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Figs. 1–2, June, 1970

INTERPRETING DETRITAL MODES OF GRAYWACKE AND ARKOSE[1]

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ABSTRACT

The determination of detrital modes in graywackes and arkoses, here grouped as subquartzose sandstones, requires special attention to the identification of detrital grain types, as defined operationally, and to the recognition of detrital textures, as opposed to textural elements of diagenetic origin. Accurate detrital modes can yield specific information on provenance that can be gained in no other way. Reserving the terms graywacke and arkose for imprecise field descriptions and abandoning the proportion of matrix as a prime means of classification, subquartzose sandstones can be described adequately using six numerical grain parameters. Three primary parameters summing to 100 permit quantitative serial designation of rock types in the form $Q_xF_yL_z$, where Q is total quartzose grains, F is total feldspar grains, and L is total unstable lithic fragments in the framework. Three secondary parameters in the form of ratios permit desirable refinement within each primary parameter: C/Q where C is total polycrystalline quartzose grains, P/F where P is total plagioclase grains, and V/L where V is total volcanic lithic grains. Stable grains, whose sum is the parameter Q, are essentially pure silica in mineralogy, and include both monocrystalline quartz and polycrystalline lithic fragments. The latter are gradational to less quartzose types and difficult to distinguish from felsite grains, which display relict textures of volcanic origin and internal relief owing to their polymineralic nature. Lithic fragments are subdivided at two levels into four main categories within which are various subcategories: (a) volcanic fragments include felsitic, microlitic, lathwork, and vitric types; (b) clastic fragments include silty-sandy and argillaceous types; (c) tectonite fragments include metasedimentary quartzose types and metavolcanic feldspathic or ferromagnesian types; and (d) microgranular fragments include hypabyssal, hornfelsic, and indurated sedimentary types. Interstitial materials include (a) exotic cements like calcite or zeolite; (b) homogeneous, monomineralic phyllosilicate cement displaying textures indicative of pore-filling; (c) clayey detrital lutum called protomatrix; (d) recrystallized lutum or protomatrix called orthomatrix with relict detrital texture; (e) murky, polymineralic, diagenetic pore-filling called epimatrix, whose growth is accompanied by alteration of framework grains; and (f) deformed and recrystallized lithic fragments called pseudomatrix. Extensive albitization and other alterations complicate the interpretation of detrital modes in many rocks, but potential errors commonly can be avoided by close attention to mineralogy and relict texture except where tectonite fabrics disrupt or transpose the original detrital framework. Most subquartzose sandstones were derived from one, or a mixture, of three salient provenance types: (a) volcanic terranes, yielding feldspatholithic rocks nearly free of quartz, (b) plutonic terranes, yielding feldspathic rocks with few lithic fragments, and (c) uplifted sedimentary and metasedimentary "tectonic" terranes, yielding "chert-grain" lithic rocks with few quartz and feldspar grains except where recycled volcanic or plutonic detritus is abundant. Many voluminous accumulations of subquartzose sandstones near continental margins had as their provenance complex volcano-plutonic orogens representing ancient magmatic arcs analogous to modern arcs associated with trenches.

INTRODUCTION

The purpose of this paper is to focus attention on aspects of graywacke and arkose petrography that have received inadequate treatment in most textbooks. Without a firm interpretive base from which to advance, many workers have failed to take full advantage of opportunities for petrographic examination of these rocks. Petrographic criteria applied to the study of the more quartzose sandstones and carbonate rocks, which continue to hold the primary attention of many sedimentary petrologists, have reached a level of sophistication beyond that which many workers bring to the study of graywacke and arkose. Yet adequate descriptions of the varied less quartzose sandstones of the orogenic belts demand a comparably rigorous approach. Detailed interpretations of original detrital modes in orogenic graywackes and arkoses can yield insights into geologic history that can be gained in no other way. On the other hand, interpretations that are too superficial or generalized no longer have the potential to stimulate fresh thinking. In many cases, the inherent problems of sedimentary petrography are complicated by overprints of incipient metamorphism.

There are three facets of graywacke and arkose petrography that particularly require fuller analysis than has usually been accorded them:

(1) *Identification of detrital grains:* particularly with respect to fine-grained lithic fragments, published identifications are commonly over-generalized, non-reproducible, or both; in this paper, an attempt is made to outline a hierarchy of nested categories of grains which can

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be distinguished directly in descriptive fashion, yet have appropriate genetic connotations.

(2) *Recognition of detrital textures:* particularly with respect to fine-grained interstitial material, many published descriptions are either too facile or unconvincing; in this paper, an attempt is made to establish some guides to interpretation that may help clarify communication of observations made by different workers.

(3) *Interpretations of provenance:* particularly where source rock terranes have undergone rapid erosion, detritus in graywacke and arkose can provide surprisingly complete information about provenance, and this information is unique in common cases where source rocks are now buried beneath younger strata or were literally destroyed to feed sedimentary sequences; in this paper, an attempt is made to classify broad provenance types as an aid to paleotectonic reconstructions.

The guidelines suggested here stem mainly from experience with rocks in western North America and the southwest Pacific region, especially in California, Oregon, New Zealand, and Fiji.

NOMENCLATURE OF SUBQUARTZOSE SANDSTONES

Despite the publication of several dozen schemes of sandstone nomenclature during the past two decades, the basic classification of these siliciclastic rocks has not been stabilized. The choice of alternative names is especially wide for fragmental rocks composed in large part of unstable silicate sand grains. These are the various kinds of graywackes and arkoses defined in slightly different ways by different workers. With reference to most classifications in current use, we can consider these rocks together as a group of *subquartzose* sandstones in which less than 75 percent of the detrital grains are quartzose, a term we shall have to define strictly in a later section. Even though the nomenclature remains unsettled in detail, most schemes approach consensus on two points of principle:

(1) Aspects of mineralogy must be kept separate from aspects of texture (e.g., Folk, 1954). This dual approach recognizes that detritus is modified in the surficial environment by two distinct trends of change:

(a) chemical processes of oxidation, hydrolysis, and solution tend to destroy constituents that are unstable in hydrous systems at low temperature;

(b) physical processes sort detritus by grain size, disintegrate weakly coherent materials, and round detrital particles of sand and gravel.

By the action of these two kinds of surficial processes, detritus can approach in parallel, but in general at different rates, two different end states:

(a) a grain assemblage that is resistant to further chemical change,

(b) a grain aggregate that is well sorted and rounded.

The extent to which each approach is realized by the detritus of a given sandstone forms the basis for the twin criteria of compositional *stability* and textural *maturity*, respectively (Dott, 1964, p. 627).

(2) A practical nomenclature must be simple enough to depict with triangular volumetric coordinates for composition; textural variance can then be handled by multiple diagrams or auxiliary terminology. The three poles are not identical in all schemes (e.g., Klein, 1963, p. 568), but the following three are most commonly used (McBride, 1963):

(a) the pole Q, meant to represent greatest stability, is the sum of quartz and chalcedony grains of all kinds;

(b) the pole F is feldspar grains, most abundant of the unstable single-crystal grains;

(c) the pole L (or R) is the sum of all unstable polycrystalline grains (lithic or rock fragments), which are the aphanite grains less chert and quartzite.

By these conventions, calcarenites, unusual rocks like greensand, and minor constituents, including heavy minerals, are ignored. Rodgers (1950) noted the potential for quantitative serial designation in the simplified scheme. For example, a sandstone whose detrital framework (Nanz, 1954,, p. 108) is equal amounts of quartzose grains (Q), feldspar grains (F), and lithic fragments (L) can be represented as $Q_{33}F_{33}L_{33}$.

USAGE OF "GRAYWACKE" AND "ARKOSE"

Much of the present confusion in sandstone nomenclature stems from failure to agree on the meaning of the terms *graywacke* and *arkose* (e.g., Huckenholz, 1963, p. 182).

Graywacke was defined by Jameson in 1808 as a kind of sandstone composed of grains of sand of various sizes bound together by a clay paste (Bailey, 1930). The presence of interstitial fine clayey material in immature rocks imparts a dark color to them, and prevents the resolution of grain boundaries with a hand lens in the field. In common field usage, graywacke is thus an imprecise term for dark gray or green, firmly indurated sandy rocks with obscure grain boundaries but without much calcareous cement.

Unfortunately, sandstones rich in aphanitic rock fragments may look similar even if well sorted. These circumstances have led to two definitions of graywacke. The majority usage (*"textural graywacke"*) is for any unstable, immature sandstone containing an interstitial matrix, mainly microcrystalline phyllosilicates, in excess of some stated volumetric proportion. The minority usage (*"compositional graywacke"*) is for unstable sandstone, whether immature or not, in which unstable lithic fragments are more abundant than feldspar grains. Many "compositional graywackes" are not "textural graywackes," and vice versa.

Arkose was defined by Brongniart in 1823 as being "composed of . . . quartz and of feldspar, mixed together unequally and including as fortuitous constituents mica, clay, etc." (Oriel, 1949). In common field usage, arkose is still an imprecise term for quartz-feldspar(-mica) sandstone of gray, green, or red color. In this sense, most geologists agree with Harker (1895, p. 193) that "arkose is . . . derived from . . . granite or gneiss. . . ." Among unstable sandstones, those rich in quartz and feldspar mineral grains point to a *plutonic* source, whether igneous or metamorphic, and those rich in lithic fragments including chert point to a *supracrustal* source, whether metamorphic or volcanic (Pettijohn, 1957, p. 286). Quartzo-feldspathic arkoses may be "textural graywackes," but cannot be "compositional graywackes."

To make the term arkose reflect all igneous sources including volcanic ones, some geologists (e.g., Folk, 1954; Hubert, 1960) put feldspar grains plus igneous rock fragments together at the F pole, thus leaving a restricted assemblage of rock fragments at the L pole. As defined in this way, arkoses can be "compositional graywackes" as well as "textural graywackes" in the terms of this discussion.

In view of the many contradictions in usage, it seems wise to me to abandon any precise petrographic definition of the terms graywacke and arkose, reserving them instead for imprecise field descriptions in their respective original senses given above. In practice, this kind of loose usage has survived all attempts to control it by rigorous application of petrographic criteria. Where specific detrital modes are known, or closely estimated, I find it equally convenient and less misleading to supply simple percentage subscripts for Q, F, and L, together with auxiliary indices introduced later in the discussion. Where general reference is made to subquartzose sandstones ($Q < 75$), the adjectives introduced by Crook (1960) permit adequate discrimination without confusion: feldspathic ($F/L > 3$), lithofeldspathic ($3 > F/L > 1$), feldspatholithic ($3 > L/F > 1$), and lithic ($L/F > 3$).

For clarity, it is well to point out that the subquartzose sandstones, containing less than 75 percent quartzose grains, include all the *unstable* types of most classifications. *Semistable* types, for which names such as subarkose, subgraywacke, protoquartzite, etc. have been introduced, include rocks containing 75 to 90 or 95 percent quartzose grains in many classifications. My own experience with such rocks has been slight, and I have never dealt in detail with problems of the *stable* quartz sandstones or orthoquartzites.

IMPLICATIONS OF THE MATRIX PROBLEM

The use of a stated proportion of matrix, dominantly phyllosilicates, interstitial to the framework grains as a primary means of dividing sandstones into two great classes has proved less successful than its original proponents had hoped. The concept was based upon the prior assumption that such matrix represents the fine-grained extremity of the detrital grain population, or its recrystallization products (e.g., Gilbert *in* Williams and others, 1955, p. 297). As such, the proportion of matrix is regarded as an index to the degree of sorting of the rock as a whole. The critical proportion of matrix to be used to separate moderately well sorted sandstones from poorly sorted ones is commonly taken as 10 percent, or even 15 percent, although I have found that a lower figure of 5 percent makes for a more useful split among sandstones I have examined. Even so, there are three outstanding obstacles to the diagnostic use of matrix in this fashion.

First, it is clear that a given percentage of fine silt and clay in a very fine-grained sandstone has different implications for sorting than the same percentage in a very coarse-grained sandstone. This is entirely a procedural problem, and can be circumvented by suitable calculations, but cannot be ignored.

Second, a serious practical difficulty arises in defining the upper visual limit of matrix in terms of grain size. Counting modes at different magnifications can operate to augment or reduce the amount of matrix perceived and reported, as an artifact of the specific technique adopted. To avoid this ambiguity, Dott (1964, p. 630–631) has suggested the arbitrary convention that the maximum visible grain diameter of matrix be fixed as the thickness of a standard thin section; namely, 0.03 mm. in diameter. This procedure automatically forces counting at the highest convenient power, hence as a bonus induces more accurate grain determination within the framework as well.

Third, Cummins (1962) compromised the utility of the matrix concept itself by successfully challenging the premise that all or most matrix is detrital, or is derived from ancestral detrital lutum. He showed that much matrix is probably a diagenetic textural element that comes to fill interstices only with the alteration of unstable framework grains. Where micas, feldspars, ferromagnesian minerals, or volcanic rock fragments have undergone extensive alteration, any assumption that all or most of the interstitial silicates were originally present in the interstices at the time of deposition is surely weak. Nor can one assume, on the other hand, that none were, for Kuenen (1966) has recently shown that lutum transported with sand grains can be expected to form a detrital matrix of modest proportions, generally less than 5 percent.

There are observational grounds, discussed below, for accepting the Cummins analysis of the meaning of what has been called matrix in many sandstones. Moreover, Hawkins and Whetten (1969) have lent some experimental support to his inferences. Consequently, the matrix problem, and all its implications for the rocks classified as "textural graywackes," is added cause to ignore the rigorous distinctions of the recent past in the usage of "graywacke" and "arkose."

PRIMARY AND SECONDARY GRAIN PARAMETERS

The ambiguity of the matrix problem cannot be fully resolved, hence the presence of interstitial phyllosilicates cannot be attributed with confidence to either detrital or diagenetic processes in every case. This uncertainty forces reliance on the surviving framework constituents as the primary petrographic means of classifying subquartzose sandstones. Conflicts in past nomenclature, and the advantages of quantitative serial designations, lead me to suggest a skeletal classification based on three primary proportional parameters, expressed as recalculated percentages summing to 100, and three secondary ratio parameters to qualify the primary three (Dickinson, 1969). Accurate determinations of the six parameters require rigorous modal point counts (Chayes, 1956), or comparable volumetric compositional data. However, approximate applications are at least as feasible as with any of the more complicated schemes of classification in the literature.

The three primary parameters (see Table 1) are the same in principle as the most commonly selected apices of triangular compositional diagrams for the classification of sandstones; namely, Q, F, and L (or R). They are defined in detail as follows, where Q, F, and L are recalculated to 100 percent ($Q + F + L = 100$) regardless of matrix, cement, heavy minerals, and exotic constituents (glauconite, fossils, etc.):

(1) *Parameter Q* is the total of (a) monocrystalline quartz grains, (b) polycrystalline quartz or chalcedony fragments, (c) cryptocrystalline opaline fragments, (d) quartz within microphanerite lithic fragments, and (e) microphenocrystic quartz within aphanite lithic fragments; the last two categories are included because these crystals would be counted as quartz grains within the sand fraction, and not as lutum or matrix, if the lithic fragments had disintegrated during dispersal; the first two categories are the most common in most graywackes and arkoses.

(2) *Parameter F* is the total of (a) monocrystalline feldspar grains, (b) feldspar within microphanerite lithic fragments, and (c) microphenocrystic feldspar within aphanite lithic fragments; the last two categories are included for the same reasons as the analogous two of the previous parameter; the first category is the most common in most graywackes and arkoses.

(3) *Parameter L* is the total of polycrystalline aphanite lithic fragments, less (a) microphenocrysts and (b) quartzose, chalcedonic, or opaline aphanite lithic fragments; the subtractions are required by the conventions adopted above to calculate parameters Q and F.

TABLE 1.—*Primary detrital grain parameters*

(Q, F, L where $Q+F+L=100$)
(1) Q is *sum* of:
(a) monocrystalline quartz grains
(b) polycrystalline quartz or chalcedony fragments
(c) cryptocrystalline opaline fragments
*(d) quartz within microphanerite lithic fragments
*(e) microphenocrystic quartz within aphanite lithic fragments
(2) F is *sum* of:
(a) monocrystalline feldspar grains
*(b) feldspar within microphanerite lithic fragments
*(c) microphenocrystic feldspar within aphanite lithic fragments
(3) L is aphanite rock fragments *less:*
(a) quartzose, chalcedonic, and opaline aphanite fragments
*(b) microphenocrysts

* Note: possibly controversial, hence optional, reapportionment of counted points; only sand-sized crystals in these categories are to be reapportioned.

TABLE 2.—*Secondary detrital grain parameters*

(C/Q, P/F, V/L where each is ≤ 1.0)		
(1) C/Q = ratio of:	(a)	polycrystalline-cryptocrystalline quartz-chalcedony-opal lithic fragments (C)
to:	(b)	total quartzose-chalcedonic-opaline grains (Q)
(2) P/F = ratio of:	(a)	plagioclase points (P)
to:	(b)	total feldspar points (F)
(3) V/L = ratio of:	(a)	volcanic rock fragments (V), with igneous aphanite textures
to:	(b)	total unstable aphanite rock fragments (L)

For the primary parameters, the procedure of recalculating points counted within microphanerite fragments and microphenocrysts of aphanite fragments out of parameter L, and into parameters Q and F, may prove controversial. If so, the procedure can be modified without any fundamental change in the design of the present classification. I have adopted the procedure to insure that parameter L represents aphanitic detritus only. The minimum size of quartz and feldspar microphenocrysts within aphanite lithic fragments and crystals within microphanerite lithic fragments to be recalculated with Q or F is taken to be the lower limit of the sand range, or 0.0625 mm. in visible diameter.

For each primary parameter, there is a secondary parameter (see Table 2) designed to identify the most significant variables hidden within the primary parameter by the conventions proposed above:

(1) *Parameter C/Q* is the ratio of (a) polycrystalline and cryptocrystalline quartz-chalcedony-opal lithic fragments, here grouped together as parameter C, to (b) total quartzose-chalcedonic-opaline grains, defined above as parameter Q. The parameter C/Q reveals how far a plotted point in the QFL triangle would move parallel to the Q-L side if the stable lithic fragments (C) were counted with the unstable lithic fragments (L) to emphasize supracrustal source rather than stability, the factor that paramater Q is designed to reveal. Where most stable grains are monocrystalline quartz, as is common, then the parameter C/Q is consistently low.

(2) *Parameter P/F* is the ratio of plagioclase (P) points to total feldspar (F) points, hence is some reflection of the relative proportions of plagioclase (soda-lime) and alkali (soda-potash) feldspars in the source rocks.

(3) *Parameter V/L* is the ratio of volcanic lithic fragments (V), with igneous aphanite textures, to total unstable aphanite lithic fragments (L), which also include clastic rocks, tectonites, hornfelses, etc. The parameter V/L reveals how far a plotted point in the QFL triangle would move parallel to the F-L side if the volcanic lithic fragments (V) were counted with the feldspars (F) to emphasize inferred igneous sources, rather than with other lithic fragments to contrast monocrystalline grains (F) from unstable phanerites with polycrystalline grains (L) from unstable aphanites.

An objection may be raised to the exclusion of heavy minerals, especially micas, from the skeletal classification. There is no doubt that they are significant constituents in many rocks. However, their distribution in detail is closely controlled by hydraulic properties related to their density and shape. To include them with the population of roughly equant light grains, with densities generally in the range 2.5–2.75, would introduce such extraneous influences on the basic modal variations that clarity is best served by their omission from the six parameters. This example illustrates well the fact that no simple list of parameters can encompass all pertinent modal variables. Each individual suite of subquartzose sandstones encountered may have special attributes that can only be handled by special classifiers that are inappropriate within an overall outline such as this one.

Indeed, to carry the grounds for classification as far as has been done in the scheme presented raises a number of problems of grain identification. These are discussed systematically below, together with means to resolve salient difficulties.

STABLE GRAIN TYPES

The dominant stable grains (Q) in many graywackes and arkoses are monocrystalline quartz grains of common plutonic type (Folk, 1968, p. 67–77) with trains of vacuoles and slightly undulose extinction. Clear, unstrained volcanic quartz with bipyramidal habit, resorbed margins, or bleb inclusions (originally glassy) can be identified in some rocks, and is the dominant quartz type in quartz-poor volcanic sandstones. Composite vein quartz or multi-crystalline metamorphic quartz may occur in some rocks, but there are probably no infallible criteria to distinguish between monocrystalline quartz sand grains of igneous and metamorphic origins. Paradoxically, the large, interstitial quartz crystals of igneous phanerites are commonly more strained than the small, annealed quartz crystals of most metamorphic rocks. Polycrystalline chalcedony and quartz lithic fragments are mainly chert and metachert in most rocks, although other varieties of quartzite occur in lesser abundance.

A clear distinction between stable quartz-chalcedony aphanite fragments (C) and unstable aphanite fragments (L) is impossible to make in principle, but can be made with difficulty by convention. Gradations exist between the following types of detrital aphanite grains: (a) argillite and chert, (b) metatuff and metachert, (c) micaceous phyllite and metaquartzite, (d) silicified volcanic rock (secondary chert) and felsite, and (e) microgranular clastic rock and orthoquartzite. In counting modes, the only workable distinction is between essentially pure quartz-chalcedony grains and all other kinds in the various gradational spectra. For example, chert or quartzite may be tinted by cryptocrystalline impurities, but murky or birefringent optical effects of clays or micas should rule a grain out of the stable class.

The distinction between chert and felsite or felsitic tuff is an important one, but must not be taken lightly, for close attention to detail is required for consistently correct identifications. Under crossed nicols, both types of grains can present to the viewer a micro-mosaic of anhedral crystals with consistently low birefringence. In chert, all the crystals are quartz or chalcedony, but many are feldspars in felsitic rocks of volcanic origin. Felsite sand grains can be recognized by the following criteria, in order of increasing difficulty:

(1) under crossed nicols, the presence of subhedral to euhedral microphenocrysts of feldspar or other minerals set in the anhedral mosaic;

(2) also under crossed nicols, the presence of crude feldspar laths (mainly plagioclase) or blocks (mainly orthose) in the anhedral mosaic;

(3) in plain light, the presence of faint curvilinear outlines of relict glass shards;

(4) also in plain light, internal relief, within the grain, between quartz and feldspar having a difference in refringence in excess of the slight difference between the ordinary and extraordinary refractive indices of quartz;

(5) finally, a yellow or red stain where the thin section has been fumed in hydrofluoric acid and treated to stain for feldspars as discussed below.

Contrasting features diagnostic of chert include ovoid or reticulate relicts of radiolarians, diatoms or spicules visible in plain light, and networks of planar, criss-crossing veinlets visible under crossed nicols.

FELDSPAR GRAIN TYPES

Most petrographers are familiar with the various means for distinguishing optically between plagioclase (soda-lime) and orthose or alkali (soda-potash) feldspars. Individual grains can be placed in one group or the other by the practiced eye with few errors. Identifications of this kind can be reduced to rote by fuming with hydrofluoric acid and staining (Laniz and others, 1964). To separate individual detrital grains within each broad group into separate categories requires the use of refractive index oils or the universal stage, and is beyond the scope of most routine modal analyses. An exception is the case where subdivisions of grains are based on degree of alteration. In some cases, also, volcanic feldspar can be distinguished from plutonic feldspar by the presence of once glassy bleb inclusions.

In general, the difficulty of distinguishing different varieties of plagioclase and orthose in sandstone thin sections can hardly be over-emphasized. The only relatively easy identification is albite, which can be distinguished readily from other plagioclase because its refractive indices are below the usual mounting media. The other plagioclases are a thorny problem, particularly because the optical properties at a given composition vary with the degree of ordering, as between plagioclase of volcanic and plutonic origin. Among the alkali feldspars, sanidine can be spotted in favorable instances by its limpid clarity and low optic axial angle, but caution must be used to avoid confusion with varieties of orthoclase. Polysynthetic twinning is characteristic of much microcline, but is not present in all crystals. Rather than simplifying feldspar identification, mineralogical research of the past ten years has shown the inherent complexity of the subject. Sedimentary petrographers should beware spurious inferences.

LITHIC GRAIN TYPES

The recognition of different categories of lithic grains, which are fragments of aphanitic rocks, must be based on specific operational criteria, else data will not be reproducible. The operational criteria must be mainly textural, for mineral identifications of tiny crystals within sand grains are dubious unless tedious observations are undertaken repeatedly. A first-level split into four categories is satisfactory in most instances (carbonate rock fragments are a fifth):

(1) *Volcanic* rock fragments have the tex-

tures of igneous aphanites, and include altered or recrystallized volcanic rock fragments where relict textures are preserved;

(2) *clastic* rock fragments have fragmental textures;

(3) *tectonite* rock fragments have schistose or semischistose fabrics;

(4) *microgranular* rock fragments, whose identity is the most difficult to specify, are made of roughly equant, well-sized grains.

These textural groupings do not depend on degree of alteration; in many subquartzose sandstones, it is nearly impossible to judge whether a given alteration occurred in the source or after deposition. Each of the four categories of lithic grains includes several discrete types whose recognition requires a second-level split (see Table 3).

TABLE 3.—*Lithic grain types (exclusive of chert, and polycrystalline quartz)*

(1) Volcanic
- (a) felsitic
- (b) microlitic
- (c) lathwork
- (d) vitric

(2) Clastic
- (a) silty-sandy
- (b) argillaceous
- (c) volcaniclastic (?)

(3) Tectonite
- (a) metasedimentary
- (b) metavolcanic

(4) Microgranular
- (a) hypabyssal—group with (1)?
- (b) sedimentary—group with (2)?
- (c) hornfelsic—group with (3)?

(5) Microphanerite (count each internal crystal, each of sand size)

Volcanic rock fragments can be divided conveniently into four main types, of which the first two are most important:

(a) *Felsitic* grains are an anhedral, microcrystalline mosaic, either granular or seriate, composed mainly of quartz and feldspar, and represent mainly silicic volcanic rocks, either lavas or tuffs.

(b) *Microlitic* grains contain subhedral to euhedral feldspar plates and prisms in pilotaxitic, felted, trachytic, or hyalopilitic patterns of microlites, and represent mainly intermediate types of lava.

(c) *Lathwork* grains contain plagioclase laths in intergranular and intersertal textures representing mainly basaltic lavas.

(d) *Vitric* to vitrophyric grains and shards are glass or altered glass, which may be phyllosilicates, zeolites, feldspars, silica minerals, or combinations of these in microcrystalline aggregates.

Clastic rock fragments can be somewhat arbitrarily divided into *silty-sandy* types lacking clay except interstitially, and *argillaceous* types in which clay is dominant or prominent. The argillaceous grains include shale with mass extinction from which slaty tectonites may not be distinguishable in every case. More massive mudstone and argillite grains are more common in most rocks. The presence of a large proportion of *volcaniclastic* rock fragments can be a potent source of ambiguity. Provided they can be distinguished from non-volcanic silty-sandy and argillaceous types, it may serve some purposes to group them with volcanic rock fragments.

Tectonite rock fragments can be split into two broad classes. *Metasedimentary* types are characterized by quartz and mica. *Metavolcanic* types contain abundant feldspar or, more diagnostic, assemblages including chlorite and amphibole.

Microgranular rock fragments include three main types that can be distinguished only with difficulty as sand grains, even though they are quite different kinds of rocks:

(a) *Hypabyssal* types are hypidiomorphic igneous rocks commonly low in quartz and rich in feldspar; where they can be recognized, they can be summed with volcanic rock fragments, to which they have a close genetic affinity.

(b) *Hornfelsic* types contain a metamorphic mineralogy, commonly including abundant quartz, and can be summed with the tectonites as metamorphic rocks where they can be identified with confidence.

(c) *Sedimentary* types include pressolved and indurated aggregates whose originally clastic textures have been modified by diagenesis or metamorphism, but they can be summed with clastic rocks where their true nature can be discerned.

Any attempt at classification has its effective limits, and the microgranular rock fragments stand at one limit. Where distinctions among them cannot be made with confidence, they become a left-over category of indeterminate significance. As their crystalline aggregates coarsen until each internal crystal has a visible diameter within the sand range, I prefer to call them *microphanerite* rock fragments, and to apportion points counted within them according to the crystal beneath the cross-hair. So defined, microphanerite rock fragments will clearly be a minor constituent of any sandstone because of the inherent relations of grain size.

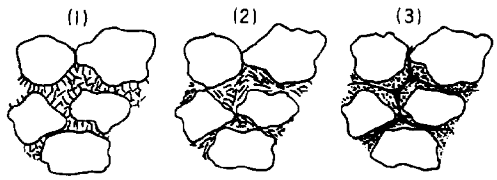

FIG. 1.—Criteria for recognition of phyllosilicate cement (see text; criteria a, clear transparency, and b, monomineralogy, not shown): (1) criterion c, radial crystal platelets; (2) criterion d, concentric color zonation; (3) criteria e, medial sutures.

TYPES OF INTERSTITIAL CONSTITUENTS

The interstitial constituents of graywackes and arkoses can be grouped into six categories, although ambiguous interpretations cannot be avoided in all cases:

(1) *Cement* of calcite, chalcedony, zeolite, or other minerals uncommon in the framework can be recognized with comparative ease.

(2) *Phyllosilicate cement* is commonly confused with matrix, but a number of criteria, observable singly or in combination, serve to distinguish inhomogeneous matrix from clear-cut phyllosilicate cement whose growth pattern in open pores is reflected by its crystalline habit. Reliable textural indicators of interstitial phyllosilicate cement include the following (e.g., Carrigy and Mellon, 1964 and figure 1):

(a) clear transparency indicating absence of minute detritus or murky impurities,

(b) monomineralogy indicating restricted composition,

(c) radial arrangement of crystal platelets indicating growth inward from surrounding framework grains toward the centers of interstitial voids,

(d) concentric color zonation indicating successive compositional changes in minerals grown in voids from interstitial fluids as coatings built on framework grains,

(e) medial sutures within the interstitial phyllosilicates indicating the lines of juncture of pore-filling crystals growing inward from surrounding framework grains.

(3) *Protomatrix* is a term introduced here for unrecrystallized clayey lutum in weakly consolidated rocks, and is as much an idealization as a description in my personal experience.

(4) *Orthomatrix* is a term introduced here for recrystallized detrital lutum or protomatrix. Definitive recognition of orthomatrix requires the perception of a relict clastic texture within it, and an appropriate inhomogeneity of its composition contrasting, for example, with the homogeneity of phyllosilicate cement. Where orthomatrix is abundant, the framework is visibly poorly sorted and grades imperceptibly into the surrounding detrital paste, not only by intergrowth at grain margins, but by size as well.

(5) *Epimatrix* is a term introduced here for inhomogeneous interstitial materials grown in originally open interstices during diagenesis, but lacking the homogeneity and clear textural evidence of pore-filling needed to classify interstitial paste as phyllosilicate cement. Confusion with orthomatrix is a constant problem. Where the framework is well sorted, and the matrix lacks evidence of relict clastic texture, the presence of pore-filling epimatrix must be suspected even though the interstitial paste is murky and polymínerallic. Especially in rocks where diagenetic alteration of the framework grains is well advanced, these circumstances point to epimatrix as a more plausible interpretation than orthomatrix.

(6) *Pseudomatrix* is a term introduced here for a discontinuous interstitial paste formed by the deformation of weak detrital grains (e.g., Dickinson and Vigrass, 1965, p. 18). In many subquartzose sandstones, grain shapes have been modified extensively by compaction and pressolution. Quartz and feldspar grains are not commonly distorted, but are locally fractured (e.g., Maxwell, 1960). Mica flakes are commonly bent and wrinkled, to display a characteristic crimped appearance megascopically. Less competent lithic fragments, argillaceous and microlitic grains as examples, are commonly mashed and squeezed between more competent grains, chert grains and mineral crystals as examples. By pseudoplastic flow, the weak grains in extreme cases conform to the outlines of the stronger grains, and assume irregular, attenuated shapes occupying volumes interstitial to the rigid grains. Failure to correctly interpret the resulting texture leads to gross overestimates of matrix abundance and severe bias in the observed proportions of framework grains. Alteration of the deformed lithic grains adds to the potential for deception, but observers must take care not to disregard any pseudomatrix present, for it was part of the detrital framework. There are several reliable criteria for the recognition of pseudomatrix (see figure 2):

(a) Flame-like wisps of crushed lithic fragments extend into narrowing orifices between undeformed rigid grains.

(b) The pseudofluidal internal fabric of lithic fragments deformed by pseudoplastic flow commonly conforms to the margins of confining rigid grains as concentric drape lines.

(c) Large "matrix"-filled "gaps" in the framework suggest pseudomatrix, and the suggestion is strengthened where each "gap"-filling is semi-homogeneous but texturally distinct from other "gaps."

Close observation of suspected pseudomatrix will be rewarded by the recognition of discernible relict lithic fragment textures and fabrics unless metamorphism has obliterated part of the detrital framework.

COMMON ALTERATION TEXTURES

Extensive albitization and other recrystallizations have affected many graywackes and arkoses that appear unmetamorphosed on the outcrop. Where the aim is to assess the detrital modes of the rocks, a petrographer must peer through this screen of alteration, as it were, to perceive the original nature of the detritus. The composition of original detrital frameworks can commonly still be determined routinely within useful limits despite wholesale recrystallization so long as a tectonite fabric has not destroyed the original grain outlines. Original grain boundaries may be obscured to varying degrees, however, by intergrowth with interstitial constituents. Where alteration products adopt unusually cloudy habits, the task of interpreting detrital modes may be too time-consuming to adequately reward the painstaking effort required. In any case, sedimentary petrographers should note that counting volumetric proportions of alteration products is not a means of establishing directly the detrital mode of a rock. Routine interpretations of the original nature of framework grains must underlie a point count, else the work becomes an exercise in metamorphic petrology, rather than sedimentary petrology.

The habits of the alteration minerals in sandstones fall into three categories (Crook, 1963):

(a) newgrowths (cement), which fill pores interstitial to the framework;

(b) replacements, which may be pseudomorphs of whole detrital grains, or irregular patches including several remnants of detrital grains, or scattered inclusions within detrital grains;

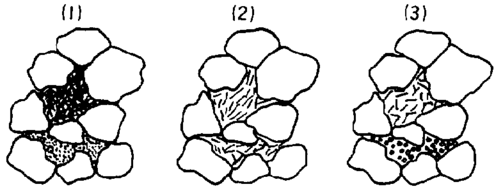

FIG. 2.—Criteria for recognition of pseudomatrix (see text): (1) criterion a, wisps extended between rigid grains, (2) criterion b, concentric form of pseudofluidal internal fabric; (3) criterion c, gaps in framework with relict lithic fragment textures.

(c) veins, filling quasi-planar structures formed by disruption of the framework.

In assessing the effects of alteration on detrital texture and mineralogy, veins can be discounted as a clearly secondary feature. Cements are visibly distinct from the framework in most cases, although confusions between cement and matrix, as well as between deformed framework and matrix, are common. The varied replacement textures, discussed in the next section, are the features that must be interpreted plainly if a detrital mode is to be determined successfully for a graywacke or arkose in which recrystallization is widespread.

The progressive development of tectonite fabrics in subquartzose sandstones in the eastern axial facies (Dickinson, 1968) of New Zealand was studied in detail by Hutton and Turner (1936; Turner, 1938; Hutton, 1940), whose work has been extended by Reed (1958, p. 20–25) and others. Within the chlorite zone of greenschist facies metamorphism, these workers established three mappable subzones recognized on the basis of textural reconstitution:

(1) Rocks of subzone 1 are mineralogically reconstituted, but relict detrital textures are faithful, hence detrital modes based on routine interpretations can be determined with confidence.

(2) Rocks of subzone 2 are commonly semischist, although they may be massive in outcrop. All display semischistose fabrics in thin section. Newgrown minerals are aligned in linear or planar patterns but the disruption or transposition of the detrital framework is incomplete. Approximate detrital modes commonly can be inferred, but rigorous point counts founder on multiple uncertainties.

(3) Rocks of subzone 3 are fine-grained schists in which textural reconstitution is thorough and detrital modes can be inferred only by recalculation of chemical data.

Blake and others (1967, p. C3) have introduced a strictly analogous textural terminology for rocks of the blueschist facies in the Franciscan assemblage of California. Their textural zones 1, 2, and 3 correspond morphologically to the subzones 1, 2, and 3 in New Zealand except that cataclasis is possibly more evident in the California rocks. Penetrative recrystallization may have played a larger role in the fabric transposition within the New Zealand rocks. Nevertheless, the extension of the zonal terminology to incipient tectonites of varied mineralogy offers a means to systematize petrographic descriptions of metamorphosed graywackes and arkoses from scattered regions. Wider use of the approach would improve communication between those working in such terranes.

PROBLEMS OF ALTERATION MINERALOGY

Systematic analysis of diagenetic or metamorphic mineral assemblages in graywackes and arkoses was placed on a solid footing by the work of Coombs (1954), who first recognized the existence of heulandite-analcite and laumontite zones of the zeolite mineral facies in rocks of the western marginal facies (Dickinson, 1968) in New Zealand. Coombs (and others, 1959, p. 65–68) later also recognized a prehnite-pumpellyite zone intermediate between his initial two zones and the greenschist facies within the eastern axial facies (Dickinson, 1968) of New Zealand. In California, McKee (1962) reported within the Franciscan assemblage the existence of lawsonite and jadeite mineral zones of the blueschist facies in sandstones giving little indication of metamorphism in hand specimen. The petrogenesis of these and other low-grade metamorphic mineral assemblages is not fully understood in terms of stability relations within a petrogenetic P-T grid (e.g., Coombs, 1961), but their widespread occurrence in circum-Pacific graywackes and arkoses is well-documented. Probably few thick sequences of graywacke and arkose containing reactive assemblages of detrital minerals have escaped wholly from mineralogical alterations that can be regarded as incipient metamorphism, whether or not severe textural changes accompanied the recrystallization.

The most common replacements encountered are those of plagioclase, ferromagnesian minerals, and volcanic rock fragments. Volcanic rock fragments alter to microcrystalline mineral assemblages in harmony with those replacing accompanying ferromagnesian and plagioclase grains, hence need not be discussed separately. Relict textures are commonly preserved in lithic fragments of all kinds, so that alteration is not a major obstacle to identification, provided the devitrification of glass to microcrystalline aggregates is not overlooked. Ferromagnesian minerals commonly alter to chlorite or other green to brown phyllosilicates with low to moderate birefringence. In calcareous rocks, either calcite or aragonite may replace parts of any detrital grains. Where carbonate other than interstitial cement is abundant, point counts are unrewarding, for accurate assessments of detrital modes prove imposssible.

Altered plagioclase is most commonly replaced by optically continuous or checkered albite containing inclusions of one or more hydrous calcium aluminosilicates from which many of the mineral zones take their names. These include: (a) zeolites, notably heulandite and laumontite, of low refringence and birefringence; (b) prehnite, pumpellyite, and clinozoisite of moderate to high refringence and low to moderate birefringence; and (c) lawsonite and epidote of moderate to high refringence and birefringence. Some albite formed by alteration may be flecked with inclusions of calcite with extreme birefringence, or with flakes of platy sericite or pyrophyllite with moderate to high birefringence. In some rocks, plagioclase is altered to one or more zeolites without the presence of albite, and in others, to the pyroxene jadeite with or without accompanying lawsonite. The alteration to sheaves of jadeite with low, anomalous birefringence may thoroughly obscure the detrital texture, but the other replacements commonly do not.

Metasomatism associated with mineral replacements may be local, as between different textural components of the same rock, or may involve varying distances of transport by interstitial fluids (e.g., Dickinson, 1962a, p. 492–495). The growth of epimatrix composed of various phyllosilicates and calcium aluminosilicates is characteristic. Widespread intrastratal solution of detrital grains has not been demonstrated, but may complement metasomatism in some rocks. The possible removal of alkali feldspar has never been adequately tested, although sericite is widespread in some rocks, and not only as inclusions in alkali feldspar. Possibly of great significance is a study by Gluskoter (1964), who reported clear evidence for authigenic growth of orthoclase in graywackes of the Franciscan assemblage, and strong circumstantial evidence for intrastratal solution of orthoclase as well.

SALIENT PROVENANCE TYPES

Subquartzose sandstones, in contrast to more stable types, are commonly composed of first-cycle detritus that is subrounded at best and commonly is subangular. Graywackes and arkoses of the orogenic belts were typically derived from highland sources within the orogenic belts. The sources represent some one, or a mixture, of three main provenance types (see Table 4):

(a) volcanic, typically andesitic-dacitic volcanic chains.

(b) plutonic, typically granitic batholith belts.

(c) "tectonic," typically sedimentary and metasedimentary uplifts.

Subquartzose sandstones derived exclusively from volcanic provenances are typically feldspatholithic rocks ($3 > L/F > 1$). The parame-

TABLE 4.—*Typical values for grain parameters in subquartzose sandstones derived from volcanic, plutonic, and "tectonic" provenances within orogenic belts*

	Volcanic	Plutonic	"Tectonic"
Q	low, <25	high, 50±25	mod, 25–50
F	mod, 25–50	high, ~50	low, <25
L	high, 50–75	low, <25	mod, ~50
C/Q	low, near 0	low, near 0	high, 0.5+
P/F	high, 1.0–0.75(?)	variable	variable
V/L	high, near 1.0	variable	mod, ~0.5
Special	pyriboles	mica	"chert-grain"

ter Q (quartzose grains) is low (typically < 25) and the V/L ratio (volcanic lithic fragments to total unstable lithic fragments) is high, approaching unity. Vitric shards, representing juvenile ejecta, may be abundant or rare, but are commonly present. In most cases, the provenance is dominantly pyroclastic blankets, rather than lavas (e.g., Dickinson, 1962b). Andesitic provenances yield detritus with the following salient characteristics:

(a) Microlitic grains are the dominant volcanic rock fragments, with felsitic and lathwork grains subordinate.

(b) The P/F ratio (plagioclase to total feldspar) is high, approaching unity, because few alkali feldspar phenocrysts exist in the provenance.

(c) Quartz is absent, or nearly so, because quartz is occult in the groundmass of source rocks, even in those containing normative quartz.

Dacitic and rhyolitic provenances yield detritus with the following characteristics:

(a) Felsitic grains are equal or greater in abundance than microlitic grains.

(b) The P/F ratio ranges downward from 1.0 toward perhaps 0.75.

(c) The parameter Q (quartzose grains) ranges upward from zero toward 25, or even 50 where reworking is a strong factor in sedimentation.

Reworking in the absence of quartz can concentrate feldspar; andesitic volcanic sandstones commonly have compositions near $Q_0\ F_{30}\ L_{70}$, but hydraulic concentration of crystals gives rise to associated rocks with compositions near $Q_0\ F_{50}\ L_{50}$. In most volcanic sandstones, the ratio C/Q (polycrystalline quartzose to total quartzose grains) is commonly low, but can be grossly overestimated if felsite grains are mistaken for chert grains. In many volcanic sandstones, pyriboles are more abundant than quartz.

Subquartzose sandstones derived exclusively from plutonic provenances are typically feldspathic rocks (F/L > 3). The quartz and feldspar grains may be derived in part from coarse-grained schists and gneisses. The parameter Q (quartzose grains) is relatively high (> 25) and the C/Q ratio (polycrystalline quartzose to total quartzose grains) is low, approaching zero. The P/F ratio (plagioclase to total feldspar) is variable, depending upon the type of granitic source rocks and upon the degree of weathering in the provenance. The V/L ratio (volcanic lithic fragments to total unstable lithic fragments) is also variable, depending on the nature of the wall rocks in the provenance. The parameter L (total unstable lithic fragments) is less than 25, and commonly less than 10. The quartz content is most commonly near 50 percent, and the mica content is high, commonly 5 to 10 percent. The abundance of quartz and the low C/Q ratio underscores the fact that the amount of quartz grains within most unstable sandstone suites is controlled more by the proportion of phanerites among the source rocks than by the degree of weathering of the source rocks. Source rocks containing sand-sized or larger quartz crystals can contribute monocrystalline quartz grains to sediment, even when rapidly eroded. Source rocks whose only quartz is microcrystalline or occult cannot contribute monocrystalline quartz grains to sediment, even if weathering prior to erosion is deep.

Subquartzose sandstones derived exclusively from uplifted "tectonic" highlands of supracrustal strata are typically lithic rocks (L/F > 3) in which the C/Q ratio (polycrystalline quartzose to total quartzose grains) is high, ranging from 0.5 toward 1.0. The parameter Q (total quartzose grains) is commonly between 25 and 50. The parameter F (total feldspar grains) is low, less than 25 and commonly less than 10. The V/L ratio (volcanic lithic fragments to total unstable lithic fragments) is variable but commonly near 0.5 ± 0.25. The source rock are mainly chert and sedimentary or metasedimentary strata of argillite, slate, phyllite, etc. with variable amounts of intercalated volcanic and metavolcanic strata. In sandstones derived from such terranes, inherent problems of distinguishing between grains of chert and felsite, metachert and metatuff, chert and argillite, shale and slate, argillite and tuff, etc. become acute. In the field, "chert-grain sandstone" is an apt term for many of these rocks (Dickinson and Vigrass, 1965, p. 18). Clearly, the presence of recycled sand grains of originally volcanic or plutonic derivation can also be expected, and give rise to feldspatholithic rocks of various kinds. In some suites, detrital fragments of carbonate rocks are important constituents of sandstones.

The three provenance types are plainly idealizations, and mixtures from two or more must be expected, yet the ideals come close to realization in a surprising number of instances. The most significant form of mixed provenance indicators are mixed volcanic-plutonic sands derived from the erosional destruction of volcano-plutonic orogens or magnatic arcs and deposited in adjacent oceanic trenches and associated troughs (Ojakangas, 1968; Dickinson, 1970).

SUMMARY OF MAJOR POINTS

In this paper, I have tried to emphasize the following points of view useful for the study of graywackes and arkoses exposed in the orogenic belts:

(1) A practical nomenclature for unstable, subquartzose sandstones, the graywackes and arkoses of various kinds, can be achieved by the definition of six semiquantitative parameters that permit serial designation of rocks and numerical manipulation of modal data. The pigeonhole classifications of previous workers are unnecessary, and the terms "graywacke" and "arkose" are best retained as loosely defined field terms only.

(2) Categories of detrital grains must be recognized on strickly operational grounds if interpretation is not wholly to supplant description in the sedimentary petrography of graywackes and arkoses. A hierarchy of nested categories of grains, within which hierarchy the certainty of identification is less at each successively lower level, affords the best means for accurately communicating and comparing detrital modes.

(3) Attempts must be made in future work to distinguish on empirical grounds between several categories of interstitial materials of both detrital and diagenetic origins. Failure to report explicitly the texture and mineralogy of these materials greatly reduces the value of published descriptions.

(4) For many graywackes and arkoses, detrital modes can be perceived only by mentally reversing the production of alteration minerals and textures. This task can be pursued successfully in many cases of interest to sedimentary petrologists, but only if the need to do so is understood.

(5) Interpretations of provenance based on detailed modal point counts can be specific enough to exert a powerful influence on major paleotectonic reconstructions. This fact should assume added significance in the future as geologists come to assess in detail the motions of continental drift and seafloor spreading envisioned in the concept of plate tectonics. Where once adjacent provenances and basins are now apart, or once distant provenances and basins are now close together, detrital modes of sandstones from sedimentary sequences may afford the most direct means of testing different hypothetical movement plans.

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