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SEDIMENTARY PETROGRAPHIC PROVINCES: AN EVALUATION

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ABSTRACT—Mineralogic provinces are compositionally distinctive three-dimensional bodies of rock constituting natural units in terms of age, origin and distribution. More than one province likely will be present within the same sedimentary basin. Unconformities and not necessarily group, formation or member boundaries are the sharpest stratigraphic boundaries of provinces. Lateral boundaries are frequently gradational; depending on the scale of the basin analysis these areas of gradation can be separately defined as hybrid provinces.

Over-generalization and over-simplification of interpretation of mineralogic provinces has resulted from inadequate appreciation and evaluation of the relative influence of the four principal factors controlling composition of a province: provenance, transportation, depositional environment and diagenesis. Each of these factors is in turn a dependent variable. A total of 13 immediate processes controlling province composition are identified.

Improved ability to interpret ancient mineralogic provinces will develop from i) better documentation of starting or parent detritus, ii) quantitative estimation of the effects of transportation and environment on sediment composition through study of Holocene sediment, iii) more precise characterization of mineralogic provinces and iv) refinement of current techniques used in interpreting the origin of detrital quartz, feldspar, and accessory minerals.

MEANING AND SIGNIFICANCE OF A MINERALOGIC PROVINCE

A *mineralogic* or *sedimentary petrologic province* was first defined by Edelman (1933, p. 6)as a a group of distinctive, homogeneous sediments ts which constitute a natural unit by age, origin and distribution . . . a three-dimensional body ***characterized by a distinctive suite of light and heavy minerals.*** Sedimentary provinces are broadly defined by unique *mineral associations.* Four principal characteristics of mineralogic or sedimentary provinces are illustrated in figure 1:

(1) Several different provinces of approximately the same age can occur in the same sedimentary basin, depending on the number of distinct source areas contributing sediment to the basin. In figure 1 source areas A and B have given rise to their own unique petrologic provinces within the same sedimentary basin by generating distinct mineral associations. The Gulf of Mexico is a well-documented actual example of a basin containing at least four petrologic provinces or sub-provinces (Goldstein, 1942, Van Andel, 1960, and Davies and Moore, 1970). Unique mineral associations in the Gulf have been derived from the southern Appalachians, the cratonic interior drained by the Mississippi River and its tributaries, the Texas coastal plain, and the Rio Grande drainage basin.

(2) Hybrid provinces can be formed by the mixing of detritus from two or more distinct, but adjacent source areas. In figure 1 province id B is a product of derivation in part from area A and in part from area B. Baak (1936, p. 13–14) referred to hybrid provinces as areas of "chaotic sedimentation" or "abnormal variations" in provinces and suggested that they seldom are of regional importance.

Hybrid provinces undoubtedly characterize orogenic source areas where a wide variety of rock types occur in adjacent drainages. Füchtbauer (1964) for example has recognized mixed mineral assemblages in the Tertiary molasse of southern Germany. The mixed assemblages are the result of coalescence of alluvial fans derived from the Alps.

(3) Major unconformities are normally the best stratigraphic boundaries for provinces be-

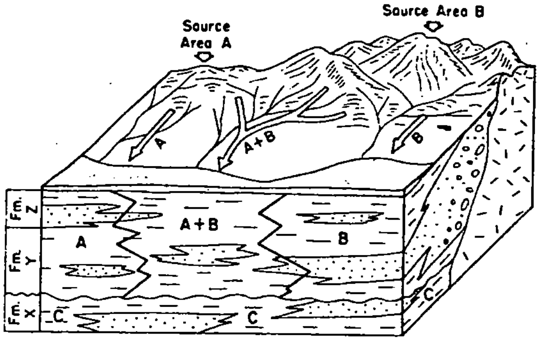

FIG. 1—Schematic block diagram illustrating multiple and hybrid mineralogic provinces within a single sedimentary basin. Province A was derived from source area A; province B from source area B; province A + B is a hybrid derived in part from both source areas; province C is an older province derived from a now extinct source area.

cause they typically reflect major changes in tectonic conditions that control sediment composition. In figure 1 province C is bounded at the top by an unconformity of basinal extent. Differences in composition between province C and the younger provinces should be sharp if the unconformity in any way reflects tectonic events within the source area, assuming that the effects of reworking are relatively minimal.

(4) Boundaries of mineral provinces need not coincide with stratigraphic boundaries (i.e., group, formation, or member boundaries) defined either paleontologically or lithologically. Time, environmental change, and new organisms yield stratigraphic boundaries, but if the sediment source area is not changing simultaneously, stratigraphic boundaries of provinces will not exist. For example, in figure 1 province A spans formation Y and Z stratigraphic boundaries, because source area A persisted in a relatively unchanged manner throughout the time environments were changing during deposition of formations Y and Z.

Conversely, environments can remain unchanged in time and space at the same time unroofing of new source rocks or changes in drainage in the source can produce new mineral associations. In such cases mineral assemblages may be useful in correlation. Numerous case histories of the use of heavy mineral assemblages in stratigraphic correlation and zonation are found in Milner (1962, v. 2, p. 413–424). Furer (1970) successfully used light minerals and rock fragment associations in correlation of the nonmarine Upper Jurassic and Lower Cretaceous from central Wyoming to western Wyoming.

PROBLEM OF INTERPRETATION OF PETROLOGIC PROVINCES

The mineralogy of a petrologic province is a function of four variables: i) provenance, ii) modification of detritus during transportation, iii) modification during deposition, and iv) modification during lithification or diagenesis. Each of these four principal variables is dependent on variables given in table 1. From table 1 it is apparent that the composition of a basin fill is controlled by a minimum of 13 immediate processes. Therefore the interpretation of a petrologic province is exceedingly complex, unless certain of the variables play insignificant roles. Currently sedimentary petrologists have insufficient empirical basis for evaluating the relative influence of each of the process variables on the compositional response—mineral associations.

Clearly tectonism exerts a dominating and overriding influence on sedimentation. Without tectonism there would be no continuous sedimentation and production of new mineral associations because tectonism triggers erosion, and unroofing of new source rocks. Also it can be argued that tectonism controls topography which in turn modifies climate in source areas. Obviously tectonism also directly affects rates of sedimentation and indirectly controls the evolution of environments. The assumption of the fundamental tectonic control of sedimetation is the basis for definition and recognition of lithologic associations—groups or suites of sedimentary rocks formed under essentially similar tectonic conditions (Krumbein and Sloss, 1963, p. 424). Within a given lithologic association however, numerous petrologic provinces can occur because of the varying influence of other variables (table 1). Failure to recognize this has resulted in a gross oversimplification and generalization of interpretation of terrigenous rock composition. An obvious tendency exists to simply relate sandstone mineralogy directly to source rock mineralogy. The role of intermediate processes in modifying detritus is assumed to be relatively unimportant. Exceptions include interpretations of quartz arenites or interpre-

TABLE 1.—FACTORS CONTROLLING THE COMPOSITION OF A MINERALOGIC PROVINCE

DM = f(P, T, D, L)
DM = Detrital mineralogy of basin fill
P = Provenance
T = Modification during transportation
D = Modification during deposition
L = Modification during lithification or diagensis

Where:
P = f(srk, w_{ch}/w_m, r) and
srk = source rock
w_{ch}/w_m = relative amounts of chemical and mechanical weathering in the source areas
r = relief in the source area

T = f(a, d, v, $t_t/t_{sa}/t_{su}$) and
a = agent of transportation
d = distance of transportation
v = velocity of transporting agent
$t_t/t_{sa}/t_{su}$ = relative amount of sediment transported by traction, saltation and in suspension

D = f(e, rdb, c) and
e = environment
rdb = rate of deposition and burial
c = climate at depositional site

L = f(po, pe, gw) and
po = porosity
pe = permeability
gw = groundwater chemistry

tations where appeal to the effects of the other processes is the last-resort explanation of anomolous observation. Thus we encounter statements such as the following in the literature:

> ". . . subquartzose sandstones derived exclusively from plutonic provenances . . . have less than 25 percent, and commonly less than 10 percent unstable lithic fragments . . . a quartz content commonly close to 50 percent and a high mica content, commonly 5 to 10 percent" (Dickinson, 1970, p. 705).

The following illustration shows that perhaps the assumption that source rock is the foremost factor in controlling sandstone composition is not always valid. Figure 2 is a photomicrograph of Holocene sand collected from a stream draining a high-relief area underlain by granodiorite in southwestern Montana. Figure 3 is a photomicrograph of sand from a stream draining a high-relief area underlain by quartz-feldspathic gneiss in southwestern Montana. The sands are representative of approximately 60 samples collected from a number of streams in the northern Rocky Mountains. They are compositionally immature. The sand in figure 2 contains 68 percent rock fragments—aggregates of two or more crystal units; the sand in figure 3 contains 78 percent polymineralic rock fragments and polycrystalline quartz. Including the feldspar bound up in the rock fragments between 30 percent and 35 percent feldspar is found in the two samples. Rarely do ancient sandstones contain this high a content of liable constituents. Obviously modification of detritus between the time it is derived from the source rock and the time it is lithified is quite significant. But insufficient empirical data currently is available to determine how much of the modification can be related to each of the processes of derivation, transportation, deposition and lithification.

Modification of Detrital Mineralogy During Soil Formation

Changes in detritus that take place between the time the detritus is released from a source rock and the time it is first moved by a transporting agent can be significant. The critical controlling factor presumably is climate, especially annual amount and distribution of precipitation, and to a lesser extent relief. In the case of the sands in figures 2 and 3 changes in the nature of the sand as it passed through the

FIG. 2—Photomicrograph of Holocene sand collected from Willow Creek in the Tobacco Root Mountains c thwestern Montana. Willow Creek's drainage basin is exclusively underlain by granite and grandiorite. M . of the grains are rock fragments consisting of quartz and feldspar (qf).

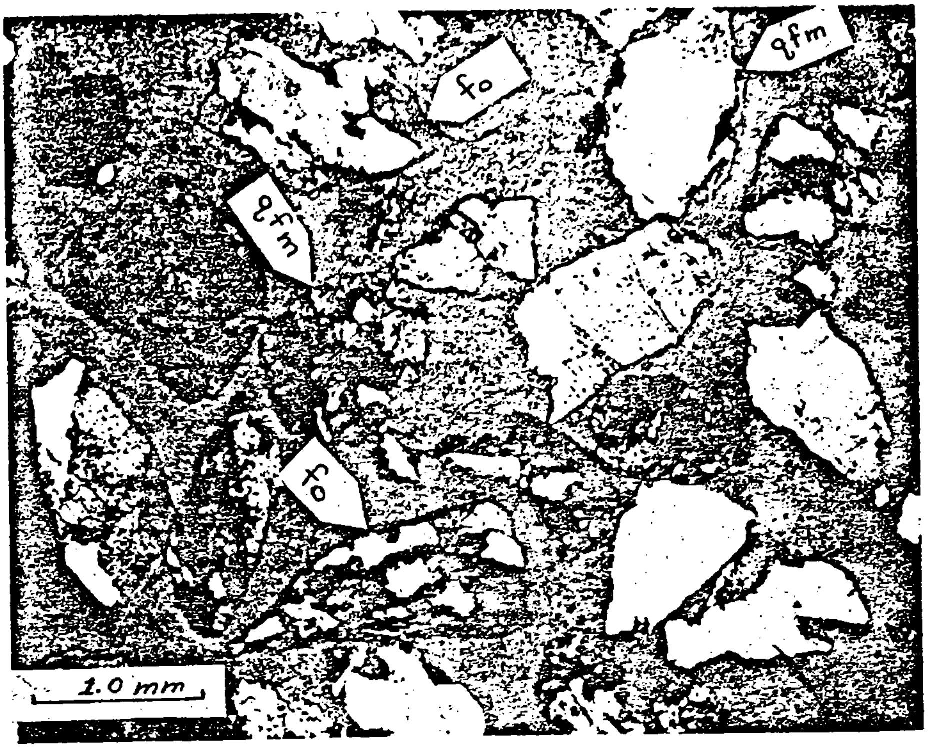

FIG. 3—Photomicrograph of Holocene sand collected from Quaking Aspen Creek in the Tobacco Root Mountains of southwestern Montana. Quaking Aspen Creek's drainage basin is exclusively underlain by Precambrian crystalline metamorphic rock, largely quartz-feldspathic gneiss. Virtually all grains shown are rock fragments. Two possess foliated texture (fo). Several are aggregates of quartz, feldspar and a mafic mineral, usually hornblende (qfm).

soil profile were obviously slight. Feldspar is fresh and abundant and most of the mineral aggregates appear to have been derived through simple disintegration of the source rocks. However, the effects of climatic modification of composition during soil formation became apparent with modal analyses of sand such as that shown in figure 2 (derived from granite and granodiorite in an area of semi-arid climate) are compared with the modal analyses of sand derived from areas underlain by granite in the more humid climate of South Carolina (fig. 4). Marked differences exist. Approximately two to three times as much feldspar and six to seven times as many rock fragments are found in the first-cycle sand from southwestern Montana versus that from South Carolina. In contrast approximately two to four times as much chemically and mechanically stable monocrystalline quartz is found in the Holocene sand from the more humid climate.

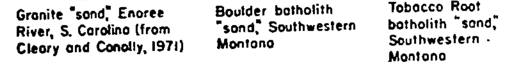

FIG. 4—Bar graphs summarizing the differences in composition of Holocene sand from streams draining the Tobacco Root and Boulder Batholiths of southwestern Montana and streams draining grainite in South Carolina, (Enoree River; after Cleary and Conolly, 1971).

Figure 5 further illustrates the interaction of climate and fluvial sand composition. Feldspar content in Holocene sand shows a near linear inverse relation with mean annual precipitation. Because most of the sands in figure 5 were sampled less than 200 miles from the stream's headwater, and several from less than 50 miles, it can be assumed that feldspar destruction during transport was probably minimal relative to ruction which occurred in the source rock weathering process.

Table 2 is an attempt to more directly evaluate the influence of precipitation in destruction of feldspar during soil formation. Although a faint inverse correlation of precipitation and frequency percent feldspar in soil is suggested by the data, it is readily apparent that a wide range of feldspar content is found within areas possessing a narrow range of mean annual precipitation. In large part this reflects the large number of variables such as soil grain size and age, parent rock type, relief, and sample depth that cannot be established or held constant in view of the limited number of publications providing the light mineral data given in the table. The shortage of such data in existing literature points to the need for carefully controlled studies of the non-clay mineral fraction of soils by sedimentary petrologists.

It is especially interesting to note that figure 5 and table 2 both suggest that only in the most exreme humid climates (annual precipitation at least 100 inches) is there near total destruction of feldspar in the weathering profile. Consequently it is necessary to reconsider the prevailing notion that quartz arenites can readily form in humid to sub-humid climates.

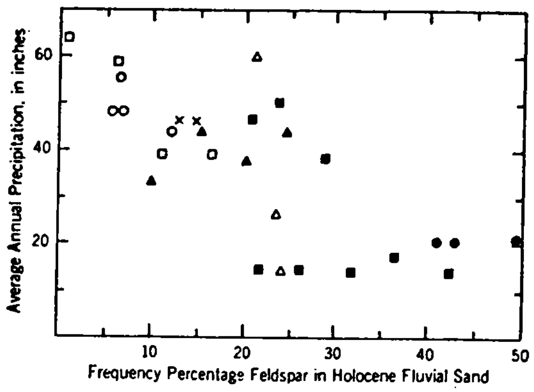

FIG. 5—Frequency percentage of feldspar in Holocene sand as a function of average annual precipitation. □ samples from Hsu, 1960; ○ samples from Giles and Pilkey, 1965; × samples from Cleary and Connolly, 1971; ▲ samples from Willman, 1942; △ samples from Whetten, 1966; ● samples from Hayes, 1962, ■ samples from this study.

TABLE 2.—FREQUENCY PERCENTAGES OF FELDSPAR IN SOILS

Parent Material	Locality	Mean annual precipitation in inches	Depth below surface in inches	Grain size	Number of samples	Range in frequency in percent	Average frequency in percent	Reference
Granite	British Guiana	100	8–32	Sand	2	2–7	4.5	Harrison (1934)
Gneiss	Malabar Coast, India	100	Not given	Sand	2	2–3	2.5	Harrassowitz (1926)
Granite gneiss	Ibadan, Nigeria	55–65	12–18	Medium sand	1		1	Nye (1955)
Granite gneiss	Ibadan, Nigeria	55–65	12–18	Fine sand	1		20	Nye (1955)
Quartz diorite and granite	Ituri, Belgian Congo	40–60	0–16	Fine sand	1		10	Ruhe (1956)
Granite	Ituri, Belgian Congo	40–60	0–28	Fine sand	3	2–40	21	Ruhe (1956)
Outwash derived from granite gneiss and schist	Connecticut Valley	45–50	0–3	Medium sand	1		15	Bourbeau and Swanson (1954)
Outwash derived from granite gneiss and schist	Connecticut Valley	45–50	0–3	Very fine sand	1		22	Bourbeau and Swanson (1954)
Granite	Piedmont, S E United States	45–50	0–12	Sand	4	12–40	28	Cleary and Conolly (1971)
Gneiss	Piedmont, S E United States	45–50	0–12	Sand	1		20	Cleary and Conolly (1971)
Granite	Ozark Mtns., Missouri	42–46	1–6	Sand	1		47	Short, 1961
Granite	Malvern Hills, England	25–35	0–10	Fine sand	2	45–58	52	Stephen (1952)
Biotitite	Malvern Hills, England	25–35	2–12	Fine sand	2	20–28	24	Stephen (1952)
Granite	Balos, Sudan	26	0–6	Sand	8	22–40	34	Ruxton (1958)
Granite	Transbaikalia, Russia	12–16	0–3	Fine sand	2	59–67	63	Sokolova and Smirnova (1965)
Granodiorite	Bighorn Mtns., Wyoming	15	1–4	Sand	1		43	Short (1961)

Modification of Detrital Mineralogy during Transportation

Most studies on the survivability of detritus during transportation have focused on feldspars in low gradient streams. The classic work of Russell (1937) on the Mississippi River sand showed less than 20 percent destruction of feldspar in 1100 miles of transport. Abrasionary destruction of feldspar in the Mississippi is minimal; most of the destruction apparently is related to soil formative processes when the sand is temporarily caught up on bars or floodplains. Pollock (1961) reported little or no compositional change in channel sands along 650 miles of the South Canadian River in New Mexico, Texas and Oklahoma. He noted that a decrease in feldspar content of coarse sand is compensated by increase in feldspar content of the fine sand due to breakage along cleavage or twin planes. Pittman (1969) found a similar significant mechanical reduction in size, but not ultimate destruction, of feldspar along 20 to 25 miles of the Merced River.

On the other hand, Plumley (1948) found a 50-percent decrease in feldspar in 40 to 45 miles of transport in Battle Creek in the Black Hills of South Dakota. Hayes (1962) found erratic variations in feldspar content downstream in the high gradient South Platte River between Fairplay and Denver, Colorado. Cameron and Blatt (1971, p. 571, p. 575) observed a reduction of feldspar from four percent to two percent in 20 miles of transport in Elk Creek in the Black Hills. More significantly they noted a 75-percent reduction in schist fragments in 20 miles of transport.

The above apparent inconsistencies in studies of grain survivability were first pointed out by Pettijohn (1957, p. 125). As Pettijohn concluded the differences probably reflect differences in the gradient of the streams studied; mechanical destruction taking place faster in higher gradient streams. Bradley (1970) has concluded that possibly a major factor affecting the survivability of grains in transport is the length of time they are not in transport, but instead subject to chemical weathering on pointbars or floodplains.

More controlled studies of sand content of both high and low gradient streams in a variety of climates are needed. Special effort in these studies must be directed to documentation of the survivability of rock fragments.

Modification of Detrital Mineralogy during Deposition

Evaluating the control of depositional environment on sandstone composition is dependent on understanding the significance of grain destruction through abrasion. It has generally been assumed in provenance determinations that the environmental processes which bring about grain destruction are minimal or obscured by more important effects (Pettijohn, Potter, Siever, 1972). In large part this assumption probably reflects the impact of a number of empirical studies of abrasion (Wentworth, 1919; Marshall, 1929; Krumbein, 1941; Rayleigh, 1944; Kuenen, 1955, 1956, 1959, 1964, and others). Kuenen (1959) for example extrapolated his experimental data to show that 20,000 km. of fluvial transport would cause no more than one percent reduction in volume of medium sand size quartz through abrasion. Similar low orders of magnitude of destruction of feldspar and limestone fragments were reported. Although destruction of quartz during aeolian transport was estimated by Keunen to be 100 to 1000 times greater than destruction during equal distances of fluvial transport, net reduction in quartz volume through mechanical abrasion was not assumed to be important. However, Swett and others (1971, p. 411–412) have calculated that sand deposited in a tide-dominated environment can conceivably travel an average of 36.5 km/year. During a million years of reworking before burial a conservative estimate of travel for grains in this environment would be in the order of 36.5×10^6 km—a distance approximately 10^4 times greater than the distance of Kuenen's experimental studies. Sand in the tidal environment is alternately wet and dry, thereby catalyzing the chemical weathering processes. Presumably, therefore, in such rigorous near-shore environments significant mineralogic maturation could occur.

Destruction of feldspar through abrasion in beach and dune environments is indicated by the average feldspar content of over 400 samples of Holocene and Pleistocene sand from North America tabulated by Pettijohn, Potter and Siever (1972, table 2-1). River sands average twice as much feldspar as either beach or dune sand. It is interesting to note however, that the beach and dune sands contain an average of 10 percent feldspar. This is well above the average content of quartz arenites, the compositions of which have sometimes been related to abrasionary destruction in high energy environments.

APPROACHES TO IMPROVED INTERPRETATION OF MINERALOGIC PROVINCES

Three of the four principal factors controlling sandstone composition have been briefly considered. The fourth, diagenesis or intrastratal solution is the most complex factor to evaluate and perhaps the least understood. In view of our overall inability to evaluate the four factors it is imperative that we re-examine the hypotheses on which interpretation of mineral provinces are based. Four avenues of approach to re-examination deserve immediate consideration.

1. *Documentation of Differences in Starting or Parent Materials.*—Currently little is known about how detritus derived from a granite differs from that derived from a gneiss; or for that matter even how detritus derived from a sedimentary terrane differs from that derived from an igneous terrane. Sedimentary petrologists and soil mineralogists have too long overlooked the nature of first-cycle non-clay mineral fractions of soils developed on different bedrock, in different climates and in areas of contrasting relief. Until the differences imparted on sediment composition by the provenance variables such as source rock, climate, and relief are determined, our interpretations of the provenance of ancient rocks will be hazardous generalizations.

2. *Estimation of Compositional Modification During Transportation and Deposition through Study of Holocene Sand.*—Major advances in igneous and metamorphic petrology were made when microscope observation was supplemented with laboratory experimentation. The same will be true in sedimentary petrology. However, the sedimentary petrologist need not simulate in the laboratory; he has natural access to sediment-forming processes. It is up to him to establish how these processes modify sediment composition within the framework of Uniformitarianism—*by looking at the Holocene,* before attempting to make provenance interpretations about the ancient.

3. *More Exact Characterization of Mineralogic Provinces through Precise Definition of Mineral Species and Rock Fragments.*—Problems of compositional interpretation are too complex to be solved with the generalized data that appear on traditional quartz-feldspar-rock fragment triangular portrayals of sandstone composition. We must begin to identify quartz and feldspar varieties in the same, if not in greater detail, than attempted for detrital tourmaline and zircon, for instance. The classic attempts by Krynine (1940, 1946) and Folk (1968) to utilize character of extinction and nature of inclusions to define sub-species of quartz are well-known examples of a means of precise definition of a single mineral species. An analogous example involving feldspar is illustrated in figure 6 and table 3. The bar graphs in figure 6 summarize the gross differences in a sand derived from a plutonic source and sand derived from a metamorphic source, using the compositional end members of standard sandstone classifications. Figures 2 and 3 are photomicrographs of representative samples from these same two populations. It is apparent from figure 6 that discrimination between the populations would be impossible on the basis of the four standard end member ingredients chosen. Moreover, several of the rock fragments in both populations lack distinctive textural identifying characteristics, thereby precluding use of this criterion in distinguishing between the two groups of samples. However, precise description of feldspar enables distinction between the two populations with a high degree of confidence. Using the feldspar data in table 3, a X^2 test of distinctness of the population of "igneous sand" and population of "metamorphic sand" indicated a probability of .98 that the two sets of samples are indeed different. Furthermore, the probability of individual samples of "plutonic sand" coming from a population different from the compound metamorphic sample is greater than .70 in 8 of the 10 samples examined. Although the provenance significance of twinning in detrital feldspar is still inadequately understood (Pittman, 1970), this sample strongly suggests that precise characterization of mineralogic provinces and standard petrographic analyses should include more than a simple tabulation of percent feldspar, quartz, and rock fragments in addition to the normal heavy mineral data.

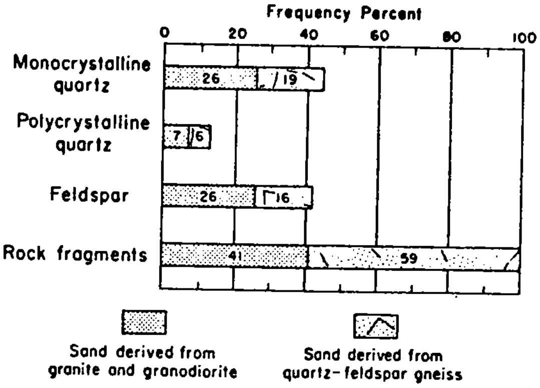

FIG. 6—Bar graphs of the average composition of 9 samples of Holocene sand derived from plutonic source rocks and 10 samples of Holocene sand derived from Precambrian metamorphic rock.

TABLE 3.—VARIATIONS IN THE KIND AND AMOUNT OF FELDSPAR[1]

Number of samples	Number of grains		Percent K-spar	Percent plagioclase	Percent untwinned plagioclase	Percent A-twins	Percent C-twins
				Plutonic derived sand			
10	2291		45	55	18	48	34
		Std. dev.	8.1	8.1	4.4	6.1	6.1
				Metamorphic derived sand			
9	1482		28	72	22	43	35
		Std. dev.	7.7	7.4	4.1	7.1	7.6

[1] Data taken from the samples of Holocene sand of plutonic and metamorphic origin portrayed in figure 6. Twin determinations were made with standard flat stage microscope. A-twins include the albite and pericline types and C-twins the more complex Carlsbad and Baveno types.

4. Improve Capabilities for Reading Genetic "Tags" or "labels" on Ubiquitous Minerals Such as Quartz and Feldspar.—Given a mineralogic province, presumably the major concern will always be determination of the source rock type or types for the province. If the grains that ultimately make it through the various destructive process filters do indeed retain some form of identity tag which in effect says "I am metamorphic" or "I was derived from a granite" we must learn how to read the tag. Obviously we must then also use those physical-property tags or labels that we best understand to more precisely define mineralogic provinces as discussed in number 3 above.

What might be the nature of such "tags" or "labels"? In the case of quartz several modern examples exist. Taylor and Epstein (1962) have shown that the ratio of the stable isotope of oxygen (O^{18}) to the less stable isotope O^{16} is a direct function of temperature of crystallization of quartz. Consequently this O^{18}/O^{16} ratio should be a key to the origin of detrital quartz. Dennen (1967) indicated that the trace element content of quartz is provenance significant. Dennen's technique was used by this author to discriminate between quartz from the populations of plutonic and metamorphic sand referred to earlier in this report. Differences in the trace-element signature of the quartz populations are tabulated in table 4. Using both mean and standard deviation values for individual trace elements a distinction between the metamorphic quartz and quartz from the Boulder and Tobacco Root Batholiths is readily possible. Probable genetic explanations for the distribution of trace elements in the quartz in Table 3 are given in Suttner and Leininger (1972).

Quartz thermoluminescence and density are other physical properties potentially useful in determining the origin of detrital quartz. Charlet (1971) proposed that the thermoluminescence of individual quartz grains uniquely fingerprints crystallization conditions. Charlet satisfactorily tested the technique through studies of the Carboniferous of the Pyrenean mountains and Alpine sediments from Sicily and North Africa. His results were in agreement with earlier interpretations of the provenance of these rocks based on more traditional techniques. Hayase (1960) has shown that the smokiness of quartz as revealed by gamma irradiation of individual grains, is indicative of the crystallization temperature of the quartz. Katz (1970) and Katz and Muravyov (1970) have developed a thermally controlled, gravitation gradient tube enabling precision measurement (± .01) of the density distribution of

TABLE 4.—PARTIAL TRACE-ELEMENT CONTENT OF QUARTZ FROM THE TOBACCO ROOT AND BOULDER BATHOLITHS OF SOUTHWESTERN MONTANA AND FROM AN AREA OF PRECAMBRIAN METAMORPHIC ROCK IN SOUTHWESTERN MONTANA

Item	Ti ppm		Mg ppm		Fe ppm		Al ppm	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Nine samples of Boulder Batholith quartz	72	9	6	4	17	16	468	447
Six samples of Tobacco Root Batholith quartz	31	7	3	2	20	11	158	124
Ten samples of metamorphic quartz	30	15	19	17	112	82	298	283

quartz grain populations. Subtle variations in the density of quartz reflect variations in the kind and amount of submicroscopic to microscopic inclusions in the quartz. Density histograms of quartz populations may form the basis for additional statistical means of better defining mineralogic provinces and determining the origin of detrital quartz.

SUMMARY

The current status of studies of the detrital mineralogy of sand and sandstone is perhaps most succinctly summarized by a quote sometimes attributed to P. D. Krynine, "The problem appears to be hopelessly complex, but given a will and a proper approach it does not need to be so."

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