity-permeability groups. The relation is complicated by the presence of non-physils, particularly carbonates.

Other major minerals in fine-grain rocks are quartz, feldspar, carbonate and organic material. Most fine-grained physilic rocks are physilites (more than 50% sheet silicates). Lamination and fissility develop after the release of overburden pressure and during weathering and probably need not be considered as a variable in buried, fine-grained physilic rocks; however, mineral orientation is a factor. The effects of mineral orientation on thermal response can probably be evaluated in the laboratory by varying the orientation of the core samples. This would materially decrease the number of samples that would have to be collected.

The physilitic rocks can be divided into four classes: clay physilites, silt physilites, physilic claystones and physilic siltstones.

PHYSILITES

Physilites by definition contain more than 50% physils. The average physilite contains 60% physils; 90% have between 50 and 80% physils. Quartz is always present. The average quartz content of physilites is 30%, and 90% of the physilites have between 15 and 45% quartz. Feldspar and carbonate minerals usually comprise a total of less than 10% (Fig. 1). Organic material is normally less than 2% (Shaw and Weaver, 1965). Thus, these 3 components can be considered to be a minor, relatively constant value for most physilites. A few physilites have a relatively low quartz content and contain 10 to 30% of either feldspar or carbonate. Most physilites have a low organic (less than 2% organic carbon) content. Those with high organic carbon (~15%) values have a relatively low physil content and are either physilic claystones or siltstones. On the basis of these natural associations the classification shown in Table 1 was constructed.

PHYSILIC CLAYSTONES AND SILTSTONES

Introduction

Fine grained rocks with less than 50% physils are mineralogically more complex than those containing more than 50% physils. The possible mineral combinations are many but on the basis of rock volume and porosity the number of rock types can be considerably reduced.

Organic-rich sediments can be treated as a discrete rock type. There appears to be only two types of any consequence. Thick, marine organic-rich sediments do not generally contain appreciable smectite or mixed-layer physils.

Cumulative and frequency distribution plots of the feldspar content of shales.

Cumulative and frequency distribution plots of the carbonate content of shales.

Figure 1. After Shaw and Weaver (1965)

TABLE 1. PHYSILITES (MORE THAN 50% SHEET SILICATES)

% NONPHYSILS	ILLITE-CHLORITE		MIXED-LAYER		SMECTITE	
	Silt	Clay	Silt	Clay	Silt	Clay
TYPICAL: 20-40 QUARTZ 10 FELDSPAR + CARBONATE	C	C-R	C	C	R	C
CARBONATE >10% <30%	R	C-R	R	C-R	R	C-R
FELDSPAR >10% <20%	C-R	C-R	R	R	R	R

C = Common
R = Rare

Illite is the predominant physil (Weaver, 1958) in these rocks. Analyses of the Chattanooga Shale (Bates and Strahl, 1957) indicate it has at quartz + feldspar/physil ratio of one. These three components comprise approximately 65% of the rock. The other type of thick organic-rich fine-grained rock is typified by the carbonate-rich Eocene Green River Formation of Utah (Picard, 1953). The physil-carbonate-organic content of these rocks varies widely. X-ray studies by Weaver indicate illite and mixed-layer illite-montmorillonite (with a relatively high illite content) are the dominant clay minerals in most units.

Carbonate rocks containing less than 10% physils are basically limestones and outside the scope of this discussion. Quartz- and feldspar-rich rocks with less than 10% physils would normally have a relatively high porosity and permeability unless cemented.

Calcareous Physilic Rocks

There is probably less data on the grain size of calcareous physilic rocks than any other. Though many of the recent marine carbonate-rich sediments are calcareous physilic clays most calcareous physilic rocks are probably composed largely of silt-size and larger carbonate grains. Most of the physils are probably of clay-size. From the standpoint of thermal reactions grain size is probably not particularly significant in calcareous physilic rocks.

Figures 2 and 3 show how the percent physil and percent quartz + feldspar vary as a function of carbonate content (Shaw and Weaver, 1965). As the carbonate content increases, the quartz + feldspar content decreases more than the physil content decreases. Figure 4 is a plot of the physil/quartz ratio versus carbonate content. The data is from Shaw (1959) and Campbell and Oliver (1968). Though there is considerable scatter, there is a definite linear relation. The physil/quartz ratio increases from 1.5 for 10% carbonate

Figure 2. Relation of physils to carbonate after Shaw (1959)

Figure 3. Relation of quartz plus feldspar to carbonate after Shaw (1959)

TABLE 2. CALCAREOUS PHYSILIC ROCKS

ROCK COMPOSITION	ILLITE-CHLORITE	MIXED-LAYER	SMECTITE
~30% CARBONATE 50% PHYSILS 20% QUARTZ	C	R	C-R
~60% CARBONATE 33% PHYSILS 7% QUARTZ	C	R	C-R

R = Rare
C = Common

to 5 for 60% carbonate. By extrapolation the ratio would be approximately 6.5 for 90% carbonate. The feldspar content is commonly less than 5% and can be neglected.

The 3 graphs indicate that calcareous physilic rocks containing 30% carbonate minerals should contain, on an average, approximately 50% physils and 20% quartz. Rocks containing 60% carbonate should contain approximately 33% physils and 7% quartz. Samples containing significantly less than 30% carbonate are mostly physilites or the carbonates occurs as a cement in quart-rich siltstones.

Assuming that grain size can be neglected, this leaves two basic rock types. The predominant physil in most carbonate rocks is illite. Mixed-layer illite-smectite and chlorite-smectite are also commonly the principal physils in carbonate rocks. Smectites are the predominant physil in some Mesozoic and younger calcareous rocks. Thus, there are potentially 6 rock types but probably only 3 or 4 would be worth testing (Table 2).

As dolomites have about twice the thermal conductivity of limestones ($5-6$ vs $11-13 \times 10^{-3}$ cal/cm sec $^{\circ}\text{C}$) (The Geological Society of America Special Paper 97) it may be necessary to treat calcareous and dolomitic physilic rocks as separate rock types; however, many carbonate rocks contain both calcite and dolomite.

Feldspathic Physilic Rocks

Feldspar is commonly present in amounts less than 10% in physilic claystones and siltstones except for those associated with arkosic rocks. The limited data for these rocks (Krynine, 1950, Triassic of Connecticut; Shaw and Weaver, 1965, Miocene of California) indicate the quartz/feldspar ratio commonly ranges from 1.0 to 1.5 and, for practical purposes, can be considered to be constant. Feldspar is usually present in amounts greater than 20%.

As the quartz plus feldspar content of these rocks is greater than 50% and coarse mica flakes are usually abundant, most of these rocks would be classed as physilic siltstones or claystones with a high silt content. Carbonate minerals are generally not present or only in minor amounts. Both illite and montmorillonite, with lesser amounts of kaolinite, chlorite, and vermiculite, occur as major constituents in these rocks. Illite is by far the most common. Three to six percent iron oxide is commonly present.

Two or possibly three rock types should be sufficient to characterize the feldspathic physilic siltstones:

30-60% physils, quartz/feldspar ratio 1.0 - 1.5, illite

10-30% physils, quartz/feldspar ratio 1.0 - 1.5, illite

(?) 20-50% physils, quartz/feldspar ratio 1.0 - 1.5, smectite.

Quartzose Physilic Rocks

Most physil rocks that contain less than 30-35% quartz are physilites. Most quartz-rich physilic claystones and siltstones should contain between 40 and 90% quartz. The feldspar content is generally less than 10%. If appreciably more feldspar is present, the rocks are commonly arkosic (greater than 20% feldspar). Thus, the feldspar content can be considered to be a constant. Physilic rocks containing more than 30% carbonate minerals are classed as calcareous physilic rocks.

Table 3 shows the possible combinations that can exist. Many of these combinations are volumetrically unimportant. For example, it seems unlikely that many rocks should exist which contain less than 50% physils and have more than half of the grains of clay-size. Such a combination is most likely to occur when appreciable clay-size (micritic) carbonate is present; however, clay-size carbonate is rare in rocks with an appreciable content of detrital quartz. Much of the carbonate is probably present as relatively coarse spar cement or fossil fragments.

Illite-chlorite are probably the most common physil in these rocks. Montmorillonite is the major physil in some Cretaceous and Teritiary silt-stones and claystones. Mixed-layer physils are not likely to be abundant in shallow buried rocks.

TEST SAMPLES

The following tables are similar to those in the preceeding section but include a selection of formations that have the approximate compositions indicated.

Formations were chosen primarily to supply a variety of significant rock types. Site suitability was of secondary importance. Formations were selected that had the best possibility of containing several rock types. In some instances it may be possible to obtain two rock types in one core. In other situations it may be necessary to drill several adjacent holes. Also, some attempt was made to select several formations from the same region so as to minimize drilling costs and the effort necessary to learn the local geology.

~~TAB 3~~ PHYSILIC SILTSTONES AND CLAYSTONES (LESS THAN 50% SHEET SILICATES)

% QUARTZ	%CARBONATE	ILLITE-CHLORITE		MIXED-LAYER		SMECTITE	
		Silt	Clay	Silt	Clay	Silt	Clay
40-50	0-10	C	R	C	R	R	C
	10-30	R	R	R	R	R	R
50-90	0-10	C-R	R	C	R	C-R	R
	10-30	R	R	R	R	R	R

R = Rare

C = Common

TABLE 4. PHYSILITES (MORE THAN 50% SHEET SILICATES)

% NON-PHYSILS	ILLITE-CHLORITE		MIXED-LAYER		SMECTITE	
	Silt	Clay	Silt	Clay	Silt	Clay
TYPICAL 20-40% QUARTZ 10% FELDSPAR + QUARTZ	Conasauga-Ten. Cincinnati-Oh. N. Albany-Ind. Chemung-Pa. Catskill-Pa. Reedsville-Pa. Stanley-Ok. Collier-Ok. C etc.	Sylvan-Ok. Chemung-Pa. Rose Hill-Pa. C-R	Atoka-Ok., Tx. Morrow-Ok., Tx. Jackfork-Ok. Floyd-Ten. C	Springer-Ok. Lewis-Wyo. C	R	Pierre-S. D., Wyo., Col. Miocene-Ga. Springer-Ok. Porters Creek- La., Miss. C
CARBONATE >10% <30%	R	Wills Creek-Pa. Ireton- Can. C-R	R	Beldon-Col. C-R	R	Pierre-N.D., S.C. Niobrara-Col., Wyo. Benton-Col. C-R
FELDSPAR >10% <20%	<u>Belt</u> -Mont. C-R	Decorah-Minn. Chugwater-Wyo. C-R	<u>Atoka</u> -Ok, Tx. R	<u>Belt</u> -Mont. R	R	<u>Pierre</u> -Col. R

R = Rare
C = Common

= First Priority

 = Source of 2 or more samples

TABLE 5. CALCAREOUS PHYSILIC ROCKS			
ROCK COMPOSITION	ILLITE-CHLORITE	MIXED-LAYER	SMECTITE
~30% CARBONATE 50% PHYSILS 20% QUARTZ	Maquoketa-Ind. <u>Sequatchie-Tenn.</u> <u>Chickamauga-Tenn.</u> C	<u>Dimple-Tex.</u> R	<u>Pierre-N.D., S.D.</u> <u>Niobrara-Col., Wyo.</u> C-R
~60% CARBONATE 33% PHYSILS 7% QUARTZ	Chickamauga-Tenn. <u>Sequatchie-Tenn.</u> C	<u>Dimple-Tex.</u> R	<u>Pierre-N.D., S.D.</u> <u>Niobrara-Col., Wyo.</u> C-R

R = Rare
C = Common

= First Priority
 = Source of 2 or more samples

TABLE 6. FELDSPATHIC PHYSILIC ROCKS.	
ROCK COMPOSITION	LOCATION
30-60% PHYSILS QTZ/FLD 1.0-1.5 ILLITE	<u>Triassic</u> - Conn., N.C., S.C.
10-30% PHYSILS QTZ/FLD 1.0-1.5 ILLITE	<u>Triassic</u> - Conn., N.C., S.C.
20-50% PHYSILS QTZ/FLD 1.0-1.5 SMECTITE	Fountain - Col. Soda Lake - Calif.

ORGANIC-RICH PHYSILIC ROCKS CHATTANOOGA-TEN.

= First Priority

= Source of 2 or more samples

TABLE 7. PHYSILIC CLAYSTONE AND SILTSTONE (LESS THAN 50% SHEET SILICATES)

QUARTZ	% CARBONATE	ILLITE-CHLORITE		MIXED-LAYER		SMECTITE	
		Silt	Clay	Silt	Clay	Silt	Clay
40-50	0-10	<u>Catskill-Pa.</u> <u>Chemung-Pa.</u> <u>Portage-N.Y.</u> C	R	<u>Blair-Wyo.</u> <u>Rock Spr-Wyo.</u> <u>Atoka, OK, Tex</u> C	R	R	<u>Miocene-Ga.</u> <u>Pierre-Wyo.,</u> Mont. C
	10-30	R	R	R	R	R	R
50-90 (HIGH POROSITY)	0-10	<u>Catskill-Pa.</u> C-R	R	<u>Blair-Wyo.</u> <u>Rock Spr-Wyo.</u> C	R	<u>Pierre, Wyo.</u> Mont. <u>Miocene-Ga.</u> C-R	R
	10-30	R	R	R	R	R	R

R = Rare C = Common \ = First Priority — = Source of 2 or more samples

REFERENCES

- Bates, T. F. and E. O. Strahl (1957) Mineralogy; petrography, and radio-activity of representative samples of Chattanooga shale. Bull. Geol. Soc. Amer., Vol. 68:1306-1314.
- Campbell, F. A. and T. A. Oliver (1968) Mineralogic and chemical composition of Ireton and Duvernay formations Central Alberta. Bull. Canadian Petroleum Geol., Vol. 16, 40-63.
- Krynine, P. D. (1950) Petrology, stratigraphy, and origin of the Triassic sedimentary rock of Connecticut. Conn. Geol. and Nat. Hist. Survey Bull., 73, 247 p.
- Picard, M. D. (1953) Marlstone—a misnomer as used in the Uinta Basin, Utah. Bull. Amer. Assoc. Geol., 37, 1075-1077.
- Shaw, D. B. (1959) The mineralogical composition of shales. M.S. Thesis, U. Houston, Texas.
- Shaw, D. B. and C. E. Weaver (1965) The mineralogical composition of shales. J. Sedimentary Petrology, 35, 213-222.
- Weaver, C. E. (1958) The clay petrology of sediments. Clays Clay Miner. Proc. 6th Nat. Conf., 154-187.