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FIGS. 1–11, DECEMBER 1976

NATURE OF FELDSPAR-GRAIN SIZE RELATIONS IN SOME QUARTZ-RICH SANDSTONES[1]

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ABSTRACT: The abundance of feldspar as related to grain size has been examined in quartz-rich cratonic sandstones of Cambrian, Ordovician, Pennsylvanian-Permian and Jurassic ages, which have traditionally been characterized as supermature quartz arenites. Feldspar contents ranged from less than 1% to more than 50%. In the Cambrian sandstones of the upper Mississippi Valley, detrital feldspar grains are almost invariably < .125 mm. Due to the great abundance of feldspar, fine and very fine-grained sandstones in this sequence are either feldspathic (10–25% feldspar) or highly feldspathic (25–65% feldspar). The percentage of feldspar is nearly linearly related to the volume of the very fine sand fraction.

The St. Peter Sandstone (Ordovician) usually contains less than 2% detrital feldspar, but larger amounts occur where it contains significant amounts of very fine sand and coarse silt. Feldspar in the St. Peter is concentrated in the coarse silt size fraction rather than in the very fine sand fraction as in Cambrian sandstones. This may indicate intensive abrasion of initially small feldspar derived from Cambrian sediments.

The Weber Sandstone (Pennsylvanian-Permian) contains up to 20% feldspar whose abundance also increases with decreasing mean size, being most abundant in samples with means below < .125 mm. In samples of the Navajo Sandstone (Jurassic), feldspar is relatively evenly distributed among the size fractions < .35 mm, yet the highest feldspar concentration occurs in the .125 to .044 mm size range.

The distribution of feldspar within various size fractions of sandstones is significant in making provenance studies, in explaining regional and stratigraphic mineralogical variations, in interpreting depositional environments, and in assessing the origin of compositional maturity or immaturity.

INTRODUCTION

In addition to showing compositional variations, sedimentary petrologists hope that sandstone mineralogy will aid in the interpretation of genetic factors often not directly observable; for example, the composition of the source rocks and the nature of depositional environments. The mineralogy also provides the most direct information on the tectonics and climates of provenance areas. Experience has shown that the most useful components for provenance interpretations are rock fragments and feldspars. Previous studies (*e.g.*, Blatt and Christie, 1963) indicate that the content of polymineralic rock fragments and polycrystalline quartz decreases with decreasing grain size due to their lesser resistance to abrasion. With the removal of these components, much information on the nature of the provenance is lost.

Although several previous studies of the mineralogy of sandstones and recent sands (Folk, 1968; Field and Pilkey, 1969; Blatt, Middleton, and Murry, 1972) have shown that feldspar concentration varies with grain size, several other studies (Hsu, 1960; Pollack, 1961) yielded essentially negative results. Because of the significance of feldspar in sedimentary petrologic interpretations, the feldspar-grain size problem clearly deserves further evaluation. Unlike rock fragments and polycrystalline quartz, feldspars during abrasion tend to be reduced in size rather than be destroyed. Thus, the distribution of feldspar among the size fractions of a sandstone should be of considerable significance in provenance studies as well as in evaluating depositional environments, sedimentary recycling and the origin of mineralogical maturity.

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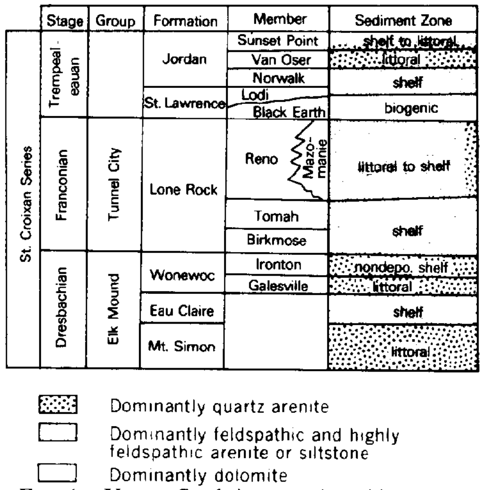


FIG. 1.—Upper Cambrian stratigraphic sequence, depositional environments, and mineralogical characteristics in southwestern Wisconsin and southeastern Minnesota (stratigraphy modified from Ostrom *et al.*, 1970).

The purpose of this paper is to report several instances in which feldspar abundance is related to texture, especially grain size, and to point out some of the ramifications that this relation may have on classification and on genetic interpretations based on petrologic data.

Samples and Methods of Study

This paper is based largely on studies by Odom of sandstones composing the Upper Cambrian St. Croixan Series and the Middle Ordovician St. Peter Sandstone, both of which occur in the Upper Mississippi Valley, and by Doe and Dott of the Weber Sandstone of middle Pennsylvanian to early Permian age which occurs in the Wasatch and Uinta Mountains of Utah and the White River Uplift in Colorado. Composition was determined from thin sections by counting a minimum of 300 equally spaced points. Grain size was determined by both sieve and microscopic methods. The thin sections of the Weber Sandstone were stained to facilitate feldspar identification. Due to the presence of twinning and authigenic overgrowths, staining was not required to identify feldspar in the Cambrian or Ordovician sandstones. Detailed comparison of feldspar composition to grain size was made on a few samples by preparing grain mounts of each sieve fraction, and then analyzing the abundance of feldspar in each fraction. These analyses were made by counting 300 points falling on separate mineral grains.

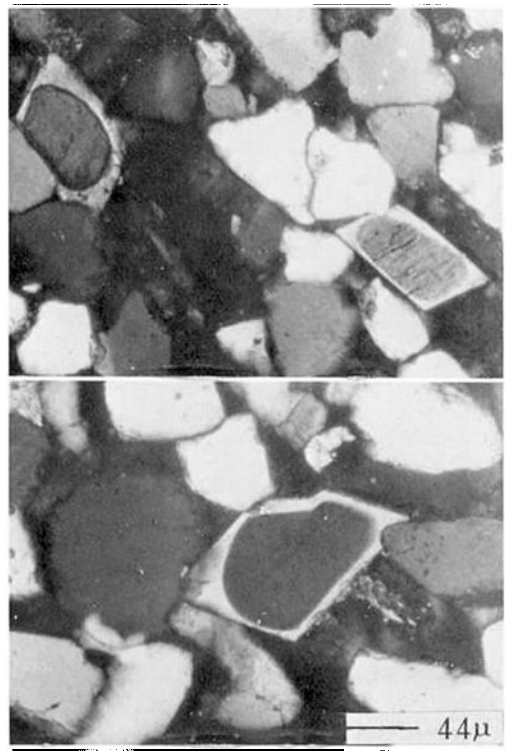


FIG. 2.—Examples of detrital feldspar grains with authigenic overgrowths in Cambrian sandstones of Wisconsin.

CAMBRIAN SANDSTONES, UPPER MISSISSIPPI VALLEY

Cambrian strata in the northern portion of the Upper Mississippi Valley consist primarily of sandstones and siltstones. The sandstones range from coarse to very fine-grained and are usually moderately to well-sorted, except for some bimodel units.

The mineralogy and texture of 100 to 150 samples from each of the Cambrian sandstone formations shown in Figure 1 were analyzed. Each formation was sampled at numerous locations in western Wisconsin and eastern Minnesota. The grain size of the sample suite ranged from coarse-grained sand to coarse-grained silt.

Except for a few instances (*e.g.*, Berg, 1952), the Cambrian sandstones in the Upper Mississippi Valley have been described as being "classic" supermature quartz arenites; but recent petrological studies by Odom (1975) show that feldspar is actually very abundant, constituting up to 65% of some samples. It consists of

K-rich, detrital grains with authigenic K-feldspar overgrowths (Fig. 2). The overgrowths constitute up to 20% of the volume of some grains but are usually much less.

Data

Figure 3 is a scatter diagram showing the volume of feldspar and mean grain size of samples which contain less than 10% glauconite and 1% or more feldspar. These samples are approximately evenly divided among the sandstone formations shown in Figure 1. The data show that feldspar content increases sharply with decreasing mean grain size below .177 mm (2.5 ϕ). The strong relation of feldspar abundance to grain size is also shown by analysis of feldspar in each ½ phi size class (Fig. 4). This relation is further verified by comparing the weight percent of grains $<$ .125 mm to total feldspar content as shown in Figure 5. All three analyses confirm that feldspar is invariably concentrated in the $<$ .125 mm (3 ϕ) sand fractions.

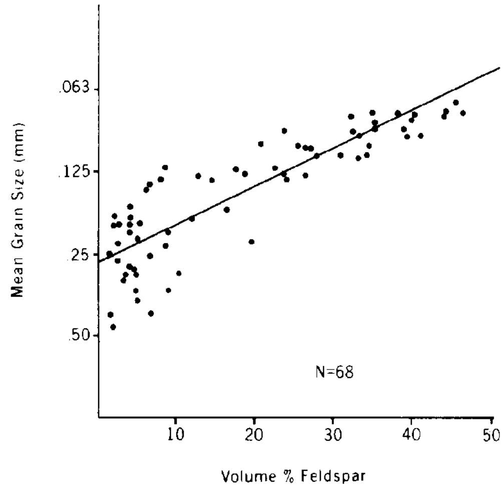


FIG. 3.—Relationship of volume percent feldspar to mean size in some Cambrian sandstones.

Data Analysis

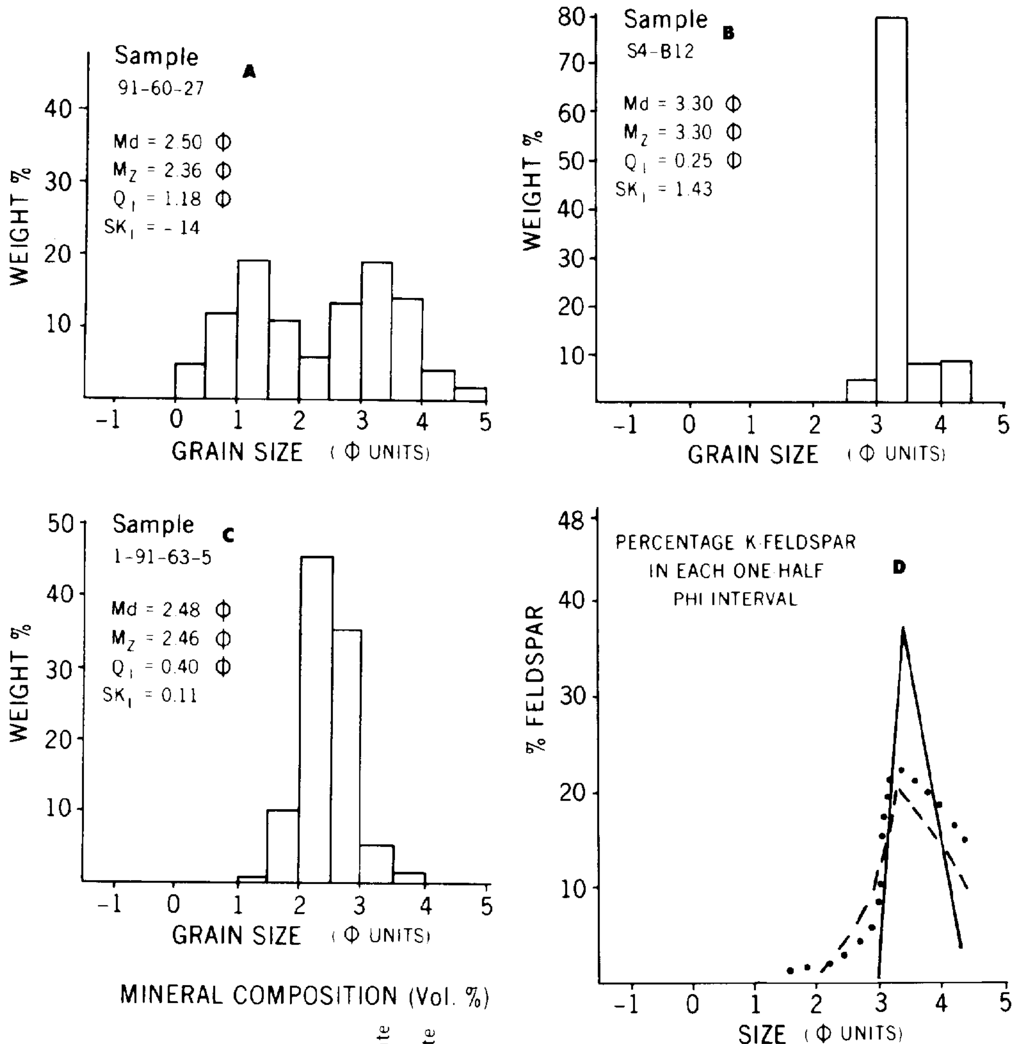
The above data show that the primary factor controlling the abundance of feldspar in Cambrian sandstones in the upper Mississippi Valley is the volume of the $<$ .125 mm sand fractions because the feldspar is concentrated in this size. The concentration of feldspar in the very fine sand size is a result of sorting, which indicates that the feldspar was initially small or was selectively reduced in size through abrasion within high energy Cambrian depositional environments. The possible origins of the small feldspar grain size in Cambrian sandstones of the upper Mississippi Valley have been discussed by Odom (1975).

In studies of Cambrian sandstones, failure to recognize the dependence of composition on grain size could lead to improper mineralogical description, to incorrect interpretation of the mineralogical compositions of the source rocks, to an incomplete understanding of the cause for regional or stratigraphic mineralogical variations, and to the wrong interpretation of the origin of mineralogical maturity. The literature contains several petrologic studies of the Cambrian sandstones in the upper Mississippi Valley in which inadequate representation of fine and very fine-grained sandstone within formations has led to a non-representative mineralogical description of the formations as a whole. Without the knowledge that feldspar content is a function of grain size, a petrologic study restricted to the highly feldspathic, fine-grained Eau Claire or Lone Rock Formations (Fig. 1) would almost certainly lead to the interpretation that the source rocks contained far more feldspar than was actually present. Conversely, a study of the Wonewoc Formation (Fig. 1), which is characteristically a fine to medium-grained quartz arenite (Fig. 1), would certainly be interpreted as having been derived from quartz-rich source rocks, when actually the greater mineralogical maturity of Wonewoc Sandstones is due only to grain size and sorting. Regional and stratigraphic variations of the feldspar content in these sandstones have been shown to be very useful in the interpretation of the energy regime within Cambrian depositional environments (Odom, 1975).

Thus, the Cambrian sandstones in the upper Mississippi Valley provide conclusive evidence that mineralogical maturity and immaturity may be controlled by grain size and sorting processes rather than by the mineralogy of the source rocks or climatic factors. Our subsequent examples show that these sandstones are not unique in the stratigraphic record.

ST. PETER SANDSTONE, (ORDOVICIAN) UPPER MISSISSIPPI VALLEY

St. Peter Sandstone occurs over a wide area of the central United States and is well known for its purity, being almost everywhere a mature quartz arenite. Dapples (1955) showed that the St. Peter is predominantly fine to medium-grained. Only in a few small areas is the



MINERAL COMPOSITION (Vol. %)

Sample No.	Quartz	Feldspar	Glauconite	Carbonate	Matrix
--- 91-60-27	73.2	16.3	-	-	6.5
— S4-B12	68.3	29.3	2.3	-	-
••• 1-91-63-5	97	3			

FIG. 4.—Grain size distribution (A, B, and C) and the percent feldspar in each ½ phi size fraction (D) of three Cambrian sandstones.

mean size < .125 mm. The St. Peter is usually well sorted.

As a rule, the St. Peter contains only small amounts of feldspar (< 2%). Some of the feldspar consists of fine silt size grains believed to be wholly authigenic in origin because these grains are euhedral and completely lack twinning. Sand and coarse silt size feldspar grains, however, contain recognizable detrital nuclei, often twinned, surrounded by authigenic overgrowths (Fig. 6). Microprobe analyses show that these detrital grains and their overgrowths are chemically identical to the Cambrian feldspar previously described. The data presented

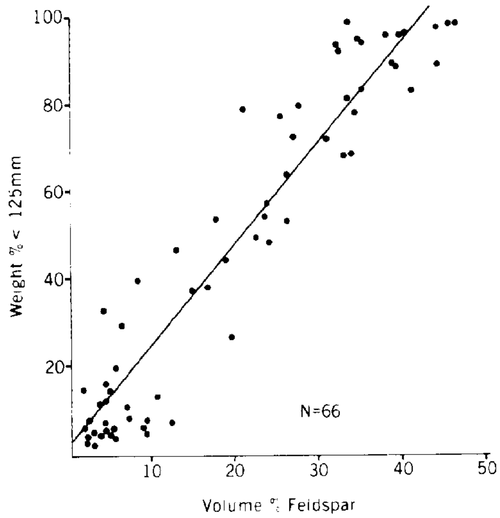


FIG. 5.—Relationship of volume percent feldspar to total weight percent of grains < .125 mm in some Cambrian sandstones.

below deal only with the feldspar grains in the St. Peter that have detrital nuclei.

Data

Figure 7 shows the grain size distribution (A, B, and C) and the feldspar-grain size relation (D) in three samples of the St. Peter which contain more than 5% feldspar. The greater feldspar content above that normally found in the St. Peter is related to an abundant < .125 mm size fraction because of poor sorting. It can be readily observed (Fig. 7D) that the feldspar in these samples is strongly concentrated in the < .125 sizes.

Data Analysis

In more than 100 samples of the St. Peter Sandstone studied, feldspar content was usually < 2% (excluding the highly feldspathic siltstones occurring at the base of the St. Peter in some areas of Wisconsin and Iowa). In all samples, feldspar, if present, is concentrated in the < .125 mm fraction and is most abundant in the coarse silt sizes (Fig. 7D).

The small feldspar content and size in the St. Peter is believed to be a function of three interrelated factors—grain size, provenance, and abrasion history. The small volume of the < .125 mm size fraction as a whole (usually < 10%) was clearly shown by Dapples (1955). Considering the overall grain size and the size distribution of feldspar in the St. Peter, a large amount of the coarse silt size might be feldspar, yet the total feldspar in any sample would be small.

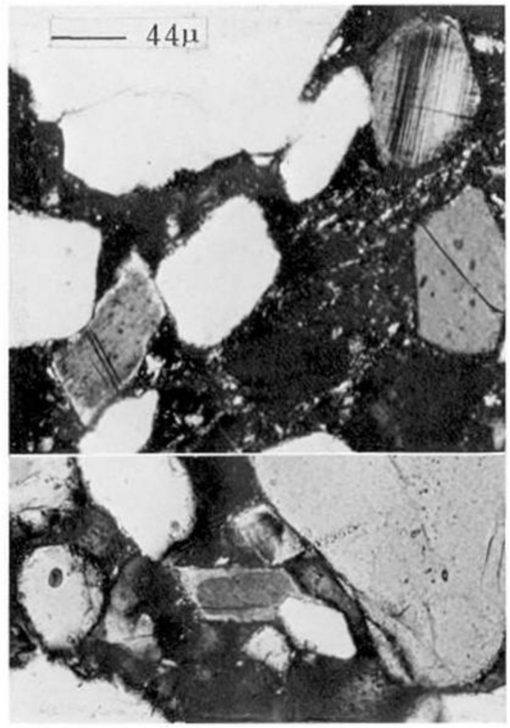


FIG. 6.—Examples of detrital feldspar grains with authigenic overgrowths in St. Peter Sandstone.

The St. Peter was possibly derived from medium to coarse-grained, relatively nonfeldspathic Cambrian sandstones located far north of the present Cambrian outcrop area. As previously shown, the feldspar in the Cambrian sandstones preserved today is primarily concentrated in the very fine sand fraction. Thus, the feldspar in the St. Peter, whether derived from Cambrian sandstones or another source, seems to have been severely abraded. Dapples (1955) concluded that most of the St. Peter was deposited under high energy conditions. Interestingly, the Galesville Sandstone (Cambrian), which is comparable to the St. Peter in mineralogical maturity and texture and known to have been deposited in a high energy environment, also often contains small amounts of silt size feldspar.

WEBER SANDSTONE (PENNSYLVANIAN-PERMIAN), NORTHEASTERN UTAH

The Weber is a quartz-rich sandstone exposed in the Wasatch and Uinta Mountains and in the

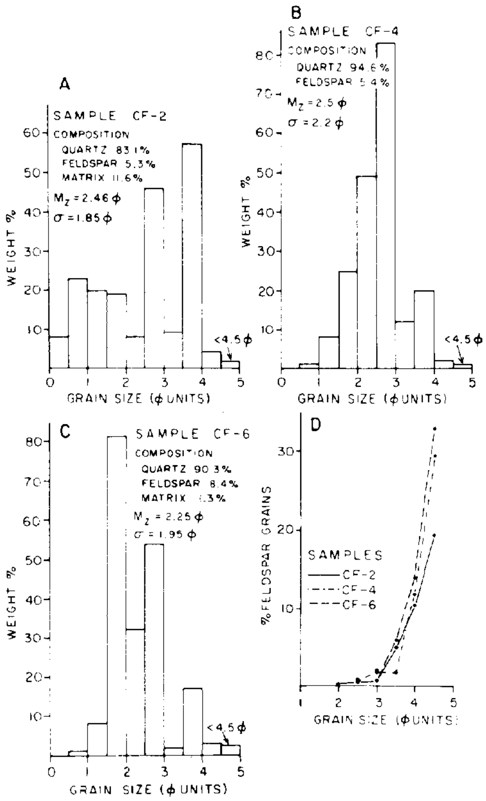


FIG. 7.—Grain size distribution (A, B, and C), mineralogy, and the percent feldspar in each ½ phi size fraction (D) of three samples of the St. Peter Sandstone.

White River Uplift of northeastern Utah and western Colorado. It is predominantly a fine to very fine-grained, well-sorted sandstone with occasional medium-grained units, but marine limestones and dolomites are interstratified in the lower part. The Weber was deposited on a stable shelf lying between the miogeosynclinal Oquirrh Basin on the west and the Ancestral Rockies on the east. Texture and presence of

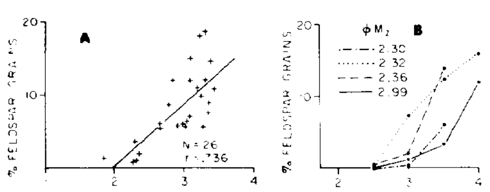


FIG. 8.—Relationship of the percent feldspar to mean size in 26 samples (A) and the percent of feldspar in each ½ phi size fraction in four samples (B) of the Weber Sandstone.

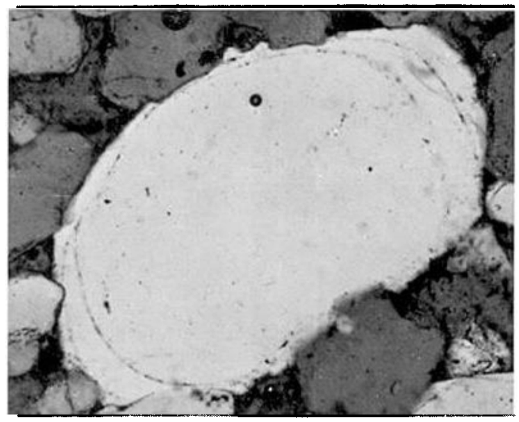


FIG. 9.—Multiple rounded overgrowths on a quartz grain from the Weber Sandstone.

large-scale crossbedding have led to an eolian environmental interpretation (Bissell and Childs, 1958); however, fossiliferous interbeds and abundant soft-sediment deformation suggests a subaqueous sand wave origin for much of it (Doe, 1973).

Samples were collected from 11 sections spanning the entire Weber outcrop area. Mineralogy and texture of 26 samples were analyzed. Quartz and feldspar make up over 99% of the detrital grains. The feldspar ranges from less than 1% to over 20%, and is predominantly orthoclase with smaller amounts of microcline and sodic plagioclase.

Data

Figure 8 is a scatter diagram showing the percent feldspar versus the mean grain size of the 26 samples (A), and the distribution of feldspar within various size fractions of four of these samples (B). As with the midcontinent quartz-rich sandstones, there is a positive correlation between decreasing grain size and increasing feldspar content, and the correlation can be traced to the concentration of feldspar in the < .125 mm sand fraction.

It is significant that the variation in feldspar content is as great within stratigraphic sections as between them. In addition, there is no discernible over-all increase in feldspar from west to east within the Weber.

Data Analysis

Pettijohn, Potter, and Siever (1972, p. 219) include the Weber among the supermature quartzose sandstones, yet many of the finer grained samples studied show feldspar contents

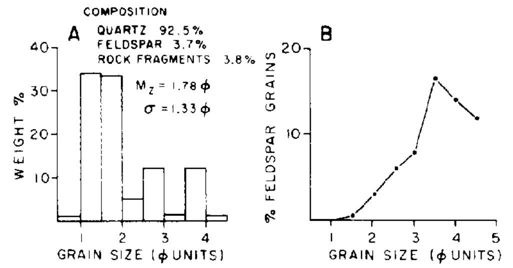


FIG. 10.—Grain size distribution (A), mineralogy, and the percent of feldspar grains in each ½ phi size fraction (B) of a sandstone from the Navajo Formation.

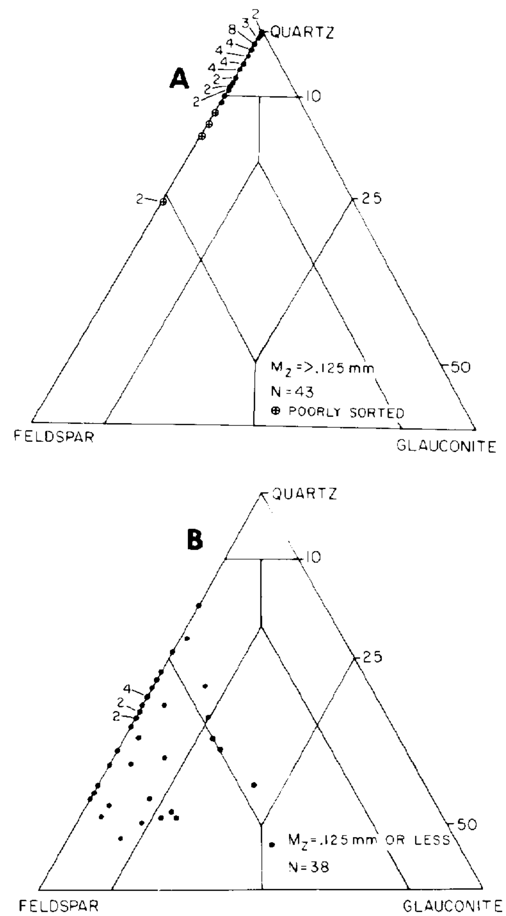


FIG. 11.—Use of multiple triangular diagrams to show the dependence of mineral composition in some Cambrian sandstones on textural properties, particularly mean grain size. (A) mean > .125 mm, (B) mean .125 mm or less. Feldspathic sandstones in A are poorly sorted.

in excess of the 5% to 10% limit generally put on such rocks. As with the Cambrian sandstones of the Mississippi Valley, the problem of sampling too narrow a range of grain sizes is apparent for the Weber.

Two major areas have been suggested as sources for the Weber—the granitic rocks of the Ancestral Rockies (Bissell and Childs, 1958), and early Paleozoic sedimentary rocks of the craton to the north (Todd, 1964). Paleocurrent data for the Weber and correlative Tensleep of Wyoming uniformly trend to the south, which makes an origin in the Ancestral Rockies questionable. Also, Todd (1964) points out that the volume of quartz-rich sand in the late Paleozoic sediments of the Rocky Mountain area are far greater than estimates of the amount available from the Ancestral Rockies. Zircon-tourmaline-rich heavy mineral assemblages point to a sedimentary source as do rare, but significant, quartz grains with multiple, rounded overgrowths (Fig. 9).

If the Ancestral Rockies were a primary source or even a secondary source for the Weber, the feldspar content should increase in the eastern part of the Weber Sandstone, which is not the case. Indeed, samples from Schoolhouse Tongue, a 100 foot thick tongue of Weber sandstone within the red arkosic sequence surrounding the Ancestral Rockies have feldspar contents and grain sizes similar to that of the rest of the Weber. The fact that feldspar content is only a function of grain size, and not of position relative to the Ancestral Rockies, suggests that the Weber consists of multicycled sand.

NAVAJO SANDSTONE

The origin of the Navajo Sandstone has been interpreted as marine (Freeman and Visher, 1975) as well as aeolian. Although no detailed study has been made of the feldspar in a large number of Navajo samples, five samples were examined, all of which are of medium grain size. One of these samples only, containing laminations of medium and fine sand with 3.7% total feldspar, gave some interesting data pertaining to feldspar-grain size distribution.

Data

Figure 10 shows a histogram of the grain size (A), the mineralogy, and the feldspar distribution in each ½ phi size fraction (B) of the sample mentioned above. In this instance, the feldspar shows a more uniform distribution in the sizes below .35 mm (1.5 ϕ) than in the other sandstones studied, but it, nevertheless, is still most abundant in the size fractions < .125 mm.

Data Analysis

Only cautious generalizations can be drawn on data from a single sample, but it is apparent that the overall feldspar distribution in this sample contrasts sharply with those previously discussed, being much more evenly distributed among the size grades present. The volume of feldspar in each ½ phi fraction shows an increase with decreasing grain size to .088 mm but then decreases in the finest sand and coarse silt sizes. There is a distinct possibility that further studies would show that fine and very fine-grained sandstones in the Navajo would be feldspathic or highly feldspathic because of this increase in feldspar with decreasing grain size.

IMPORTANCE OF GRAIN SIZE IN CLASSIFICATION

In several existing classifications many of the sandstones described herein would qualify as arkoses or subarkoses, but to apply these terms to samples of the Weber or the Cambrian without clarifying the origin of their mineralogy would imply a level of tectonic activity and perhaps a source not at all compatible with their textural maturities and depositional environments. Discrepancies of this nature can be avoided by incorporating mineralogical-grain size relations into sandstone classification.

Because most of the current classification schemes use triangular diagrams, we suggest using two (or more) such diagrams with each defining a specific mean size range as shown in Figure 11. The advantages of this approach are (1) that it visually demonstrates the petrologic evidence for mineralogical-grain size relations if they exist, and (2) that it is compatible with most classifications in common use. Of course, multivariate statistics could also be utilized if desired. For our samples, 3 ϕ (.125 mm) seems to represent a significant boundary, but further work of this sort will be needed before any natural boundaries can be identified.

One relation that the use of multiple triangular diagrams will not show is the presence of a large amount of < .125 mm size feldspar or other component in a sandstone with a mean > .125 mm because of poor sorting. In Figure 11A sandstones that contain appreciable < .125 mm size feldspar, because of poor sorting, yet have a mean size > .125 mm are identified.

In more mineralogically complex sandstones, feldspar-grain size relations might be overlooked because of dilution effects. The study of such sandstones can often be aided by calculating the ratio of the various components to each other or by using multi-variate statistics. For example, in the Cambrian sandstones of the upper Mississippi Valley, the presence of more than 15% glauconite or carbonate tends to obscure the strong feldspar-grain size relation, yet it is clearly shown by comparing mean grain size to the amount of feldspar divided by the amount of quartz plus feldspar.

DISCUSSION

Although this investigation is limited in stratigraphic range, the results indicate that in sandstones deposited in strongly agitated environments or that were possibly derived from sedimentary sources, feldspar abundance may be strongly related to grain size. The importance of this relation in mineralogical classification, in provenance studies, in environmental interpretations, and in evaluating the origin of compositional maturity is obvious.

Our data suggest that when feldspar abundance is grain size dependent, the feldspar tends to be concentrated in the < .125 mm sand fractions, or in some cases, in the coarse silt fractions. Perhaps the 3 ϕ size represents a threshold below which feldspar tends to be less susceptible to further size reduction by abrasion.

Detrital feldspar which has been reduced to predominantly very fine sand or coarse silt sizes would appear to indicate either intensive mechanical abrasion or selective sorting. In the St. Peter Sandstone, the feldspar is predominantly in the coarse silt size but is associated with medium to fine-grained quartz. This relation implies derivation of initially small feldspar from Cambrian sediments and further mechanical abrasion in St. Peter depositional environments. Conversely, there are many very fine-grained, highly feldspathic sandstones in the Cambrian sequence of the upper Mississippi Valley formed by sorting of feldspar from contiguous high energy environments.

It has long been realized that matrix (< 0.03 mm) often increases sharply in very fine-grained sandstones and to an even greater extent in siltstones. A review of the data in a study of sandstone composition and depositional environments recently published by Davies and Ethridge (1975) shows that matrix increases and quartz decreases sharply in many of their samples having a mean size below .125 mm (3 ϕ). Blatt and Christie (1963) and Blatt, Middleton, and Murray (1972) have conclusively shown that polycrystalline quartz and polymineralic rock fragments decrease sharply in grain sizes < 3 ϕ. Field and Pilkey (1969) showed that feldspar in shelf and beach sands off North Carolina is concentrated in fine and very fine sand sizes as a result of abrasion. These relations and the concentration of feldspar in the $< 3\ \phi$ sizes shown herein, indicate that more importance should be placed on grain size in mineralogical classification, in the interpretations of stratigraphic and regional mineralogical variations, and in the evaluation of mineralogic maturity.

In regards to mineralogical maturity or immaturity, the increase in feldspar content with decreasing grain size has important implications, particularly when one is considering the maturity of a single sedimentary unit or a sequence of units. Sandstones having the same provenance and similar sedimentary histories can vary considerably in apparent textural and compositional maturity depending on which grain size fractions are predominant. This problem is well illustrated by the relatively high feldspar contents we have found in the "classic" supermature sandstones of the midcontinent Cambrian and of the late Paleozoic in the Rocky Mountains. Consideration of only the coarse or fine sandstones within a sequence could lead to erroneous interpretations of their origins and provenance areas.

CONCLUSIONS

1. The distribution of feldspar among various size fractions of a sandstone is important in understanding compositional variations, in provenance studies, in the interpretation of depositional environments, and in evaluating the origin of compositional maturities.

2. In the Cambro-Ordovician sandstones of the upper Mississippi Valley and in the Weber Sandstone of late Paleozoic age, feldspar is concentrated in the $< .125$ mm sand, or in some cases the coarse silt size fractions, and commonly amounts to more than 25% of these supposedly supermature quartz sandstones.

3. Regional or stratigraphic variations in composition, which might seem to be caused by changes in the source rocks, may often be related only to grain size. Recognition of such a relation is very important in the evaluation of provenance and depositional environments.

4. Removal of feldspar by abrasion and sorting appears to be an important process in the origin of the mineralogical maturity of many sandstones.

5. Multiple triangular diagrams like those commonly used in the classification of sandstones, each denoting a specific mean size range, are an effective way to illustrate that mineral composition is size dependent.

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