PETROGRAPHIC METHODS OF DETERMINING THE SOURCE OF CLASTIC SEDIMENTS

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by

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1. INTRODUCTION

Petrographic methods as generally understood comprise the methods by which material collected in the field is investigated in the laboratory. Although for strictly petrological purposes it may be sufficient simply to effect the qualitative and quantitative examination of sediments, geologically speaking the investigation is incomplete without carrying the inquiry still further, viz. to a consideration of the source or sources of origin of the sediments and its bearing on the palaeogeography of the area at the time of deposition.

Commenting on the value and nature of such investigation Milner (1940 p. 490) says "The perusal of this more philosophical aspect of the science is not merely academic; indeed, one might almost say that without such inquiry all petrographic work must lose both in precision and value: it will certainly lack vitality.

"Tracing the source of constituent particles of a deposit is often by no means a straightforward matter, especially where the locale of a distributive province capable of furnishing the material is obscure or where, owing to widespread erosion, no direct evidence of such a province exists. The problems to be faced are, from their very nature, some of the most complex and absorbing that a geologist has to solve and each case must perforce be dealt with on its own merits."

2. PRINCIPLES INVOLVED

The basic principles underlying the technique of determining the source of clastic sediments by petrographic methods are essentially those fundamental to the science of geology.

These principles are practically all embodied in the modern conception of the geographical cycle, in its geological interpretation. Briefly stated, the cycle implies terrestial uplift of a peneplaned region; consequent reanimation of the forces of denudation; their slow operation in wearing down this newly formed land surface and the persistence of these forces until a new base-level is once more attained. The complete cycle is thus a geological episode and modern stratigraphy owes much to the recognition of these periodic recurrences. Expressed in another way, it is the alternation of geosynclinal and orogenic phases of earth-history.

Now this kind of cycle of geological events can, for our purpose, be broadly construed as a cycle of sedimentation. The newly uplifted land-mass, composed of igneous and/or sedimentary rocks, undergoes sub-aerial denudation and from the very first incident of destruction gives rise to a new sediment. With continued disintegration of the mother rocks there is built up a collateral deposit derived therefrom; so the process matures with the achievement of the base-level phase, assuming no interruptions of a diastrophic or similar disturbing character. Thereafter this newly formed and, by this time, consolidated sediment itself becomes involved in orogenic movements and, probably rent and deformed with igneous intrusions, rises to initiate the next cycle of sedimentation.

It is necessary to examine the component factors of the sedimentation cycle in further detail. First of all the newly uplifted land-mass; this, or the rocks of which it is composed, is essentially the provenance of the sediment formed by its denudation. The term provenance implies source of origin: but, in addition, it has been found convenient in petrographic work to introduce some qualifying definition which enables that source to be visualised as a geological entity. The term "Distributive Province" first introduced by A. Brammall, has been generally adopted and implies the environment embracing all rocks, igneous, metamorphic and sedimentary, contributing to the formation of contemporaneously accumulated sediment. It is essentially the rocks of the distributive province which, on weathering, yield up their minerals, the stable species to survive rigours of chemical reaction and mechanical transport, the unstable components to perish. The more diversified the rocks of the distributive province, the more variable the sediment formed from it.

In some cases the province may be entirely sedimentary; this implies that the sediment formed receives its constituents second-hand; in other words, it represents redeposition of a pre-existing sediment. By contrast, disintegration of igneous rocks furnishes primary sediments.

Conversely, accessory minerals of a sediment, sometimes individually, generally collectively, constitute a measure of its provenance, leading to a reconstruction of the nature of the distributive province even though all traces of this may long since have disappeared. This is because certain minerals or groups of paragenetic species are inferential of definite rock types. Thus the reciprocal relationship between provenance and sedimentary rock is a simple and fundamental relationship complicated only by the varying stability of the minerals involved.

3. HISTORY OF INVESTIGATION

Prior to 1890 attempts were made to obtain some ideas regarding the possible source or sources of a particular mineral assemblage and of the direction of transport. But all such deductions were tentative and vague.

The decade 1890-1900, however, saw the production of the papers by Artini, Cayeaux, Hume, Mackie and Retgers, which, like milestones mark the progress of the investigation of sedimentary rocks. Much of this work was concerned with the intensive study of recent deposits and with the task of determining the probable source. Apparently to Retgers belongs the distinction of having first explicitly suggested (although the implication may be found in earlier papers) the possibility of determining the source of origin, drainage directions, conditions of transport etc. of more ancient geological formations (as he says: " diluvial and Tertiary, and even harder Mesozoic sandstones"), as well as of recent deposits. He also observed, as did Artini, what may be termed the varietal characters of many of the minerals he found, and was able, for example, to refer quartz by its inclusions to granitic, gneissose or volcanic sources, respectively. Mackie developed more fully this aspect of the study, his classification of quartz grains by their inclusions being still widely used.

In the period from 1900 methods of investigation have been immensely improved. Interest in the subject has rapidly increased, and not only was the investigation of recent sands and incoherent deposits undertaken, but rocks of all ages, from Pre-Cambrian onwards, were examined. The results serve to emphasize the remarkable variety of mineral assemblages that occur in rocks of different ages. But the assemblages also indicate that within limits the petrological character of a particular sediment might remain constant as it was traced laterally. In other cases, lateral variation occurred and could be used as an indication of source and drainage-direction, position of shore line and other palaeo-geographical features. Added to all this was the warning note sounded with regard to the limited and varying stability of minerals.

4. THE DETERMINATION OF SOURCE

(a) Mineralogy of the Sedimentary Rocks.

The sedimentary rocks consist basically of 3 kinds of material (1) detritus or clastic materials, (2) chemically precipitated materials and (3) organic matter. Mixed in various proportions these form the sedimentary rocks as we find them. Both (1) and (2), are derived ultimately from the break-down of an igneous rock. Igneous rock is mechanically and chemically unstable under surface conditions and as a result of a complex weathering process, yields 3 kinds of materials which go to form the sedimentary deposits. These materials are: (1) stable primary minerals of the parent rock which survive the weathering and which are released upon the break-down of the source rock (quartz for example), (2) stable secondary minerals formed by chemical decay of the unstable primary minerals in the source rock (as kaolin), and (3) solutions from which are precipitated the chemical end members of the sedimentary rocks (such as calcite).

The stable primary detritals are mainly of sand size, as might be expected since they were the predominant constituents of the phaneritic igneous rocks. The stable secondary products, however, are of clay size because they are the products of decomposition of the unstable primary components of the igneous rock. They are mostly crystalline though of very fine grain; some are wholly amorphous, as far as known. The precipitates from solutions, mingled with the above sandy and clayey materials, or alone, vary in grain size because grain size is governed by the conditions at the time of deposition.

TABLE I

Classification of the Minerals of Sedimentary Rocks

(with the principal species)

After Pettijohn

DETRITAL COMPONENTS:	
A. Stable "primary" minerals: "sand"	1. Stable: Quartz 2. Metastable: Feldspar, mica
B. Stable "secondary" minerals: "clay"	1. "Clay minerals": kaolin, montmorillonite, illite 2. Hydroxides: "limonite", "bauxite"
CHEMICAL COMPONENTS:	
C. Precipitates	1. Silica: opal, chalcedony, quartz 2. Carbonates: calcite, dolomite, siderite 3. Sulfates: gypsum, anhydrite, barite 4. Chlorides: halite 5. Sulphides: marcasite, pyrite 6. Phosphates: collophane 7. Silicates: glauconite 8. Oxides: limonite, hematite

Table 1 is by no means complete in so far as the minerals listed are concerned. There are many minor constituents of the parent igneous or metamorphic rock, for example, which are very stable and which survive weathering as well or nearly as well as quartz. These minor constituents forming usually less than 1% of the sediment, are usually of higher specific gravity than the quartz, and hence are known as the "heavy minerals". Representatives of this class are zircon, tourmaline, garnet, rutile and monazite. Less stable "heavies" include hypersthene, epidote and andalusite.

TABLE 2

Comparison of the Calculated Mineral Composition of the Average Igneous Rock and the Average Sediment

(After Pettijohn)

Mineral	Average Igneous Rock		Average Sediment
	Clarke	Leith and Mead	Leith and Mead
Quartz	12.0	20.4	35
Feldspars	59.5	50.2	16
Ferromagnesian Minerals	16.8	24.8	..
Mica	3.8		15
Miscellaneous	7.9	4.6	34

Table 2 gives the significant differences in mineral composition between the average sediment and the average igneous rock from which it is derived. The marked increase in quartz and the sharp decline in feldspar content is to be noted. The sedimentary feldspar, moreover, is not wholly a survival product; some of it is secondary or authigenic. The gain in quartz and decline in feldspar both result from the desilication of the feldspar on weathering. It follows, therefore, that the amount of free silica (or quartz) is greatly increased during repeated cycles of weathering and erosion.

The ferromagnesian constituents of the igneous rocks are almost wholly destroyed (except perhaps the mica of some micaceous sandstones and shales).

(b) The Relative Abundance and Stability of the Detrital Minerals.

The list of primary detrital minerals which have been reported in sediments is long. If the source rock was subjected to incomplete weathering and transportation was short, almost any known mineral can occur in sands that is of sand size in the parent materials.

In practice, however, relatively few species are encountered, and in thin sections the number of minerals is even more restricted. Quartz is dominant in most sandstones and in many samples it forms more than 90 per cent of the detrital portion. The feldspars, though common play a subordinate role in contrast to their importance in the igneous rocks (Table 2). In addition to quartz and feldspar, mica is the only other constituent of the parent rock likely to form an appreciable part of the detritus in the normal sandstone. Rock fragments occur mainly in the orogenic sediments, while the heavy minerals rarely exceed 1% and more commonly form less than one-tenth of one per cent of the rock. Of this latter group zircon, tourmaline and rutile appear to be the most common. Further, Boswell (1933) has pointed out that the proportion of heavy minerals varies with the mechanical composition of the sediment. Sediments of coarse sand grade (diameter greater than 0.5 mm.) are usually deficient in heavy minerals, the proportion often being much less than 0.01%. Those of medium grade (including medium sand, 0.25 to 0.5 mm., fine sand, 0.05 to 0.1 mm. diameter) contain a relatively high proportion. Because of the resistance offered to gravitational subsidence by surface area, the minerals in the grades of fine silt and clay often cannot be separated with sufficient accuracy to enable one to form conclusions as to the proportion of heavy residues in them. Sediments of coarse grade even near to their source may thus show but few heavy detrital minerals.

The table below lists the 50 most common detritals of sands. The twenty-five most common minerals in recent sediments are capitalized. Light minerals are underlined; all others are the heavy minerals.

TABLE 3

Detrital Minerals of the Arenaceous Sediments

(after Pettijohn)

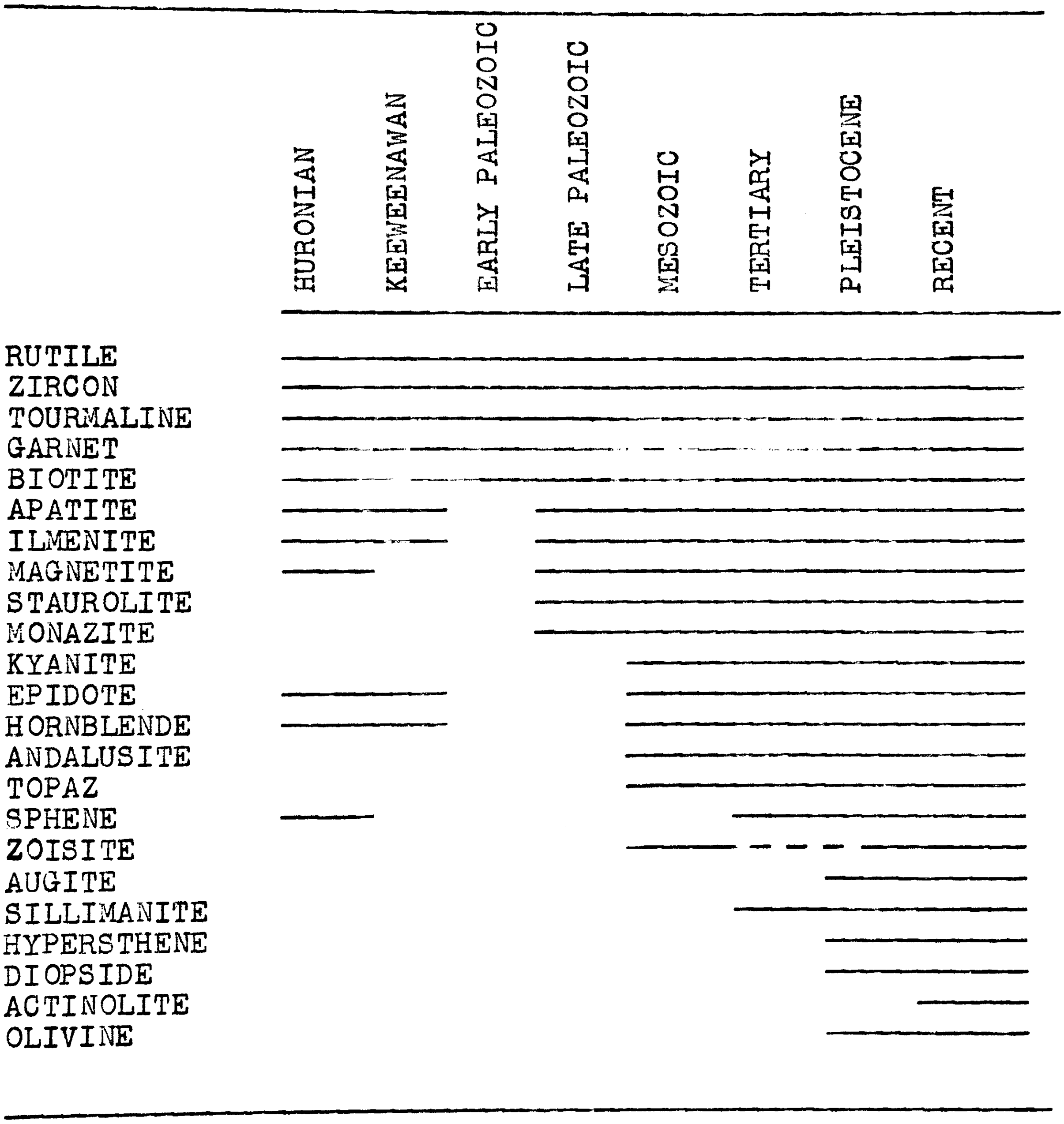
1. Actinolite-tremolite
2. Anatase
3. ANDALUSITE
4. APATITE
5. AUGITE
6. Barite
7. BIOTITE
8. Brookite
9. CALCITE
10. Cassiterite
11. Chalcedony
12. Chloritoid
13. CHLORITE
14. Clinozoisite
15. Collophane
16. Cordierite
17. Corundum
18. DIOPSIDE
19. DOLOMITE
20. Dumortierite
21. EPIDOTE
22. Fluorite
23. GARNET
24. Glauconite
25. Hematite
26. HORNBLENDE
27. HYPERSTHENE-ENSTATITE
28. ILMENTITE
29. KYANITE
30. LEUCOXENE
31. Limonite
32. MAGNETITE
33. Monazite
34. MUSCOVITE
35. Olivine
36. RUTILE
37. Serpentine
38. Siderite
39. Sillimanite
40. Spinel
41. SPHENE
42. STAUROLITE
43. Topaz
44. TOURMALINE
45. Vesuvianite
46. Xenotime
47. ZIRCON
48. ZOISITE
49. FELDSPAR
50. QUARTZ

Stability: Pettijohn (1941) has made an analysis of the literature on the mineralogy of sediments and has tabulated his results in the form of a "mineral persistence" chart. (Fig. 1). It is apparent from a study of the chart that some minerals notably zircon and tourmaline, show almost no

FIGURE I

Mineral Persistence Chart

(After Pettijohn)



change in frequency of occurrence with decreasing age. Others, also present in sediments of all ages, show an increase in number of times reported with decreasing age. Some of these, such as garnet and biotite, show but a feeble increase, while others-- notably epidote, hornblende, magnetite, ilmenite, staurolite, sphene and feldspar -- show marked increase. Some minerals are absent in the older deposits and make their appearance late in time and then increase toward the present. In this category fall andalusite, sillimanite, and zoisite. A few like olivine, occur only in recent and pleistocene deposits.

A "negative" persistence is suggested for several minerals. These minerals are more commonly reported from older sediments than from younger deposits. Octahedrite, in particular, shows a marked decline in frequency of occurrence with decreasing age of the deposit. Rutile shows the same decrease but to a lesser degree. The muscovite record is less clear but possibly also demonstrates a negative persistence.

Finally from the data assembled, an "order of persistence" may be worked out. The order of persistence is as follows:

-3. Octahedrite
-2. Muscovite
-1. Rutile
1. Zircon
2. Tourmaline
3. Monazite
4. Garnet
5. Biotite
6. Apatite
7. Ilmenite
8. Magnetite
9. Staurolite
10. Kyanite
11. Epidote
12. Hornblende
13. Andalusite
14. Topaz
15. Sphene
16. Zoisite
17. Augite
18. Sillimanite
19. Hypersthene
20. Diopside
21. Actinolite
22. Olivine

The order of persistence is in general accord with opinions held by most investigators. Thoulets' "order of destruction" was olivine, pyroxene, amphiboles, apatite, feldspar, biotite, muscovite, quartz, rutile, zircon, and corrundum. The "stability series" of Goldich (1938) is muscovite, biotite, hornblende, augite, hypersthene, and olivine. These minerals are in the same order in this series as they are in the persistence series. Holmes (1930 p. 174) has also compiled a list indicating the relative stability of various minerals. He says: "Field observations and laboratory experiments on the solubility of minerals in water charged with CO_2 indicate that nearly all minerals are attacked to an appreciable extent. The minerals most readily altered are, in order, the felspathoids and olivine, the pyroxenes and amphiboles, and serpentine and epidote. The plagioclase feldspars follow, those rich in the anorthite molecule being more rapidly affected than those near the albite end of the series. Next in order come orthoclase and biotite, while muscovite and quartz are but slightly altered or dissolved. Among minor minerals pyrite and apatite are likely to be soon decomposed; magnetite and andalusite are more resistant, and garnets, kyanite, staurolite, zircon, rutile, monazite, corrundum, ilmenite, and chromite are practically stable and are only altered after exceptional treatment."

Finally, Smithson (1941) after a study of the Triassic and Jurassic rocks of Yorkshire, classed the minerals of these rocks according to stability. Smithson's ratings were:

Stable	Somewhat Unstable	Unstable	Very Unstable
Zircon Rutile Tourmaline Apatite	Monazite	Garnet Staurolite Kyanite	Ferromagnesian minerals, etc.

The stability of minerals appears to depend on a number of factors. Goldich formulated his stability series after a careful study of mineral and chemical changes observed in weathering. He pointed out the relation between the position of the mineral in the stability series and its corresponding position in Bowen's reaction series. Minerals formed at highest temperatures in the most anhydrous magmas are less stable under surface conditions than those formed under lower temperatures in the more hydrous end magmas.

The order of persistence determined by statistical summary of the literature by Pettijohn enables us to extend the stability series to include many species not studied by Goldich or involved in the reaction principle.

Secondary enlargement is a self-evident criterion of stability just as etched surfaces, etc., are a criterion of instability. Both tourmaline and zircon -- the two most stable detrital minerals -- exhibit secondary outgrowths. The alkali feldspar, on which persistence data is difficult to obtain, presumably would rank high in stability if the secondary growth criterion is reliable. Its frequency of occurrence confirms its high stability. It would be number 9 in the stability series. Since quartz is commonly secondarily enlarged, it too should have a high stability. Its ubiquitous nature confirms this conclusion. If, however, the frosted appearance of the quartz in some of the older sandstones is due to solution and is the visual expression of fine etching (analogous to that produced on glass by hydrofluoric acid), then quartz is not wholly stable. It is never deeply etched, as is garnet, and therefore ranks higher in stability than that very stable mineral.

The negative persistence of a few species, that is, those more abundant in the older deposits than the Recent, is due partly to oversight and partly to authigenic formation.

A little zircon and tourmaline, for example, may well be overlooked in the amphibole- and pyroxene-rich glacial suites of the Pleistocene and the Recent sediments derived therefrom. Octahedrite, on the other hand, may be more frequently reported from the older sediments, because it is largely authigenic. The possibilities for its formation are enhanced with passage of time. In like manner rutile seems to be authigenic in so many cases that it, too, is slightly more common in the older deposits than the Recent. The apparent negative persistence of clastic muscovite is less clear, owing perhaps to the uncertain position of muscovite. It was regarded as a light mineral by many investigators.

Boswell (1924) has noted a relationship between density and stability in polymorphic varieties. Kyanite is both denser and more persistent than either sillimanite or andalusite. Rutile is likewise denser and more persistent than octahedrite or brookite. Further, Harker (1919) has noted a relationship between minerals developed under shearing stress (stress minerals) and stability. These minerals, characteristically developed under the influence of directed pressure, include many of those which are produced during the pneumatolytic and hydrothermal stages of igneous activity and are formed under conditions which demand low solubility. They are therefore well fitted to resist decomposition by weathering agents. As confirmation of this fact, Holmes

(1930 p. 308) points out that "it is interesting to recall the fact that most of the heavy detrital minerals of sediments are of metamorphic or pneumatolytic origin."

(c) Provenance versus Mineral Stability as the Controlling Factor in the Composition of Sediments.

The presence of a particular clastic mineral in a sediment requires the presence of that mineral in the parent rock, its ability to survive weathering of the parent rock and to resist abrasion and decomposition during transportation of the sediment, its deposition with the sediment (and not its removal by sorting action), and its ability to survive post-depositional solution or decomposition. R. Dana Russell (1937) has shown that loss during transportation is not an important factor in the Mississippi River. Most minerals, even the amphiboles and pyroxenes, withstand abrasion well. The general absence of these and other minerals from the older sediments cannot, therefore, be described to their inability to survive transportation. Neither can their absence be attributed to the lack of these minerals in the parent rock, since they are present in the source rocks of all ages. Since they occur in the younger geologic deposits, it may be assumed that they were also deposited in the ancient sediments.

The two possible reasons for the increasing complexity or "richness" of the mineral suite with decreasing age are (1) progressive increase in complexity of the terrain from which the sediments were derived and (2) loss of less stable minerals by intrastratal solution. Pettijohn (1941 p.620) believes the first possible explanation seems to be the less probable one and in support of this view he says: "No doubt each geologic revolution is accompanied by the invasion of the upper crust by magma and by dynamic and thermal metamorphism. Such activity yields new rocks later to be unroofed by erosion and to shed new material to the basins of sedimentation. There is not much evidence to show that these successively younger crystalline source rocks are fundamentally different from those of ancient date. If simplicity of mineral suite is a consequence of reworking older sediments and further elimination of the less stable minerals by abrasion and weathering, why, then, should not sediments become progressively simpler with decreasing age since the newer sediments should contain a larger proportion of reworked material? Just the reverse is true. It is not reasonable to believe that the older, mineralogically simpler sediments should all be re-worked sediments, while only the Tertiary and later sediments be first-cycle deposits. More probably the mineralogical simplicity of the older deposits is due to intrastratal solution.

"The correctness of the hypothesis of intrastratal solution is best demonstrated by the persistence order of the important rock-making ferromagnesian minerals. The order is -- in reverse order of persistence -- (1) olivine (2) hypersthene (3) augite (4) hornblende (5) biotite, and (6) muscovite. This order is precisely that given by Goldich in his stability series. Since the position in the stability series is a measure of susceptibility to weathering, it seems very improbable that the order of persistence based on the geologic record can mean anything except loss by solution following deposition. Only by the most improbable coincidence can their persistence order be otherwise explained."

Direct evidence of intrastratal solution of even the more stable species has often been described. Etched garnet is often reported as is also etched staurolite. The "hacksaw" and"cockscomb" phenomena displayed by augite, hypersthene and hornblende have been commented on by several authors and have been shown by C.S. Ross, H.D. Miser, and L.W. Stephenson (1929) to be due to post-depositional solution.

F. Smithson (1929), moreover, has shown that the richness of the suite, even in different parts of the same formation, is a function of post-depositional changes rather than an original character. The richness of the suite is inversely related to the authigenic features of the deposit. Wherever authigenic changes -- outgrowths on zircon, etc. -- are most prominent, the suite is impoverished; where the authigenic action is feeble, the suite shows a maximum variety of species. These antipathetic relations suggest a causal relation between the chemical activity responsible for authigenic growth and solution of the less stable minerals. Analogous reciprocal reactions are those associated with octahedrite. Octahedrite is both detrital and authigenic but since it has marked negative persistence, it is usually authigenic. The older the deposit, the more probable is its formation. Since it bears a reciprocal relation to sphene, it seems likely that it forms at the expense of this mineral. This relation has been confirmed by P.G.H. Boswell who noted a similar reciprocal relationship in the frequencies of these two minerals in the various beds of the same age. In deposits of the earlier sediments, where octahedrite is most frequently reported, the associated mineral suite is most restricted in composition.

Finally, Bramette (1941) has presented atrong evidence to show that two of the relatively unstable minerals, hornblende and epidote, have disappeared from some Miocene sandstones of California.

In the sandstones calcareous concretions within the clastic sedimentary rock indicate that many of them formed within the strata, but at an early period before much of the compaction and lithification; this may thus be considered a typically diagenetic process.

Samples were collected from these concretionery masses and from the immediately adjacent sandstone and analysed. In one case the hornblende that constitutes nearly half of the heavy mineral fraction in the samples from the concretions is nearly lacking in the adjacent sandstone samples (the basaltic hornblende entirely lacking) while in the other case the disappearance of the epidote from the sandstone and its preservation within the calcified body of concretionery sandstone is evident.

Bramette concludes that the loss of hornblende and epidote described is not the result of weathering processes but of intrastratal solutions.

P.D. Krynine (1942 a) after a critical review of the evidence believes that: (1) Intrastratal solution exists only on a limited, local and erratic scale. It depends upon absolute leaching intensity and upon relative length of time during which effective circulation is actively maintained. Paleozoic sediments sealed tight by early post-depositional cementation are less leached than highly permeable Pleistocene terraces (2) Thin-section work shows that most (90% ±) sediments poor in unstable minerals are reworked sediments frequently loaded with fragments of shale, slate, phyllite, sandstone, quartzite, low-rank schist, and particularly detrital chert. Sediments rich in unstable minerals generally contain igneous and high-rank metamorphic rock fragments. Krynine (1950) further points out that although Pettijohn believes that heavy unstable minerals get destroyed in sediments with time under the influence of intrastratal solution, when it comes to another equally unstable component, this time a major constituent, namely feldspar, Pettijohn believes that the presence of feldspar is and indicator of tectonism and relief during sedimentation.

TABLE 4

Feldspar Content of Pre-Pleistocene Sandstones

(after Pettijohn)

Age	Number of Formations	% Feldspar
Pre-Cambrian	5	8.2
Paleozoic	28	3.0
Paleozoic (pre-Pennsylvanian)	20	2.2
Paleozoic (Pennsylvanian)	8	5.0
Mesozoic	10	22.6
Tertiary	11	27.3
All formations	54	12.4

Table 4 shows the completely abrupt break between the feldspar content of Paleozoic sediments (average 3%) and Mesozoic and Tertiary sediments (average 25%). It so happens that exactly the same type of break also takes place in the distribution of unstable heavy minerals, a fact which becomes apparent from a consideration of Figure 1. Krynine concludes "Obviously it is difficult to claim, and even more difficult to believe, that the presence or absence of major unstable constituents is controlled by tectonism whereas the presence or absence of unstable accessories is controlled by intrastratal solution (which solution, furthermore, is not gradual but appears to have been considerably checked after the Permian)". Krynine believes that intrastratal solutions are operative, but that primary tectonic control and provenance probably accounts for most of the occurrence and distribution of these unstable minerals locally modified by intrastratal solution.

The evidence seems to indicate that the mere absence of some relatively unstable minerals cannot be safely used as a basis for interpretations regarding the stratigraphic relations or the source rocks of clastic sediments. From the evidence of the corrosion of some relatively stable minerals, even garnet under some conditions, it would seem that due consideration should be given the possibility of their complete disappearance in some of the oldest strata. The relatively small assemblages of heavy minerals in many of the early Paleozoic formations, and especially the fact that these small assemblages commonly include only the relatively stable minerals (zircon, tourmaline, rutile, black opaques and garnet) suggests that a loss of less stable minerals from within the strata may be the explanation. Further the presence of some of the less stable minerals in some of these older strata does not necessarily vitiate the general relationship suggested, as factors such as permeability and composition of the solutions would doubtless prevent any great regularity of a relationship showing progressive modification of these minerals in the geologic column. Also, the presence of small amounts of one of these less stable minerals, such as pyroxene in early Paleozoic strata, would suggest the desirability of careful checking to see that this is not the result of contamination or inclusion of the mineral within larger grains that may have been crushed in the laboratory treatment.

However, many additional data are necessary before the relative stability of detrital mineral grains, under various conditions can be profitably considered. Composition of the solutions within the strata, as pointed out above, would seem to be one of the important features as some sandstones of Eocene and Cretaceous age in California contain minerals such as hornblende and epidote, though these minerals have disappeared in some of the Miocene sandstones described.

In this controversy of provenance versus mineral stability the truth probably lies in some middle ground. The mineral composition of a sediment being controlled by many factors, including provenance and intrastratal solution.

The above conclusion that intrastratal solution may be just as important as provenance in determining the mineral composition of clastic sediments does not discredit the value of heavy mineral studies of sediments. However, it seems to emphasize the importance of another one of the many factors that must be considered in any interpretation. The mere absence of certain minerals in ancient sediments, particularly of the unstable minerals, seems of doubtful significance, and if additional data show that the small suite of relatively stable minerals in the oldest sedimentary strata is largely due to the stability relations of the minerals, it is evident that conclusions regarding the source rocks of these sediments are difficult and of questionable value except as interpreted from the minerals actually present, and distinctive characteristics of these minerals.

(d) Minerals as Clues to the Source of Sediments.

The mineralogical analysis of a sediment will show a certain suite of detrital grains which may or may not be suggestive of the source of origin, either individually or collectively. Generally speaking, there is seldom an instance where the petrographer fails to gain some clue, however small, to the source of some at least of the species represented. In the descriptions of the detrital minerals, such as given by Milner (1940), possible sources of origin of the several species are included to enable an initial estimate to be made; this information, however, only applies to individual grains. Paragenesis is just as important a factor in detrital sediments as in igneous or metamorphic rocks and more often than not indication of the source of origin of the deposits comes from association of species noted rather than from particular minerals.

The association of sillimanite, kyanite, andalusite and garnet or again, a garnet-staurolite-kyanite suite, are both suggestive of derivation from a definite thermo-metamorphic province, just as a titanite, apatite and zircon assemblage (if marked) is indicative of acid or intermediate plutonic rock types as possible sources of supply. The characteristic association of rhombic and monoclinic pyroxenes, often with ceylonite and possibly a chlorite group mineral in addition, points to derivation from basic or ultrabasic rock-types, while the prevalence of cassiterite, topaz, white mica and rare-earth minerals in certain sands may be equally suggestive of their primary environment. On the other hand, a predominance of the more stable minerals such as zircon, tourmaline, rutile and iron-ores, probably to the total exclusion of such other species as are mentioned above, implies derivation from pre-existing sediments and in such cases location of the ultimate source of origin may be rendered considerably more difficult.

A more comprehensive table of mineral suites indicative of source rock types is given by Pettijohn (1948 p. 98) and reproduced below:

TABLE 5

Detrital Mineral Suites Characteristic of Source Rock Types

Reworked Sediments

Barite
Glauconite
QUARTZ (esp. with worn overgrowths)
CHERT
Quartzite fragments; (ortho quartzite type)
LEUCOXENE
Rutile
TOURMALINE, rounded
ZIRCON, rounded

Low-Rank Metamorphic

SLATE and PHYLLITE FRAGMENTS
Biotite and Muscovite
Chlorite (if clastic)
Feldspar generally absent
QUARTZ and QUARTZITE FRAGMENTS (meta-quartzite type)
TOURMALINE, (small pale brown euhedra with carbonaceous inclusions)
Leucoxene

High Rank Metamorphic

GARNET
HORNBLENDE (blue green variety)
KYANITE
SILLIMANITE
Andalusite
STAUROLITE
QUARTZ, Metamorphic variety
Muscovite and biotite
Feldspar (acid plagioclase)
EPIDOTE
ZOISITE
MAGNETITE

Acid Igneous

APATITE
BIOTITE
HORNBLENDE
Monazite
Muscovite
Sphene
ZIRCON, euhedra
QUARTZ, igneous variety
MICROLINE
MAGNETITE
Tourmaline, small pink euhedra

TABLE 5 (continued)

Basic Igneous

Anatase
AUGITE
Brookite
HYPERSTHENE
ILMENITE and magnetite
Chromite
Leucoxene
Olivine
RUTILE
Plagioclase, intermediate
Serpentine

Pyroclasts

Sanidine
Zoned feldspar
VOLCANIC GLASS
LITHIC ROCK FRAGMENTS with typical volcanic rock structure

Pegmatite

FLUORITE
TOURMALINE, typically blue (INDICOLITE)
GARNET
Monazite
MUSCOVITE
Topaz
ALBITE
Microline

(Capitalized species are more common)

Once a particular mineral association is established and its relationship to a definite source of origin inferred, confirmation of such provenance should be sought by appealing to significant varietal characters of such minerals as quartz, tourmaline and zircon. The varietal characters of other minerals may be important but their use implies detailed knowledge of the parent rocks themselves, quite apart from the sediments involved. In working out problems involving provanance, therefore, it is advisable firstly to note the possible types of rocks from which each mineral suite may have been derived and secondly to investigate the presence (or absence) of such types within a likely region capable of furnishing the material. As W. Mackie (1896 p. 158) says: " (To trace) the various groups of sand grains back to the particular localities in the crystalline rocks from which they were originally derived...we must come armed with microscopic sections of all the important rocks of the area, which, we have reason to believe, yielded the debris which has gone to make up the sandstones in question."

The Value of the Varietal Characters: It frequently happens that certain mineral suites do not connote a particular source, since the minerals making up the suite may be such that could be derived from almost any igneous or sedimentary rock. Therefore, one must turn to the varietal character of individual minerals.

The value of the varietal character of certain minerals in tracking down the parent rock or rocks of a given sediment was early recognised (Artini, Retgers, Mackie). P.G.H. Boswell more recently (1933) again drew attention to these varietal characters. He believes that the importance of the differences shown by common minerals derived from different rocks cannot be emphasized sufficiently, and concludes that varietal characters inevitably assist in tracing these minerals to their parent rocks and give precision to deductions regarding ancient drainage directions.

Unfortunately there appear to be extremely few minerals which are (a) sufficiently abundant (b) sufficiently persistent throughout geologic time, and (c) have sufficiently distinctive varietal characteristics to be of any real value. The most important and frequently used being quartz, tourmaline and zircon. An analysis of the literature shows conclusively that these three minerals approach very closely the ideal since they are the most abundant and stable of all the detritals and may be expected to occur in clastic sediments of any age.

(1) Quartz: Quartz may be derived -- and so most of it is ultimately derived -- from the phaneritic quartz-bearing igneous rocks. In any given deposit, however, much of it is "reworked", i.e. derived from preexisting sediments or their metamorphic counterparts. Few sediments are of the "first cycle" type; most contain quartz from diverse sources. Krynine (1942 b) estimates that 25% of the average arenaceous sediment is derived directly from igneous and crystalline sources, 45% is of metamorphic derivation (mostly low rank), and 30% is reworked sedimentary material.

The common character of detrital quartz is that of the shapeless, slightly turbid grain often with sharply defined inclusions; diagnosed by its low R.I., and in the majority of cases by the "concentric ring" interference colours yielded by other than basal grains; the latter are isotropic and normally exhibit a positive interference figure. Inclusions are either fluid or mineral. When subject to considerable pressure, quartz acquires strain shadows, undulatory extinction, and fractures. It may even become anomalously biaxial.

The principal problem in identification is to distinguish quartz from feldspar. This may be done by:

(1) Refractive Index: The potash and soda-rich feldspars have an index less than quartz (and less than balsam). The calcium-rich members are of a higher index than quartz. Oligoclase and andesine, however, are too near quartz to be rapidly distinguished on basis of index.

(2) Cleavage: The feldspars exhibit two good cleavages nearly at right angles to each other : (001) perfect and (010) somewhat less so; also (110) imperfect. Quartz may show at times a rude cleavage (rhombohedral) or parting.

(3) Twinning: The multiple twinning of the plagioclase is well known. Unfortunately, many feldspars lie on the (010) plane and, therefore, do not show the twinning lamellae, but only an imperfect extinction. Quartz frequently shows optical anomalies which give rise to imperfect extinction.

(4) Staining: This method is regarded by Russell as the most rapid and reliable where quantitative data are required. It is accomplished by treatment of the suitably mounted grains with hydrofluoric-acid solutions. The grains are then

washed and stained with a water-soluble organic dye, such as malachite green. The feldspar stains, but the quartz does not.

From his work on the sands and sandstones of Eastern Moray, W. Mackie (1896) was able to divide quartz into 4 main groups on the basis of inclusions. These 4 classes of quartz are: (i) Quartz containing "regular" inclusions (ii) Quartz containing "acicular" inclusions (iii) Quartz containing "irregular" inclusions (iv) Quartz with no inclusions.

(i) Quartz containing "regular" inclusions (R): The regular inclusions are crystals -- often perfectly regular, rigidly mathematically outlined crystals of other minerals enclosed in the quartz. These mineral inclusions are most commonly quartz as an inclusion in quartz, chlorite, muscovite, biotite, rutile, apatite, zircon, garnet, magnetite, titaniferous iron.

(ii) Quartz containing "acicular" inclusions (A): Here the inclusions appear as fine dark lines running in all directions through the quartz grains. The mineral character of the needles appears to be doubtful, some however, are apparently sillimanite occurring as perfectly colourless, tufted or sheaf-like aggregates, the individual needles often showing a transverse cleavage which easily distinguishes them from the finer dark variety which has generally, though not invariably, been ascribed to rutile. Whatever the nature of the latter class there can be little doubt that they are very widely distributed. Small prisms of apatite occur in many grains, and these, along with fine tourmalines, have from time to time, in all probability, found their way into and been classified in the acicular group.

The acicular group is capable of extensive subdivision into smaller groups in virtue of peculiar differences of arrangement of the needles within the quartz grains, and also in several cases by reason of their association with various inclusions of the regular type. This variety of arrangement and association often makes it possible to trace many of these sub-groups with more or less certainty back to their parent rocks.

(iii) Quartz containing "irregular" inclusions (I): Irregular inclusions need no particular description. They are almost always fluid lacunae, with or without gas bubbles, often arranged in streams. Various rocks are characterized by the presence or absence of gas bubbles in these fluid lacunae.

(iv) Quartz with no inclusions (N): Under this heading are included those quartz grains in which inclusions are absent, or so minute as to escape observation.

As regards the value of these 4 classes of quartz in determinations of source rock Mackie says: "Now it may be stated as a fairly general law that acicular (A) and irregular (I) inclusions pre-eminently abound in the quartz of granite (quartz-diorite and related rocks including quartz veins); that the regular (R) group is to be found in various proportions, but always in relatively large numbers in the quartz of gneiss and the younger schistose rocks."

To avoid complication in the classification a grain containing more than one type of inclusion is placed preferentially in the acicular group when inclusions of that type are present, and in the regular group when regular inclusions are present and acicular inclusions are absent. That is to say, the acicular character is given precedence over regular, and regular over irregular.

The figures obtained by Mackie for the relative proportions of the four groups of quartz in different types of rocks from the Eastern Moray district are given below (Table 6).

In the case of granites, schists and other parent rocks the specimens were crushed to the size of ordinary sand grains, and the character of the inclusions in each particle was then observed and recorded as it came into view when examined under the microscope.

TABLE 6

Proportions of the Four Groups of Quartz in the Rocks of the Eastern Moray District

(after Mackie)

Rock Types	Number of Specimens Examined	N	R	I	A
Granites	6	17	10	27	46
Quartz-diorites	2	3	2	26	69
Schists and Gneisses	8	96		3	1
Lower Old Red Sand-Stone	23	23	65	6	6
Upper O.R.S.	31	40	38	9	13
River-sands	32	21	57	12	10
Sea-sands	5	36	50	6	8

The results clearly demonstrate the correlation between the N + R group and schists and gneisses, and that between the I + A group and quartz-bearing igneous rocks. Interpreting the results given for sandstones and recent sands, it is seen at once that the bulk of the quartz grains have been derived ultimately from a metamorphic complex, granite and allied igneous rocks having supplied only a limited proportion.

Further, if one considers the irregular (vacuole) group alone it appears that numerically it tends to diminish during transport. According to Holmes (1930) the percentage of grains belonging to the irregular group found in the sands of the Findhorn and Nairn Rivers near their mouths is 24. In the Cublin sands this figure has diminished to 15, and at Burghead to 3. Progressive attrition has therefore reduced the irregular group preferentially, leaving the other groups relatively more abundant. Evidently the vacuoles constitute a source of weakness and the grains containing them break down more easily than the others, so that ultimately the fractured and more finely graded material is blown or washed away.

Yet another point is worthy of mention. Mackie found that in different granites the ratio of A to I inclusions appear to vary and this fact may well be used for source determination when two or more granites occur in the distributive province, e.g. Western granites of Ardclach and Kinsteary $A \angle I :: 2 : 3$

Eastern granites of the Berinnes type $A > I :: 5 : 1$.

Krynine (1940) divided the quartz of the Third Bradford Sand (Devonian) of Pennsylvania into seven types. The igneous varieties consisted of (1) normal igneous quartz, marked by no strain shadows, few inclusions (or at most planes of liquid and gas inclusions), and microlites of zircon and biotite, (2) end-phase quartz, formed under slight pressure of the rest-magma state and with weak strain shadows and abundant inclusions of tourmaline and rutile, (3) hydrothermal quartz, marked by inclusions of green, vermicular chlorite, and (4) modified igneous quartz, with strongly marked strain shadows. The metamorphic varieties were (1) quartzite fragments and lensoid grains with strong undulose extinction, crenulated borders, and inclusions of sillimanite and kyanite, (2) quartzitic aggregates, and (3) schistose quartz, elongated -- usually parallel to the c-axis.

Authigènic or secondary quartz, as overgrowths on detrital quartz forms another principal variety likely to be seen in sandstone.

The secondary outgrowths were described early by Sorby. The phenomenon is widespread and may be universal in all sandstones in which crystalline quartz serves as a cement. In the least cemented specimens, the quartz grains may be broken apart readily and examined microscopically. The quartz outgrowths restore the fundamental form and symmetry of the quartz crystal. If the detrital grain is stained with iron oxide, the nucleus and secondary rim are distinguished readily. In the better-welded quartzites, however, the distinction between the detrital and the authigenic quartz is less clear and in some cases cannot be made.

The value of these secondary overgrowths, when they can be detected, is obvious in source rock determinations. Second-cycle quartz, i.e. quartz derived from pre-existing sediments is recognised by worn and rounded overgrowths or by two overlays of secondary silica.

(2) Tourmaline: Tourmaline is one of the most widespread non-opaque heavy accessory constituents in sediments. It shares first place with zircon as the most abundant and most frequently found heavy mineral. It occurs in sediments of all types and of all ages.

General Character: Tourmaline is a complex alumino-silicate of boron with a variable formula in which considerable replacement and proxying takes place. Specific gravity averages around 3.1; hardness, around 7.5. Tourmaline is hexagonal and optically negative. The normal habit is prismatic, terminated with asymetrical pyramids. There is practically no cleavage, but in some grains a rude basal parting is present. The prisms may show a trigonal cross-section with pseudo-curved sides.

Tourmaline is ultra-stable, both chemically and mechanically. It is possibly the most wear-resistant of all common minerals.

Grain Morphology: In addition to colour, relief and birefringence, which depend upon chemical composition, tourmaline shows considerable variations in its morphology (both external and internal), depending upon the conditions of its genesis. The following physical characters are easily observable and may be of great diagnostic importance in tracing the origin and history of each grain:

1. Size - Small prisms versus large prisms versus fragments of still larger prisms. Large crystals do not survive in sediments in one piece, and hence the abundance in a sediment of large tourmaline fragments is evidence of still larger crystals within the source area.
2. Shape and Roundness - Since tourmaline is extremely resistant to wear it is quite common to find in one sediment, owing to mixing from several source areas, a collection of tourmaline grains in different stages of modification (rounding). Shape may range from original prismatic (idiomorphic) to perfectly rounded (globular) with angular fragments in between. Rounded grains may be refractured during a later cycle of abrasion.

   The study of basal parting (i.e. of primary versus clastically produced elongation) belongs here.
3. Inclusions - Common in tourmaline and may be highly diagnostic of its provenance. These inclusions may be: (a) Cavities (empty vacuoles or bubbles, frequently with coloured walls); (b) microlites of rutile (common), magnetite, zircon, cassiterite, topaz, fluorite, quartz, feldspar (?), muscovite, anatase, brookite, and titanite; and (c) carbonaceous particles (locally abundant).

Origin and paragenesis of Tourmaline: Five main types of large-scale provenance are recognised by Krynine (1946). These are:

(1). Granitic Tourmaline: Formed as an end-phase product within large plutonic igneous bodies. Typical morphology is small or medium sized idiomorphic crystals, frequently full of bubbles and cavities. This may suggest deuteric replacement. Typical colour is dark brown, green or pink (with greenish cast) suggesting a possible Fe composition with Li (±).

(2). Pegmatitic Tourmaline: From pegmatites and vein rocks. Typical habit is that of very large crystals (hence occurs in sediments as angular fragments). Typical colour is blue, with pleochroism in shades of mauve and lavender; composition is Na with some Li. Other varieties are possible but less typical. Inclusions are rare.

(3). Tourmaline from pegmatized injected metamorphic terranes: Habit and colour are variable and to a very large extent, are related to the petrography of the host rock and apparently to its texture, porosity and permeability.

In pegmatized sandstones (and hence in metaquartzites, quartz-schists and quartz-mica-schists) the morphology of tourmaline is variable. Sometimes almost the same types occur as in granites (brown and pinkish, less commonly green). In other, more common, instances the tourmaline crystals are pale to deep brown and generally are poor in inclusions. Their size, as a rule, is smaller than that of granitic tourmaline.

In slates, phyllites, and non-quartzose mica-schists the typical morphology is very small idiomorphic crystals, frequently full of black carbonaceous inclusions. These carbonaceous inclusions occur only if the injected phyllite was originally a dark or black shale. Such carbonaceous inclusions, as is generally known, are also common in andalusite and staurolite. Colour is colourless to very pale (or less commonly deeper) brown. Composition is MgFe. Possibly, the very pale colour in some tourmalinized phyllites may be due to a selective adsorption or absorption effect by the host rock on the Fe in the pegmatitic juices. Complications occur, for instance, a metamorphic terrane consisting of alternating layers of quartz-mica-schist (old sandstone) and mica-schist (old shale) may in some cases show both types of tourmaline (pale and deep coloured), alternating layer by layer, possibly even foot by foot, with the darker tourmaline present in the more permeable layer (quartz-schist, former sandstone). During igneous tourmalinization of sediments and metamorphic rocks the tourmaline may occur either as overgrowths (very rare) or more commonly as newly formed crystals with no visible nuclei. The overgrowths are extremely rare, because at high temperatures an almost total reorganization of the nucleus is likely to take place. Furthermore, almost all of the tourmaline in injected terranes is new, having been formed de novo without the aid of pre-existing nuclei.

(4). Sedimentary authigenic tourmaline (cold water) formed at bottom of sea penecontemporaneously with the including sediment: Typical morphology is that of overgrowths which show polar development at one end only of the c-axis. According to Alty's pyroelectric tests, these overgrowths are restricted to the antilogous pole, which is characterized crystallographically by the faces r $(10\bar{1}1)$ and $m(10\bar{1}0)$.

Typically, these overgrowths are colourless to very pale blue, indicating an Mg composition, with possibly some Ca or Na. Their refractive indices are very low.

These outgrowths are generally small ranging from 5 to 25 per cent of the size of the nucleus; but they may become very large, reaching 50, 100 or even 200 per cent of the nucleus. In absolute figures the largest overgrowth seen by Krynine reached 0.25 mm. in length.

The overgrowths are identical in their properties throughout the same formation, but the nuclei naturally are different. Hence, colourless (Mg) overgrowths may develop on brown, blue, green yellow, or black cores all of which have different chemical compositions. Between the overgrowths and the nucleus is found a zone of "roots" or reorganization, where the core and the outgrowths are welded together. This zone of roots is characterized by pitting and etching of the nucleus, with roots of the outgrowth entering these pits. The composition of this pitted root zone is apparently intermediate between that of the overgrowths and that of the nucleus. If the overgrowth is broken off this pitted surface remains at the antilogous pole as evidence of its former existence. The overgrowth may contain inclusions, engulfed during the period of growth.

Pseudo-overgrowths which can be mistaken for authigenic tourmaline by overenthusiastic observers can occur in two ways: (a) Tourmaline grains may be fractured and abraded at one end in such a way as to produce a thinning of the grain (which may render the thinned portions almost colourless) and also to produce some sort of crystal outline along incipient partings parallel to the original prismatic faces of the grain. This, in some cases, may give the impression of an overgrowth upon casual examination. (b) In rocks which are cemented by a mixture of secondary quartz and recrystallised micas, such as illite or sericite the cementing material may adhere to the grains upon crushing of the rocks (other cements usually do not do this). These particles of cement form irregular pale-blue wisps rather similar to authigenic tourmaline overgrowths, especially if the central cores are dark. However, these wisps are not in optical continuity with the nucleus.

Authigenic tourmaline is a typical sedimentary development. It is usually restricted to relatively thin stratigraphic horizons, but geographically it may cover areas well in access of 50,000 square miles. The occurrence with the same formation takes place regardless of the changes in permeability or cementation of the formation and is present even in completely welded, early cemented orthoquartzites or nonporous calcareous sandstones, thus establishing the early sedimentary age of the overgrowths development.

(5) Reworked Tourmaline from older Sediments: This is probably the most abundant single source of tourmaline found in sediments. After entering a sediment from one of the four primary sources, tourmaline survives the destruction of the sediment during the next cycle of erosion and sedimentation and passes into a younger sediment. Hence, long periods of peneplanation characterized by vigorous and prolonged chemical decay, are especially favourable for the concentration of tourmaline types in the produced detritus at the expense of other less stable mineral species. Such periods of diastrophic quiescence increase both the relative abundance of tourmaline in the following sediment and also the absolute number of tourmaline varieties in it. Up to 21 tourmaline varieties have been found in some sediments.

Study and Interpretation of Tourmaline Varieties in Sediments: As in all heavy-mineral work, the study of tourmaline can yield the following results: (1) Establish the petrology of the source area, both ultimate and immediate (2) Establist the general diastrophic, tectonic, and climatic history of both source area and basin of sedimentation (3) Establish paleogeographic relations between ancient land and sea before and during deposition of the sediment (4) Establish correlation and differentiation criteria for the formation under study; and (5) as a result of 1, 2, 3 and 4, important economic results can be attained.

In order to proceed with such studies, it is necessary to establish the ultimate and immediate provenance of the tourmaline and the history of the grains subsequent to the uncovering of the source area. The amount of detailed work necessary to do this will depend upon which one of the following 3 types of provenance is met: (a) There is only one, or at most two, closely related tourmaline varieties, both of which came from the same parent rock and hence have similar colour and morphology and are in the same stage of modification. (b) There are several varieties of tourmaline which came from entirely different parent rocks and hence differ considerably in colour and internal morphology, but all of them have been eroded at the same time with the same source area and hence have suffered approximately the same amount of modification and thus show the same amount of rounding. Such assemblages from the same source area can be treated as a unit. (c) There are several varieties of tourmaline which come from different source areas and were eroded at different times and under different tectonic conditions; hence, the varieties differ in colour, internal morphology, and rounding.

The recognition of possibilities (a) to (c) and its practical application to the solution of problems 1-4 rests upon a thorough break-down of the tourmaline varieties present into usable types. This differentiation should proceed on the basis of the external shape and internal morphology of the tourmaline grains.

TABLE 7

Summary of Tourmaline Types and Source Rock

(after Krynine)

Plutonic Bedrock	Pegmatites	Injected Terrane	Non-injected bedrock	Authigenic
Medium crystals; dark brown, green or pink to green; Inclusions frequent; bubbles, cavities and microlites.	Large crystals breaking into angular pieces during erosion. Typically blue to mauve or pink; few inclusions.	Very small to medium crystals; colourless to pale yellow or brown; may have carbonaceous inclusions.	Abraded detrital grains of many mixed types.	Colourless overgrowths on detrital grains.

(3) Zircon: Zircon is one of the most fascinating minerals occurring in detrital sediments, on account of its widespread occurrence throughout the geological record and its great variation in form, colour and intimate properties. To appreciate fully its significance in any given sediment, the most careful investigation of each variety present is essential, especially as colour, zoning and inclusions are significant of provenance.

Crystallization from the Magma: Microscopic evidence shows beyond any doubt that the minute zircons (they are rarely over 0.5 mm. in length) which seem to occur in nearly every igneous rock have in general crystallised as an original constituent. Moreover, such methods as are used in determining the order of crystallisation of minerals indicate that zircons have usually formed very early in the consolidation of the magma.

Formation in Rocks Secondarily through the Agency of Water or Gases: Derby (1891) was of the opinion that all zircons in rocks have resulted from the crystallisation of igneous melts and that they could not be formed in a rock secondarily. He argues: "Unless, therefore, these rare chemical agents are introduced into the mass subject to metamorphism by the action of the so-called mineralizing agents (as fluorine, boron, and tin are supposed to be in the formation of tourmaline, topaz and cassiterite) it is difficult to conceive how the minerals in question can appear as newly formed elements in a metamorphosed sedimentary. Their early crystallisation and uniform distribution in eruptives as well as their absence from schists metamorphosed by contact (in the rare cases in which zircon has been noticed it may be presumed to have existed in the original sediment) exclude the hypothesis of such an introduction."

Thurach (1884), on the other hand, was of the opinion that zircons could form from watery solutions and cited as proof the zircons which occur in druses in the chlorite schist of Tyrol and also the well developed crystals in the sericite schist of Taumes which is associated with a quartzite containing well rounded grains. There is just a possibility, however, that in the latter case the sericite schist may have been formed from material which was not as well sorted as the underlying quartzite and consequently more easily rendered schistose. In such a case one would not expect the zircons to be as water-worn as in the purer variety.

The following two cases cited by Trueman (1912) furnished additional proof that the views expressed by Derby must be considerably modified. In the crystalline limestone of Grenville, Ont., large crystals of zircon with well developed faces have been found. They are associated with graphite, wollastonite and titanite and were probably formed through the action of intrusives. The evidence here seems to show that zirconium is capable of being carried in solution some distance from the main body of the intrusive.

At Rib Hill, Wausau, Wis., there is a quartzite which is cut by granite and which contains abundant zircons, many of which exhibit secondary enlargement. The new material has added largely to the ends of the grains, usually forming pyramidal faces terminated by the basal pinacoid, though the latter is sometimes absent. In one case the new growth was observed to completely envelop the original grain. This suggests that the material for the later crystallisation was, in part at least, introduced from without and field relations seem to point to the granite as the source.

While working through a batch of slides of heavy minerals of the Millstone Grit of the Pennine region J.A. Butterfield (1936) encountered similar outgrowths on zircons. Referring to the significance of these outgrowths Butterfield says: "So far as the writer's work is concerned these outgrowths are important because they are going to play a part in the study of the genesis of the heavy minerals of the Grit. The fact that they are always of perfect shape and unworn, and that they are attached as water-clear colourless outgrowths to rounded purple and yellow zircons suggests that they have been formed in the Grit since the deposition of the material forming this rock."

For purposes of identification Butterfield's description of the outgrowths is given below:

"The outgrowths are observable on small zircons in mounted residues of heavy minerals and they take the form of small zircon pyramids growing out from the parent zircon as shown in the sketches. As a general rule their growth seems to be from the prism faces (if present) of the parent zircon and their direction, in those noticed so far, is always at right angles to the principal axis of the original zircon. They are in complete optical continuity with the parent crystal. They vary considerably in size from the minutest tooth-like serrations fringing the side of the zircon and only visible by careful focussing with high power, to quite large outgrowths occasionally as large or larger than the pyramidal terminations of the parent crystal. In the former case they are usually numerous (Fig. 2, 1) perhaps a score or more minute pyramids fringing one side of the crystal, although often only a single minute pyramid is seen attached to large zircon crystals. In the case of large outgrowths they are fewer and restricted to one or two regions on the parent crystal face. Between these two limits there is a complete gradation of sizes. Often crystals carrying large outgrowths also possess a complement of smaller outgrowths (Fig. 2, 6 and 10). In rare cases the outgrowths have grown so closely and uniformly as to form a straight edge (Fig. 2, 11). Occasionally they are so rampant as to form

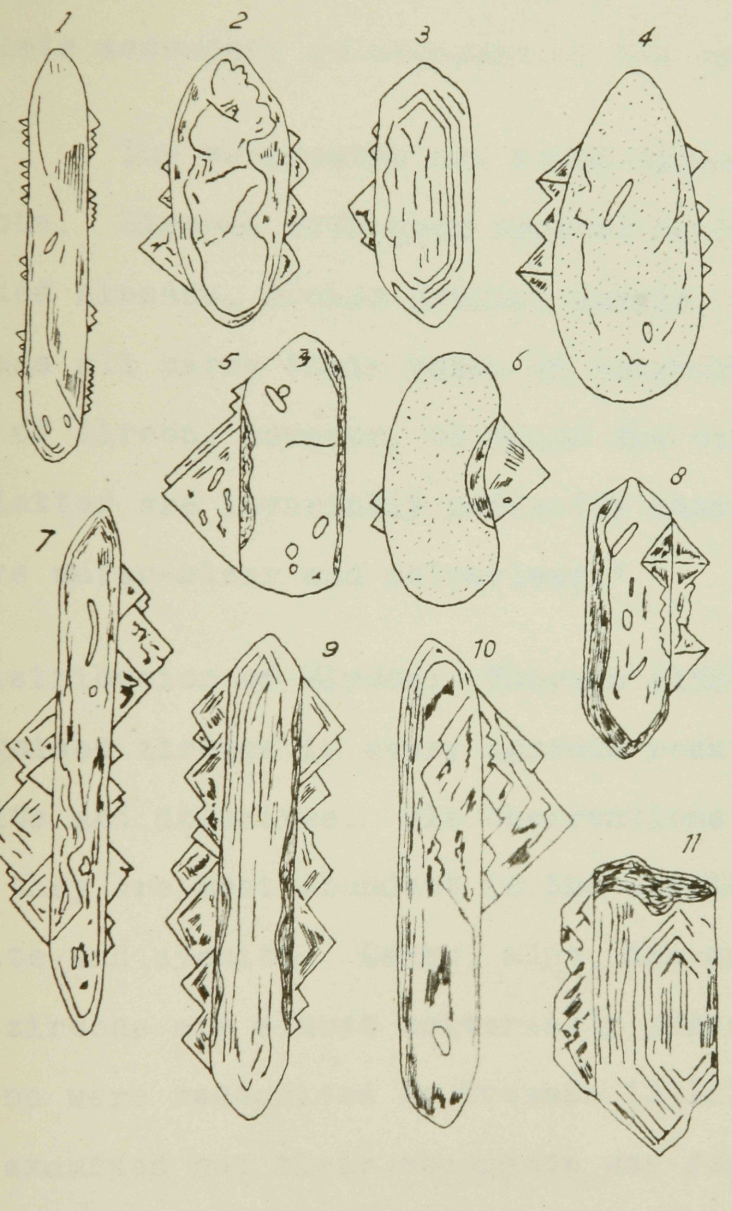


Fig. 2 Outgrowths on zircon (After Butterfield, Geol. Mag., Vol. 73, 1936, p 511)

a complete shroud for the parent crystal, and in one or two doubtful cases the latter seems to be entirely surrounded by a complete envelope yielding what is to all appearances a complete secondary enlargement of the original crystal.

The outgrowths are found attached to all types of zircons. Zircons with good crystal outline, subangular and rounded zircons, broken grains, purple, dusky, and yellow zircons all carry their share of outgrowths. Whatever the type of zircon, however, to which the outgrowths are attached the latter are invariably perfectly sharp in outline and always water-clear and colourless."

Distribution of Zircon: Thurach (1884) stated that he had recognised zircons in every igneous rock tested, including basalts and dolerites. His observations indicate, however, that they are most abundant in the acidic types such as granite and syenite. Derby, also, has expressed the opinion that zircons are almost universally present in eruptives. Zircons were recognised by Trueman (1912) in every granite rock examined but their abundance was found to vary greatly in specimens from different localities. They appeared to be much less numerous in basalts and other basic rocks than in the acidic varieties, none, for example, being detected in a test on material from a specimen of diabase from Gowganda, Ont.

Zircon appears to be present in varying amounts in practically every arenaceous rock. Thurach reported its presence in every sandstone examined and Trueman's observations are similar, eight quartzites all showing zircon and generally abundant.

Shales, however, appear to be comparatively free from zircon though Thurach's thorough tests revealed its presence in nearly every case examined. Derby says that zircon is almost absent from argillaceous deposits and they were only observed occasionally in such rocks by Trueman.

Thurach found zircon to be generally abundant in feldspar-rich gneisses (presumably largely of igneous origin) and less common in, but seldom absent from, mica gneisses (probably mostly of sedimentary origin). Derby's observations show that schists free from quartz such as amphibolite and amphibole schist frequently show abundant zircons but that micaceous schists contain only comparatively few grains of that mineral.

Conclusions: (i) The Significance of the Presence or Absence of Zircon in a Rock: The facts on hand seem to show that when zircon is present in a rock in considerable abundance the original rock was probably either igneous or a sandstone and not an argillaceous rock or a chemical deposit.

The absence of zircon in a rock is not so significant. It, however, favours the idea that the original rock was of sedimentary origin and suggests somewhat strongly that it was not a granitic rock or a sandstone.

(ii) The Significance of Rounding: It has been previously noted in a general way that the zircon grains in igneous rocks have well-developed crystal outlines while those in sedimentary rocks are more or less rounded. These facts of observation should, however, be stated more fully in order that the amount of confidence to be placed in this distinction as a criterion can be determined.

Thurach has stated that the zircons in granites and syenites generally show well-developed crystal forms while many roundish grains occur in diorites. In basalts and dolerites he observed that the zircons were generally roundish and frequently showed a zonal banding parallel to the boundaries of the grain. In sedimentary rocks according to Thurach, the zircons are generally rounded but some possess distinct crystal boundaries.

While Derby has noted that the crystal forms in igneous rocks are, as a rule, better developed than those occurring in sands, he has expressed the opinion that in the former perfectly sharp-angled crystals are the exception rather than the rule and apparently characterize the amphibolitic rather than the micaceous types.

The investigations of Mackie (1896) on the rounding of sand grains indicate that zircon is more readily rounded than quartz, probably on account of its higher specific gravity. Four sands discussed by this writer showed a predominance of rounded forms in each case.

Scherzer (1910), in an article on the recognition of the types of sand grains, is interesting in this connection. Scherzer considers that well rounded grains are typical of eolian deposits. In this paper reference is made to the experiments of Daubree which seem to show that granules less than 0.1 mm. in diameter cannot be rounded by water action. However, typically rounded grains of zircon were observed by Trueman (1912) under 0.06 mm. in diameter.

Trueman's tests indicate that the zircons of granitic rocks have generally good crystal form, sometimes with perfect faces and in other cases having somewhat rounded outlines. Tests made on about 15 specimens of rocks derived from sand showed that the zircons were generally more rounded than is usual in igneous rocks.

From a consideration of the above facts Trueman acknowledges that the zircons in igneous rocks are sometimes roundish in character and that in sedimentary rocks, if the original materials were not subjected for considerable time to the abrasive action and sorting action of rivers, waves, and wind, perfect crystal forms may have been preserved. Notwithstanding these possibilities it seems safe to say that the presence of good crystal outlines in zircons indicates that the immediate parent rock was probably igneous while rounded forms suggest a sedimentary source. When the rounding is pronounced the proof of sedimentary source is strong, but when it is slightly developed it is of little significance.

(iii) The Lustre of Zircons: The lustre of zircon grains is a character closely allied to their form. According to Trueman's observations the zircon in igneous rocks usually have a clear, fresh, vitreous appearance while those in sedimentary rocks frequently have a dull, pitted look like ground glass. Derby (1891) has noted their distinction and remarked that: "A lack-luster aspect without evidence of alteration is the most certain sign of wear."

While it is true that a fresh appearance, like good crystal form, may be preserved during sedimentation this feature may prove of value as additional evidence of igneous or sedimentary source.

(iv) The Significance of Outgrowths: As regards outgrowths on zircons it seems probable, on the basis of Butterfield's and Trueman's findings, that they will prove of some value in determining the source rock of the sediment in which they occur e.g. should zircons with rounded and worn outgrowths be encountered in a sediment the conclusion that the immediate source rock was a clastic sediment, or more probably a metamorphosed clastic sediment seems justified.

(v) The Significance of Varietal Features: The zircons in many rocks possess distinct individuality in their form and colour. Unfortunately, it seems impossible, with one exception, to relate the observed changes in varietal characteristics of the zircon directly to a rock type or particular mode of formation with any certainty. The only variety described in the literature examined which can be definitely related to a rock type is the zircon found in a granophyr in the Lake Superior Pre-Cambrian by Tyler and described below.

The varietal character of zircon, therefore, only attains importance after an examination of the zircons in the suspected distributive province has been undertaken. Once the type of zircon occurring in the various rock types making up the distributive province is known it is a relatively simple matter to relate the sediments derived from the distributive province to their particular source rock. This method of attack has been widely used by British petrographers in tracing various sediments containing purple zircons to their source in the regionally-metamorphosed rocks of the Highlands (the Lewisian gneiss and Moine schist).

In short, once the ultimate geological source is established of a mineral whose specific properties proclaim it an adequate indicator, it becomes per se, an invaluable guide not only in "placing" the distributive province, but also in reconstruction of the salient events with which the particular sediment or sediments have been concerned.

Varieties of Zircon: As regards physical properties the majority of zircons appear to fall into 3 major groups: (1) The Hyacinth (2) the Malacon and (3) the "Normal" type zircon. The following descriptions are based on the work of Tyler, Marsden, Grout, Thiel (1940) in the Lake Superior Pre-Cambrian.

(1) The Hyacinth: The colour of the zircons ranges from a very faint pinkish tint to a deep brownish purple, purple and pink. The distinctly coloured ones are slightly pleochroic from dark to light purple and are known as hyacinth. Prismatic grains with several pyramidal faces are common; in some grains this gives the impression of rounding. Grains with definitely rounded crystal angles are common, and some are so well rounded that they resemble detrital grains although they occur in granite. Some grains have a ditetragonal prism, whereas others have only the normal prism associated with a steep pyramid. The grains commonly show faint zoning and contain a few crystalline inclusions. The surfaces of the zircons may be smooth or may show slight irregularities and striations.

The fractures, evident in some grains may be related to the crushing operation or may be primary.

The indices of refraction were determined at 26°C. with sodium light using a series of index liquids consisting of methylene iodide, sulphur and yellow phosphorous. The index of refraction of the liquid was determined by the minimum deviation method using a hollow prism. No = 1.900 - 1.905, Ne = 1.940 - 1.945, Ne - No = .04. Probable accuracy of index 0.005 ±.

The hyacinths are very similar to the "purple zircons" from the rocks of Scotland. Mackie described these in the Lewisian gneiss and Moine schist and proved their distribution from that source to the sedimentary rocks of the British Isles. He also reports this variety of zircon in some granites and gneisses of Canada.

(2) The Malacon: This variety of zircon is characterized by abnormally weak birefringence, dull lustre, and cloudy altered appearance. The grains usually have a rounded prismatic to spherical outline; a few are euhedral elongated prisms with steep pyramids. The dimensional ratios observed range from 6:1 to about 1:1. The zircons are colourless to pale dirty yellow, and many contain abundant dust-like inclusions suggesting alteration. A few are zoned parallel to the exterior form and many grains have etched and striated

surfaces.

Zircons of this type show birefringence of the first order grey and yellow, and occasional large grains show the first order red. In some the birefringence is variable. Grains of normal zircon comparable in size would have birefringence in the second and third orders. The index of refraction ranges from 1.795 to 1.850. Shadowy extinction and a double Becke line makes it difficult to obtain accurate results. It is evident, however, that this variety has a wide range in index of refraction and that the upper limit is below the lower index of hyacinth. This type is the variety "malacon" or more specifically the "c" zircon of Stevanovic (1903). According to Chudoba and Stackelberg (1936) when "c" zircon is heated to 1450°C. for 6 hours it changes to normal "b" zircon with normal high sp. gravity, refringence, and birefringence.

The altered appearance of this type of zircon suggested that the grains might be hyacinth decolourized by exposure to heat or a radioactive element. To check this possibility, hyacinth grains were decolourized by heating; however, they retained their original bright lustre and normal birefringence. In no way did they resemble malacon. An attempt to colour the malacon by exposure to radium chloride, similar to the method described by Strutt (1914) proved unsuccessful. There was no noticeable change in colour. Hyacinth was also exposed to 4 milligrams of radium chloride for 120 hours with no change in properties.

Malacon may simply be a hydrated form of zircon, resulting from weathering of ordinary zircon. This does not seem to be true, however, for malacon occurs in dykes cutting metamorphosed sediments, whereas the metamorphosed sediment adjacent to the dyke contains only zircon of normal birefringence. The alteration would have to be selective, affecting the zircon in the dyke and not that in the metamorphosed sediment. This suggests that the zircon in the dyke and sediment originally differed in chemical composition. If this is true, the malacon is probably related to the igneous history or chemical composition of the intrusive.

A few hyacinths occur within grains of malacon. The knife-edge contact between the two types of zircon could be the result only of a marked change in the composition of the zircon. The converse is not true, for in none of the hundreds of slides examined by Tyler et al have hyacinths included malacon grains. The hyacinths included within malacon are thought to be xenocrysts from earlier rocks which have become incorporated in the granite containing malacon. If this is true, the association of the two types of zircon should be particularly common in localities where a later granite containing malacon intimately intrudes an older granite containing hyacinth; this appears to be so in the field occurrences. Zircon xenocrysts apparently are not rare, for Mackie refers to them in Scotland and Tyler has described them from the Lake Superior Pre-Cambrian.

(3) The "Normal" Type Zircon: The "normal" zircons usually have a well developed crystal form with sharp crystal angles. The habit is simple, commonly consisting of a combination of a unit prism and pyramid, the pyramid faces usually making an angle of about 45° with the prism. Some crystals are terminated by a basal pinacoid. A few show both first and second order prisms. The crystals vary somewhat in shape and have dimensional ratios from 10:1 to 1.3 : 1.. The most common form has a dimensional ratio of about 3:1. Many are zoned with the inner zones following the external crystal form, but there are notable deviations. There are numerous acicular, crystalline, and irregular gaseous and opaque inclusions, most of which have a random orientation, but a few show parallelism with a crystallographic direction. Some grains show imperfect growths, and others, slightly rounded, suggest resorption of an earlier crystal. Many grains are cracked and broken, possibly by the laboratory crushing. In some grains the fractures seem to be natural for iron staining extends into the cracks. Most of the zircons are water-clear, although some are light tan to yellow. They have strong birefringence and high refringence. The

indices of refraction are as follows: No = 1.915 - 1.920, Ne = 1.950 - 1.955. No - Ne = .040.

Zircon in Granophyr: The only variety of zircon which can be definitely related to a rock type, as mentioned above, is the zircon found in the granophyr of the Lake Superior region and described by Tyler. It is an universal variety, associated with a minor percentage of the "normal" type and occurred in 4 of the 10 samples of granophyr (a granitic differentiate of basic intrusives) examined by Tyler. This variety has a corroded appearance with jagged, serrated edges and a pitted, striated, and irregular surface. The grains have an irregular outline often vaguely suggesting prismatic form. They are usually cloudy and brownish but are occasionally colourless; the cloudy brown colour is caused by numerous brown dust-like inclusions.

This variety is thought to be due to partial resorption of earlier formed crystals, resulting in the irregular serrated grains. Some retain a portion of the crystal form characteristic of the "normal" zircon -- a part of the grain may be irregular and the other part may show the normal crystal habit. This probably resulted from the partial inclusion of the crystal in some other mineral which protected it from resorption. This variety seems to indicate a particular environment of development which must be closely related to formation of the granophyr.

(e) Rock Fragments as Clues to the Source of Sediments.

Investigation of provenance must take into account not only mineral evidence but also that arising from a study of the coarser constituents, i.e. boulders, pebbles and rock fragments of macroscopic size. Many examples of the significance of these components occur throughout the literature e.g. A. Gilligan's (1919) investigation of the pebbles of the Millstone Grit of Yorkshire; T.G. Bonney's (1900) work on the Bunter Pebble Beds of the Midlands and Milner's (1923) study of Wealden deposits of S.E. England.

As pointed out by Pettijohn (1948), although coarse grained rocks, both igneous and metamorphic, rarely appear as detrital grains in the medium-grained clastics (the latter being derived primarily by the disintegration of the former) fragments of rocks of fine grain may appear in the arenites and in some instances they form the dominant clastic constituent, exceeding even quartz.

Almost any fine-grained rock can appear as a detrital grain. Most common, however, are those most resistant to chemical or mechanical break-down. Of special interest is chert. This material appears in both the orthoquartzites and in the greywackes. Its presence is one of the best indications that the containing rock has been derived from pre-existing sediments. In most cases the presence of chert probably is the record of the condensation of a great body of limestone in which it was once a minor constituent. Similar to chert and difficult to distinguish from metamorphic chert are fine-grained quartzite particles. Those of coarser grain, consisting of but a few individual quartz grains, are most readily recognised. As is typical of quartzites, the constituent grains exhibit sutured contacts with one another.

Less common in most arenites, but very abundant in the greywackes, are fragments of slate, phyllite and schist. These rock particles are recognised by the parallel arrangement of their constituent grains, of which the micaceous minerals are most common. To those rocks in which schist particles play a leading role, the name "schist arenite" has been given by Krynine (1937). Some of the shale or slate fragments have ill-defined boundaries, which suggest partial disintegration of the particle following burial. These may be intraformational.

Clastic limestone particles are rare in most arenites, but the calcarenites are composed of little else. Such particles, however, were probably of subaqueous fragmentation and are not the product of normal rock weathering.

The aphanitic igneous rocks, such as rhyolite and trachyte, may appear in some arenites and be abundant in those which contain a generous amount of volcanic glass and other tuffaceous debris. The microstructures and textures of these particles and their associations serve to identify them.

(5) THE DETERMINATION OF DIRECTION OF SOURCE

The direction of source may be determined from an analysis of:

(a) the orientation of detrital particles

(b) the lateral variations of detrital particles.

(a) The Orientation of Detrital Particles.

The preferred orientation of pebbles in some gravel accumulations has long been noted. The overlapping shingling effect of flat pebbles in certain conglomerates has commonly been described as "imbricate structure".

Imbricate arrangement of tabular pebbles is a common structure in river-laid rubble and gravel deposits, both ancient and modern, and may also occur, though probably rarely, in beach deposits. In this structure made by platy fragments and pebbles that are considerably longer and broader than thick, the long axis of the pebble dips upstream since in that position the fragment offers least resistance to the current. Hence in stream gravels the pebbles are shingled upstream, whereas in beach deposits they are imbricated seaward and down the slope of the deposit.

Becker (1893) fully explained the manner of formation and relation to current flow of imbricate structure as follows: "If a flattened pebble is dropped into a running stream, the water will exert a pressure upon the stone until its inertia is overcome, and during this time the pebble will tend to swing across the current so as to present its greatest area to the pressure. As soon as the resistance due to its inertia is overcome, the pebble will sink through the water as if the fluid were at rest till its edge touches the bottom, and it will then tip downstream till it meets support. In rapid stream irregularities in the bottom cause local upward currents, which project pebbles into the main current much as if they had been dropped into it. These pebbles sink to the bottom again where the movement of the water is more uniform. Many pebbles thus deposited will, with few exceptions, be inclined downstream and will rest against one another like overlapping tiles.

"This relation explains the fact that both in modern streams and in the ancient river channels containing the auriferous gravels, many of which have been tilted since their deposition, the pebbles "shingle upstream" or "imbricate" toward the source. Elongated, rod-like pebbles are usually found lying across the channel. The indication afforded by this behaviour of pebbles seems entirely trustworthy so far as the local current is concerned. In applying it, however, it must be remembered that powerful streams are often accompanied near shore or close to obstructions by local "back currents", in which the pebbles would be arranged in a direction opposite to that of the main stream."

Such preferred orientation, however, is not always apparent in the outcrop and is discovered only by plotting on a stereographic net the long axes, or normals to prominent faces, of several hundred pebbles. The graph thus constructed usually discloses a weak though clear preferred orientation (Fig. 3). In aqueous gravels, the fabric is a response to water-current flow; in till it records ice-movement. The orientation of the till pebbles is a valuable criterion of direction of ice flow if striae on bedrock are not available or are very scarce.

Finally, Krumbein (1942 a) from his recent studies of the gravel deposits of San Gabriel and Arroyo Seco Canyons concludes as follows: "Considering the numerous swirls, eddies, and reverse currents that may be present in floods, the general agreement of the preferred orientation to valley trend is significant. Apparently the mean azimuth may be safely considered as a statistical index of direction of stream flow."

In a manner somewhat analogous to that outlined

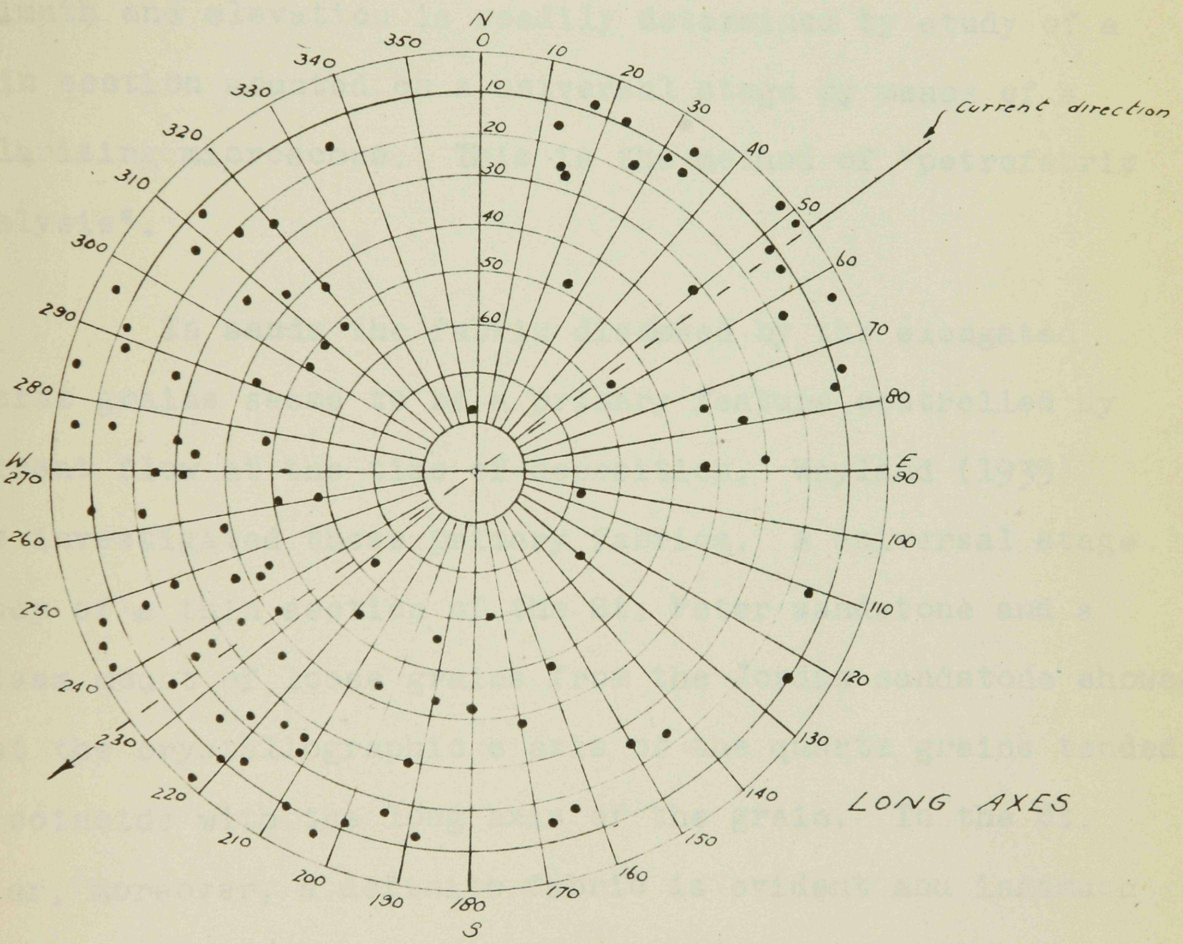


Fig. 3 River-gravel fabric. Polar co-ordinate chart of long axes. (From Krumbein, Geol. Soc. Am., Bull., Vol. 51, 1940, fig. 3, p. 652)

for the pebbles, the positions of the long axes of quartz sand grains may be plotted. Usually the long axis itself is not determined, but rather the optic axis of the quartz which is the crystallographic axis along which the quartz grain is elongated. The position of the optic axis, i.e. its azimuth and elevation is readily determined by study of a thin section mounted on a universal stage by means of a polarizing microscope. This is the method of "petrofabric analysis".

In sands the fabric disclosed by the elongated quartz grains seems to be a primary feature controlled by current flow at the time of deposition. Wayland (1939) has investigated these primary fabrics. A universal stage study of a thin section of the St. Peter sandstone and a balsam mount of loose grains from the Jordan sandstone showed that the crystallographic c axis of the quartz grains tended to coincide with the long axis of the grain. In the St. Peter, moreover, a definite fabric is evident and inasmuch as this rock is without any other evidence of deformation, Wayland concluded that the fabric was primary and was produced at the time of deposition by alignment of the elongate quartz grains by the bottom currents. Further, E.C. Dapples and J.F. Rominger (1945) from an orientation analysis of fine-grained clastic sediments, based upon the projection of the grains visible on the stratification plane, reached the following significant conclusions:

(i) The particles of fine clastic sediments are not oriented at random but exhibit diagnostic patterns which are a product of their depositional environment.

(ii) A preferred elongation parallel to the current direction exists among grains in fluvial and eolian environments; long dimension orientation in gravity sands is apparently random.

(iii) In fluvial, eolian, and gravity environments the larger ends of the grains tend to lie toward the source.

It is obvious, therefore, from what has been said above, that the source direction of fluvial and eolian sediments can be determined accurately by means of fabric analyses.

(b) Lateral Variations of Detrital Particles.

The transportation and redistribution of the products of weathering comprise a group of complicated processes acting on a vast scale.

The agents of transportation are wind, running water, ground water, waves and subaqueous currents, ice, and -- independently of any medium -- gravity. Of these running water, waves and subaqueous currents are by far the most important, though ground water carries appreciable quantities of dissolved solids. Materials transported by fluid agents may be carried in solution, in suspension, by saltation, or by rolling.

The effects of transportation on sedimentary detritus are due to (1) abrasive action and to (2) sorting. These two processes bring about a progressive change in size, shape, roundness, and composition of the detrital particles with increasing distance from the source. It follows, therefore, that if these lateral variations of the detrital particles are traced within a given area they will provide an accurate indication of the direction of transport, in other words they will indicate the source direction.

The nature of the lateral variations in size, shape, roundness and composition of detrital particles under the influence of transportation is best discussed under two separate headings: (1) Abrasion and (2) Sorting.

(1) Abrasion:

(i) The effects of abrasion on the size, shape and roundness of detrital particles: Krumbein (1941 a) investigated the relations among size, shape and roundness during abrasion experimentally. In the experiment a load of rock fragments was abraded for varying intervals of time in a tumbling barrel, and after each interval measurements were made of the size, sphericity, and roundness of each of the particles.

Figure 4 shows the results of the experiment graphically. The curve of arithmetic mean weight (size) descends rapidly from its initial value of 155 grams, but the curve shows a continuously decreasing slope as distance increases. The graph of roundness rises rapidly from its initial value but flattens noticeably beyond the first 3 or 4 miles; toward the end of the experiment there is practically no further increase in rounding. Sphericity shows only a slight change during the entire experiment. From an initial value of 0.65 the graph rises moderately rapidly during the early part of the experiment, but during the later stages there are no marked changes in the numerical values.

The experimental data present several suggestions regarding the nature of the changes which take place during abrasion. It seems fairly clear that size will be continuously reduced until ultimately the particles will be worn away. On the other hand, although the roundness and sphericity increase continuously during the experiment, there is strong suggestion that they approach limiting values which may depend upon certain initial values. That is, a pebble with noticeably different values of its three size axes may never reach the value of 1.00 for either its roundness or sphericity.

(ii) The effects of abrasion on Mineral Composition: It is generally supposed that certain minerals, notably the pyroxenes,

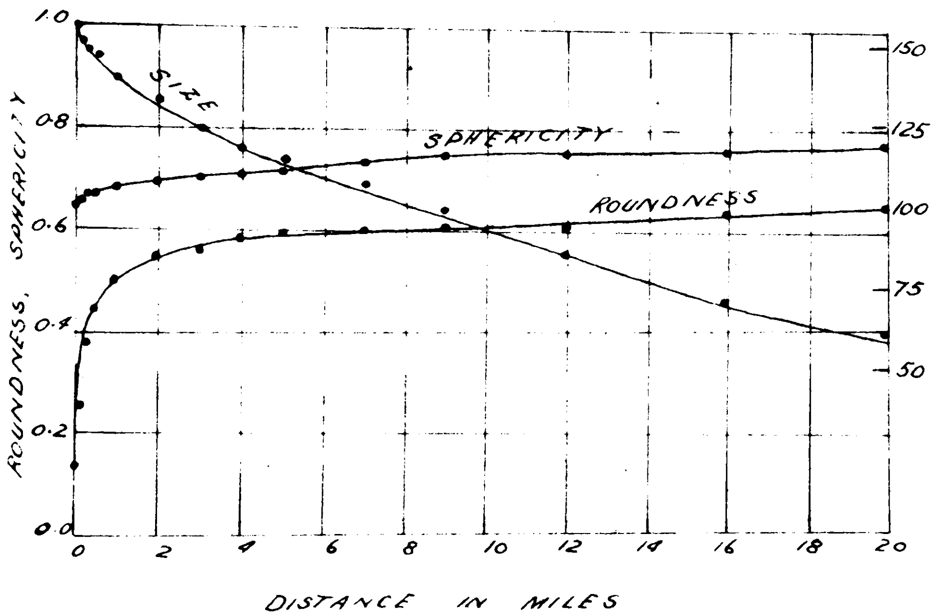


Fig. 4 Size (weight), roundness, and sphericity of limestone fragments as functions of distance during abrasion (After Krumbein, Journ. Geol, Vol. 49 1941, fig. 3, p 492)

amphiboles, and feldspars, are rapidly eliminated during transport, and that therefore their presence in sediments indicates proximity to the source rocks. Conversely, the absence of these minerals is taken to indicate (1) deep weathering of the source rocks, (2) derivation from pre-existing sediments, or (3) transportation for a considerable distance from the source area. The third alternative, namely, elimination during transport, does not appear probable. Most available evidence indicates that wear is a relatively slow process. In their Mississippi River studies Russell and Taylor (1937) found that selective destruction of "less resistant" minerals appears to be of slight consequence between Cairo, Illinois, and New Orleans, Louisiana, a distance of 950 miles. Rittenhouse (1943) found that in the Rio Grande, many grains show little evidence of either wear or breakage, while at Bosque, New Mexico, the original crystal form of the easily abraded minerals apatite and hypersthene commonly has only been slightly modified. At the same locality, many grains of hornblende and pyroxene are characteristically sharp cornered, and some grains of these minerals have needle-like projections. Preservation of such features after a minimum of 60 miles transportation (from above Alameda, New Mexico) must indicate very slow wear. Further, Theil's (1940) tumbling barrel experiments with quartz, feldspar, garnet, tourmaline, hornblende, and apatite show that differential wear occurs but is very slow. Apatite was reduced in size most rapidly, quartz least rapidly. Even after travel of 5000 miles, however, about 15% of the apatite of the coarsest size (2 - 1 mm.) still remained in that size grade. According to Rittenhouse (1943), Theil's experiments apparently similated bedrock transportation and therefore in streams like the Rio Grande, where suspended-load transportation of fine sand is important, the absolute and differential rates of wear may be expected to be much slower.

On the basis of the above observations and from his work at Cedar Point, Ohio, Pettijohn (1933) concludes that change in mineral composition is due to selective sorting. The selection is due to both specific gravity and shape. Neither chemical stability nor resistance to abrasion seem to be factors in changing mineral composition.

(2) Sorting:

That most agents of transportation tend to sort the particles carried according to their size, shape, and specific gravity, is known to all students of sediments. This sorting may be divided conveniently into two types, following Russell, (1939), namely, "local" sorting and "progressive" sorting. The first is expressed by bedding, each bed being characterized by a different assortment of grains. The second type is lateral variation or facies change. A bed may become coarser grained in one direction, finer-grained in the opposite.

The factors involved in either type are the size, shape, and specific gravity of the particles.

(i) Effects of Sorting on Size, Shape and Roundness: Lateral facies change expressed by change in mean size of grain is well known. In general, sediments coarsen in the direction of their source. Only a few quantitative studies of such changes have been made, and the laws governing such change are poorly understood. According to Pettijohn (1948) none of the studies undertaken has demonstrated any progressive increase (or decrease) in the uniformity (coefficient of sorting) of the material in the down-current direction. In other words it seems that in most cases size decrease in the down-current direction results from abrasion not sorting.

Both experimental evidence and field observation indicate that of grains moved by suspension, the most spherical grains, other things being equal, will settle out before those of lower sphericity. Therefore the less spherical will tend to outrun the more spherical in the down-current direction. If traction is the dominant mode of transport the opposite will tend to prevail. Grains of high sphericity will tend to roll more readily than those of lower sphericity, and therefore will outdistance the flatter ones.

Progressive sorting according to shape may result in a progressive change in mean roundness. Krumbein's (1942 b) work bears out theory in the assumption that roundness itself is not a significant factor in sorting. But because there is a rather good correlation between shape and roundness, a shape sorting carries with it a roundness sorting. If the selective action segregates the more spherical grains, it will also segregate the better-rounded grains, and conversely. Thus, progressive changes in the mean roundness of sediments, usually ascribed entirely to abrasion, actually must be mainly the result of sorting according to shape.

(ii) Mineral Composition and Sorting: Sorting according to size, shape, and specific gravity tends to produce lateral variations in the mineral composition of a sediment.

Theoretically, suspension sorting leads to the largest, most spherical, and heaviest minerals being first deposited and therefore these minerals, under current conditions, lag behing those with the opposite characteristics. A series of samples taken of sediment in transit should show the changing proportions in accord with this principle.

The sands of Cedar Point, a spit built across Sandusky Bay, of Lake Erie, and described by Pettijohn and Ridge (1933) afford an illustration of this law. In the direction of transport garnet declines notably; hornblende shows a complementary increase (Fig 6). Diopside and hypersthene of intermediate specific gravity show only little change.

Variations in nature are governed by other factors than sorting alone. The Mississippi River sands, according to Russell (1937), disclose no important changes in mineral composition during transit. The sands of the River Tessin did show marked progressive changes but these were ascribed by Burri (1929) neither to sorting nor to selective abrasion, but to contamination. The notable decline in hornblende exhibited along the course of the stream is explained by progressive dilution of the bed load by non-hornblende-bearing sands.

The problem of "contamination" has received considerable attention since it was first formulated by Cayeux (1929). As pointed out by Cayeux, a sediment in process of transport by a stream is diluted or contaminated at the junction point of each tributary. In general the tributary introduces material coarser than the far-travelled debris of the master stream. The stream pebbles, therefore, reflect the character of the local bedrock, whereas the sands are a clue to the character of the rocks of the headwater area. Full appreciation of the contamination principle, therefore, will lead the investigator to recognition of multiple sources of the material of which any clastic is composed, and especially to reworking of older sediments.

In conclusion it may be noted that considerable doubt seems to exist as to the relative importance of abrasion and sorting in bringing about lateral variations in detrital particles. For the purpose of the present investigation, however, the relative importance of these two processes is of little consequence. Suffice that under the influence of transportation there is a progressive change in the character of the detrital particles with distance transported. As stated above, if these progressive changes in composition, size, shape, and roundness are carefully traced they will indicate the direction of transport, and thus the direction in which the source rocks lie. The progressive changes in detrital particles, under the influence of transportation, which have been observed in the field by such workers as Krumbein, Pettijohn, Russell and others are indicated in the accompanying graphs. (Figs. 5-11).

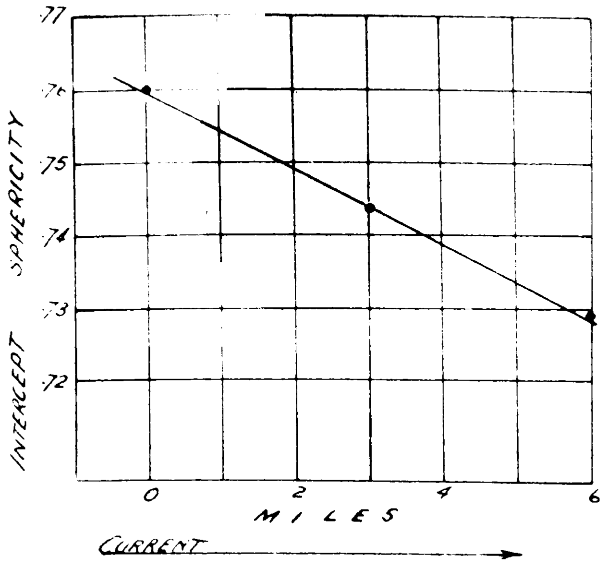


Fig. 5 Relation of arithmetic mean sphericity of 0·35-to-0·25mm size grade and position on beach, Cedar Point, Ohio. (After Pettijohn and Lundahl, Journ. Sed. Pet. Vol. 13, 1943, p 73 fig. 4.)

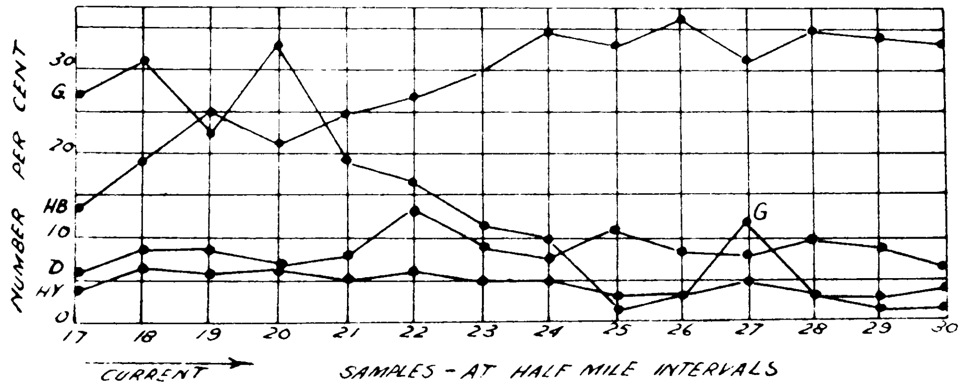


Fig. 6 Diagram of mineral. variations in 0·177-to-0·125 grade of spit, Lake Erie, Ohio, G, garnet; HB, hornblende; D, diopside, Hy, hypersthene (After Pettijohn, Recent Marine Sediments, Fig 5, p610)

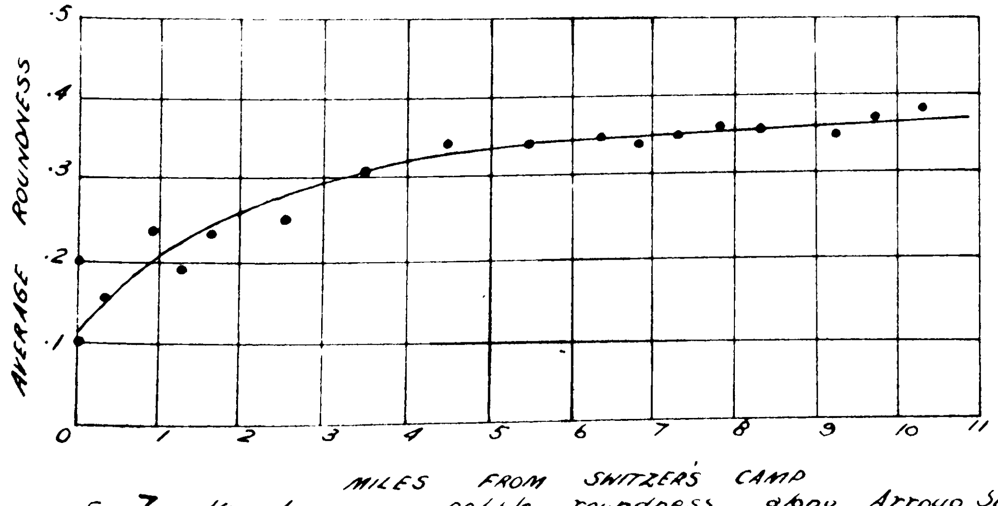


Fig 7. Variation in pebble roundness along Arroyo Seco, California. (After Krumbein, Bull Geol. Soc. Am., Vol. 53, 1942, fig. 14, p 1386)

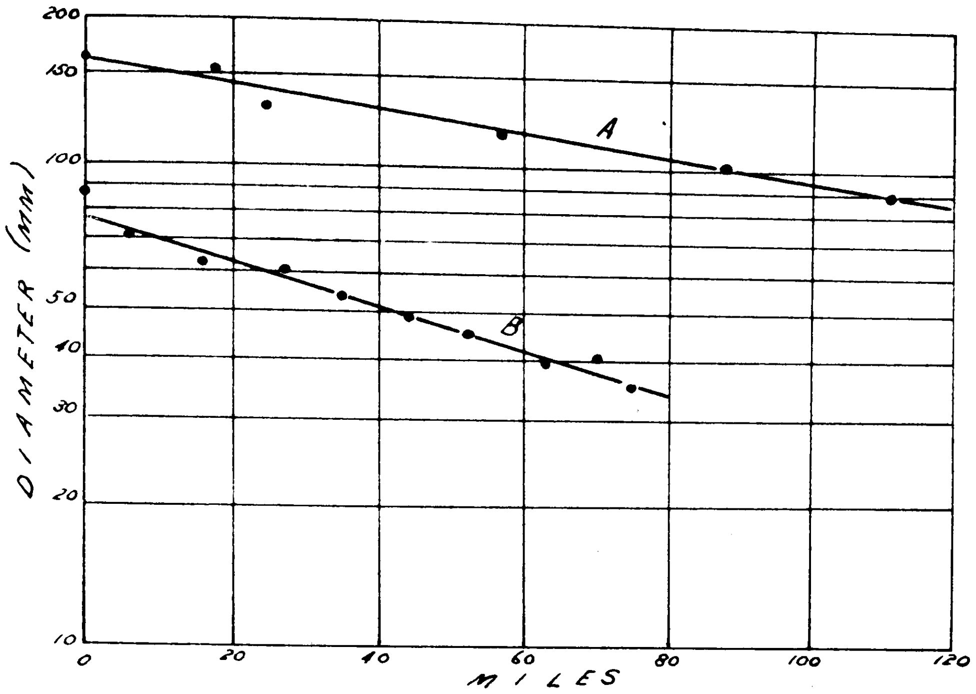


Fig. 8. Relation of diameter of pebbles to distance of travel. A, largest cobbles in Rhine River (after Sternberg and Barrell); B, River Mur (after Grabau and Hochenburger.)

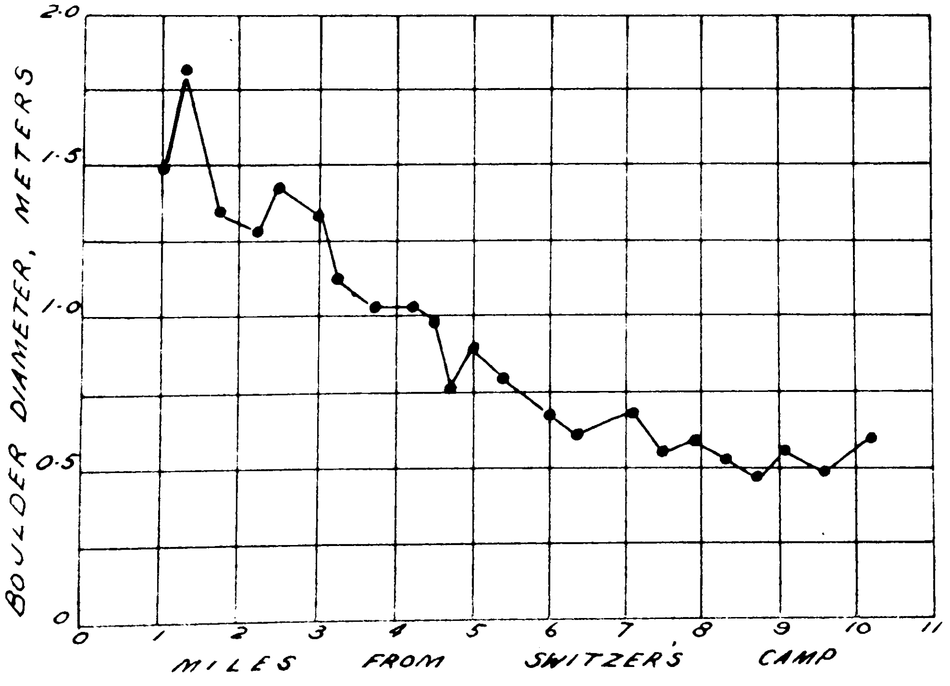


Fig 9 Variation in size of granodiorite boulders along the course of the Arroyo Seco, California. (After Krumbein, Geol. Soc. Am. Bull. Vol. 53, 1942, p 1381, Fig. 11)

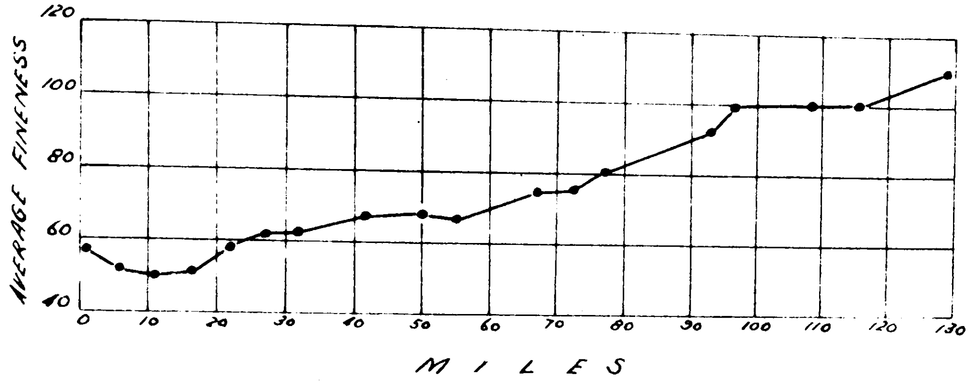


Fig. 10 Apparent decrease in size with distance of transport of sand on Atlantic coastal beach. (After MacCarthy, Am. Journ. Sci., series 5, vol. 22, 1931, p. 38)

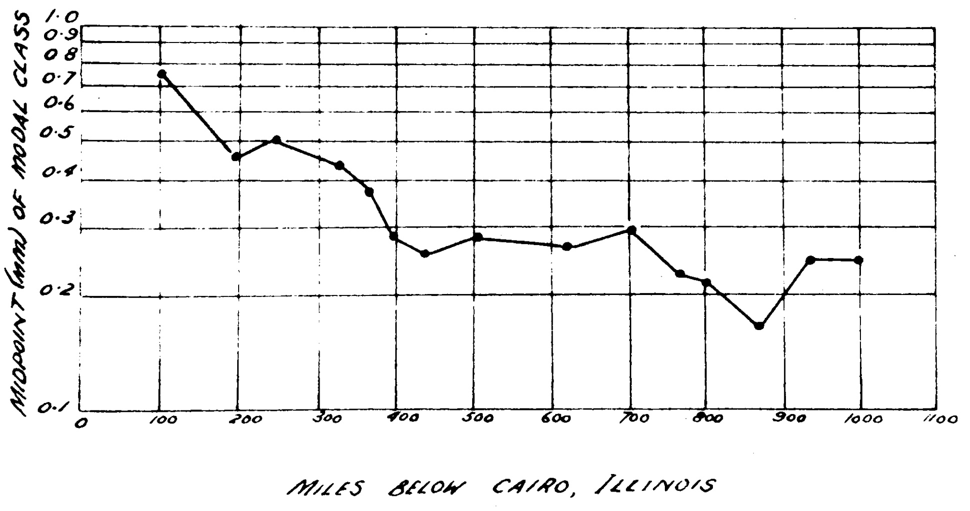


Fig 11 Downstream decrease in grain size of Mississippi River sands as shown by mid-points of modal size class. Moving average of three values (data from Russell)

(6) TECHNIQUES INVOLVED

The techniques involved in determining the source of clastic sediments are essentially those fundamental to the science of sedimentary petrography. Numerous texts have been written on methods of study of sediments, and that these methods are continually being modified, or replaced by supposedly simpler and more accurate methods is evident from a study of the literature. In the final analysis it seems that the choice of technique depends on the personal preferences of the worker, and on his experience.

An outline of the techniques involved in any basic study of the sedimentary rocks is given below, while a detailed treatment of the subject is to be found in the following texts:

(i) A. Holmes: Petrographic Methods and Calculations, London, Thomas Murby and Co., 1930.

(ii) W.C. Krumbein and F.J. Pettijohn: Manual of Sedimentary Petrography, New York, Appleton-Century Co., Inc., 1938.

(iii) H.B. Milner: Sedimentary Petrography (3rd Ed.), London, Thomas Murby and Co., 1940.

(iv) W.H. Twenhofel and S.A. Tyler: Methods of Study of Sediments, McGraw-Hill Book Co., New York, 1941.

(a) Sampling.

Sampling should be effected at chosen intervals along and transverse to the strike of the beds, such intervals depending on the extent of the deposit, persistence of lithological facies and topographical and structural considerations.

Sampling may be done by channeling if the sedimentary formation is rather homogeneous or if it is desirable to represent the average characteristics of the sediment. However, some rocks are so hard and tough that cutting of channels is very difficult and time consuming. In such cases a representative sample may be obtained by breaking off chips along an assigned line. This procedure is similar to that of channeling but the chips must be so obtained that equal distances are represented by equal quantities of material. This method is not so reliable as channeling, for the personal factor is greater in chipping.

A sample may be obtained by collecting one or more chips of rock at a given point in a sedimentary unit. If the unit is homogeneous throughout, the sample is representative, but if there is vertical or lateral variation, a single sample is of little value as a basis for generalization.

Composite samples may be obtained by combining any number of single samples. The value of the composite sample lies in the fact that it consists of many individual samples from various parts of a sedimentary unit and therefore is representative of the unit as a whole.

In determining the direction of provenance the variations from place to place on a given horizon are of the greatest importance. In order to determine these lateral variations of a sedimentary unit or units, channels should be cut at intervals of a 1000 ft. or more, and the position of the sample with respect to definitely recognisable layers should be recorded.

(b) Preparation of Sediments for Analysis.

Preparing a consolidated sediment for analysis involves crushing or disaggregation, sieving and splitting of the sample.

The rock should be crushed with a heavy chilled-steel pestle in a steel mortar which it closely fits. A few small lumps are taken one by one, and the pestle is given a dozen sharp blows with a hammer. Grinding and rubbing must be avoided, as such motions lead to the production of an objectionable amount of fine dust. The fragments are then sifted through a fine sieve. One having 60 meshes to the inch or apertures of about a millimetre is generally suitable, and ensures that a majority of the grains that pass through consist of single minerals. The coarser fragments are then again pounded, and a second crop of fine materials sifted out. This alternation is repeated until the whole of the sample taken is reduced to grains of the desired grade. Frequent sifting is desirable to avoid over-production of finer material than is necessary, and to preserve small crystals in an unbroken state.

If accurate analyses of size, shape, and roundness are to be made disaggregation without breaking or crushing the constituent grains is advisable. Taylor and Georgesen (1933) disaggregated clastic rocks by placing them in a pressure chamber where they were subjected to pressures as high as 350 pounds per sq. inch and to accompanying high temperatures. In addition a solution of sodium sulphate was used on some samples to disaggregate rocks by force of crystallisation, while on other samples solutions to dissolve the rock cement were used. It was found that the stronger acid solutions containing stannous chloride gave the best results with rocks tightly cemented by ferruginous compounds. A two-tenths normal sodium hydroxide solution proved satisfactory for dissolving siliceous cements. Rocks held together by calcareous cements were readily disaggregated in weak acids. As far as Taylor and Georgesen could determine the solutions dissolved the cementing materials without appreciably affecting the constituent grains of the rock. A weighed pebble of quartz was included in each sample to check the effect of the solutions on crystalline silica and the solvent action on the crystalline silica was found to be negligible.

In most cases a saturated solution of sodium sulphate proved to be the best solution for disaggregation. Further, covering each sample with liquid, whether water or some solution was found to be very important for in the experiments specimens placed in dry beakers and subjected to the action of vapour, showed very little disaggregation as compared to identical samples placed in beakers filled with liquid.

Taylor and Georgesen found that all the types of sedimentary rocks used were weakened by subjecting them to appropriate solutions under pressure. Many of the specimens were completely disaggregated. Most of those not completely disaggregated were weakened sufficiently to make it possible to complete the process of disaggregation by tapping the sample with a rubber mallet.

The crushed or disaggregated material, after sieving, must next be split to the desired workable quantity in such a manner as to obtain a representative fraction. Splitting is most satisfactorily accomplished with a mechanical sample splitter. If a sample splitter is not available, the splitting may be done by hand as follows: the sample is poured in the form of a cone and then flattened into a round, disk-like pile. This is then divided into four quarters. Two opposite quarters are rejected and the other two are retained. These are again piled into a cone, and the procedure repeated until the desired fraction is obtained.

(c) Mineral Separation.

The following procedure is recommended as a simple and effective method of mineral separation.

(i) Examine sample with binocular microscope, noting chief mineral constituents and their relative abundance, presence of any rarer heavy minerals, fossils, etc.

(ii) Liquids used for separating minerals may be bromoform or tetrabromoethane. S.G. 2.9. Determine S.G. by means of a Jolly balance or pycnometer. See Dana or Technical Paper 381 U.S. Bureau of Mines (J.D. Sullivan: Heavy Liquids for Mineralogical Analyses).

(iii) Fill one-third evaporating dish with heavy liquid. Sift sand onto the liquid as thoroughly as possible covering the entire surface. Stir it gently with a glass rod around edges and in middle, each stroke being in an opposite direction to avoid setting up currents. Entire sample should be added to heavy liquid, and worked in this manner. Pour off lighter grains suspended in bromoform into a large filter paper which has been marked with the laboratory number of the sample and "light". Collect filtered liquid and rinse evaporating dish containing now heavy and some light minerals with heavy liquid, and decant again, repeating procedure until only the heavy grains remain in the dish. Place used undiluted liquid in a labelled bottle. Wash the light grains on filter with carbon tetrachloride and collect liquid in a separate bottle. Dry light grains in filter paper at 105°C. and save.

(iv) Wash off the heavy grains remaining in the evaporating dish with benzol or carbon tetrachloride on to a filter paper numbered and marked "heavy". Wash the grains thoroughly with the wash liquid and add diluted liquid to "Dilute" bottle. This recovered liquid must be distilled later to separate the heavy liquid.

(v) Magnetic Separation: If sample contains much magnetite this should be separated here by use of a horse-shoe magnet or Ding's magnetic separator.

(vi) Second Separation: This may be done to remove any light grains missed in the first separation and foreign matter such as bits of filter paper. Use the same apparatus as in the first separation, but fresh heavy liquid, collecting used and diluted heavy liquid in their respective bottles. Throw any light material away. Be sure and label the heavy grains in numbered filter papers.

(vii) Finally the minerals separated are examined and identified.

(d) Quantative Determination of Mineral Content.

Lateral variation in the abundance of individual minerals, especially heavy minerals, of a particular grade size is of importance in determining the direction of provenance.

Three general methods of determining the abundance of the various minerals in a sample have been followed; estimation, counting of particles or grains, and separation of particles followed by weighing.

For the present investigation counting the grains would seem to be the most satisfactory method. Dryden (1931) has shown that counts of large numbers of particles are not essential for accurate results, and that it is necessary to count only a few hundred grains to obtain workable accuracy. He suggested 300 from a representative slide. Accuracy increases as the square root of the number of grains counted, but above 300 the rate of increase is small. If 600 grains are counted, the error will be only half as great as if a count of 300 grains had been made. The probable error for the abundant species is much less than for the rare minerals. Percentages should be recorded in whole numbers, since fractional percentages suggest an accuracy that does not exist.

(e) Determination of Size, Sphericity, and Roundness.

(i) Size: Size may be expressed as:

(a) Volume
(b) Weight
(c) Surface Area
(d) Cross-sectional area or projection area
(e) Settling velocity
(f) Intercepts through particle or particle projection.

Of these measures of size, only the volume is independent of shape and density. The volume or the cube root of the volume can be taken as an index of size. Most often the nominal diameter or radius is used, which is the diameter (or radius) of a sphere having the same volume as the particle. Owing to practical difficulties, the volume is rarely measured directly excepting on very large fragments.

Weight is a good measure of size provided that all particles are of the same density. Like volume weight is rarely measured excepting on large fragments of uniform composition.

Surface area is a size measure, provided all fragments have the same shape. This fact, together with difficulties of measurement, renders such an index of size of little practical value, though the surface area of the particle or total area of the aggregate is an important property.

Cross-sectional and projection areas are commonly measured and taken as an expression of size. Sieving, for example, classifies on the basis of the least cross-sectional area. Long, pencil-shaped particles, therefore, may pass a sieve and be weighed with others of lesser volume (and hence of smaller size). Grains under the microscope, either loose or in thin sections, are photographed, microprojected, or drawn by use of a camera lucida. These projection images can be taken, with qualifications, as measures of size. As in the case of sieving and all other methods of size measurement, the results are usually reduced to a "diameter" basis, i.e. the diameter is calculated on the assumption that the particles are of spherical form.

The settling velocity is an expression of size only if both density and shape are constant, and is usually reduced to a diameter (or radius) basis on the assumption of spherical form and density of 2.65 (quartz). Small and large particles, however, obey different laws and no simple scheme of particle-size measurement of size of both large and small fragments exists.

Direct measurements of the particle "diameter" can also be taken as an expression of size. Here again the irregular shape of the particle creates difficulties.

(ii) Sphericity: Tickell's (1939) method of determining shape or sphericity consists in taking the ratio of the area of the particle as shown in a single place to the area of the smallest circle that will circumscribe the particle, or

$$\text{Shape} = \frac{\text{area of particle in plane of observation}}{\text{area of circle circumscribing particle.}}$$

Wadell's (1932) method for determining the sphericity of a particle requires measurement of the volume of the particle and of its longest diameter. The diameter of a sphere having the same volume as the particle is then calculated and the ratio of this "nominal diameter" to the long diameter is the sphericity of the particle.

Krumbein (1941 b) has recently devised a method in which only the long, intermediate and short diameters of a particle are measured; the sphericity is read directly from a chart by means of the two ratios between pairs of the diameters. This "intercept method" reduces the time required to a small fraction of Wadell's method, and yet the average values of the two methods agree within a few per cent.

Of the methods to determine sphericity that of Wadell seems to be the most exact, but the method of Tickell seems most easy to apply and gives results that are sufficiently accurate for most purposes. Further, according to Twenhofel (1941), in the present state of knowledge, too precise measurements seem to have doubtful value and it should also be realized that sphericity is probably largely controlled by original shapes of particles.

(iii) Roundness: Russell and Taylor (1937) set up five roundness grades as follows:

Angular: Showing very little or no evidence of wear; edges and corners sharp. "Secondary corners" numerous (15 to 30) and sharp.

Subangular: Showing definite effects of wear. The fragments still have their original form, and the faces are virtually untouched; but the edges and corners have been rounded off to some extent. Secondary corners numerous (10 to 20), though less than in the angular class.

Subrounded: Showing considerable wear. The edges and corners are rounded off to smooth curves, and the area of the original faces is considerably reduced, but the original shape of the grain is still distinct. Secondary corners much rounded and reduced in number (5 to 10).

Rounded: Original faces almost completely destroyed, but some comparatively flat surfaces may be present. There may be broad re-entrant angles between remnant faces. All original edges and corners have been smoothed off to rather broad curves. Secondary corners greatly subdued and few

(0 to 5). At roundness of 0.60 all secondary corners disappear. Original shape still readily apparent.

Well-rounded: No original faces, edges, or corners left. The entire surface consists of broad curves; flat areas are absent. No secondary corners. The original shape is suggested by the present form of the grain.

This arrangement has practical justification because the eye can readily distinguish slight differences in roundness when the roundness values are low, but cannot make such distinctions when the values are large. Fragments can be readily classified visually into these roundness classes by comparing them with standard images (Fig. 12).

(f) Determination of Sediment Fabrics.

Fabric is the orientation in space of the elements of which a rock is composed. The elements involved in sediments are of several kinds and include pebbles, mineral grains, and shell and fossil fragments, the first two elements generally being the most important.

(i) Pebble Orientation: Determining the orientation of pebbles in a deposit involves clearing an outcrop area (the size of which depends upon the abundance and size of the pebbles) and removing all loose pebbles from the face. The trend of the cleaned face is carefully determined with a compass and recorded as an azimuth measured clockwise from

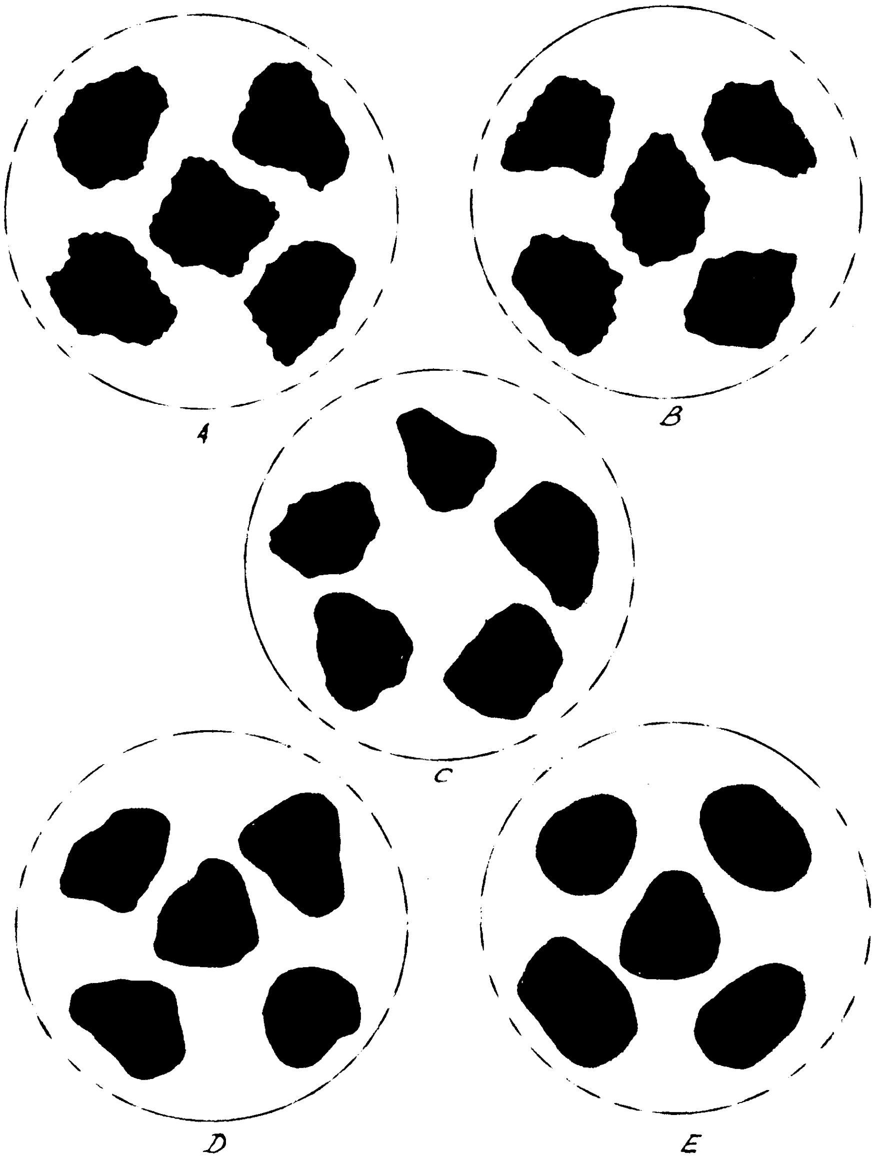


Fig. 12. Chart to show roundness classes A, angular, B, subangular; C, subrounded; D, rounded; E, well rounded. (From F.J. Pettijohn, Sedimentary Rocks, Fig. 24, p. 52)

the north point. The dip and strike of the sedimentary beds are also recorded. Vertical and horizontal lines are drawn on the individual pebbles with red and black pencil, respectively, while the pebble remains in its original position in the outcrop. The pebbles are then taken to the laboratory for further study.

In the laboratory the pencilled lines are carefully traced with India ink so that the marks will not be destroyed by subsequent handling and the pebbles are freed from the matrix. The marked pebble can now be reoriented in the same position with reference to the meridian and zenith in the laboratory as it had in the field and by use of a goniometer the azimuth and angle of dip of the long axis (a-axis) is measured. The axes thus recorded for a 100 or more pebbles may be represented by dots on polar co-ordinate paper (Fig. 3).

(ii) Grain Orientation: The orientation of the optic axis of quartz which is the crystallographic axis along which the grain is elongated may be determined by methods of petrofabric analysis. These methods have been fully described by Fairbairn (1949) and Knopf and Ingerson (1938).

Dapples and Rominger (1945) have investigated a two dimensional analysis of the position of a particle in a stratum. The method, depending primarily on the outline shape of the projection of grains, apparently provides sufficient diagnostic data to merit description.

A specimen of the material whose orientation pattern is to be investigated is photographed through a standard petrographic microscope. Magnification is increased further by photographic enlargement until the dimensions of the grains are raised to lengths ranging from 1/2 to 1 inch. Best results are obtained by using low-power magnification with the microscope and photographing onto a 3 1/4 in. x 4 1/4 in. negative. In this manner a large number of grains in sharp focus are obtained, and magnification is achieved principally through enlargement of the negative. Correct orientation of each photograph is insured by suspending a needle-point over the N.W. quadrant of the microscope field.

The method of determining and statistically studying the grain orientation is based upon the projection of the grains visible on the stratification plane. The bedding plane was selected as a surface of prime importance for several reasons: (1) it is generally recognised easily in outcropping strata and in drill cores; (2) knowledge of the orientation of the grains in the stratification-plane direction is necessary to give the source direction of the sediment; (3) the surface approaches a plane; (4) slight weathering of the bedding surface commonly results in the grains standing out in relief, hence, in the photograph the grain boundaries are distinct.

Types of Measurement: Two main types of measurements are employed in this analysis: (i) Elongation direction and (ii) end position with respect to that direction.

Knowledge of preferred elongation direction and the fact that this direction is parallel to the current direction in fluvial and eolian environments, limits the current to two possible directions. For example, if the elongation trend of grains in a fluvial environment is found to be statistically north-south, the current could have flowed from the north or from the south. A method of making the correct choice between the two possibilities is provided by determining the end position for each grain on the assumption that the larger end of a grain tends to lie up-current from the smaller end.

(i) Elongation direction: The most satisfactory method of measuring elongation direction is the least projection method. Elongation direction is considered as that of two parallel lines with the minimum amount of separation which can be drawn tangent to the grain projection (Fig. 13). In practice these lines are constructed readily with the aid of a parallel rule. This dimension has theoretical importance in that the least projection in most cases probably offers least resistance to a circumfluent medium.

(ii) End Position: The position of the greater area of a grain projection with respect to the centre of its elongation

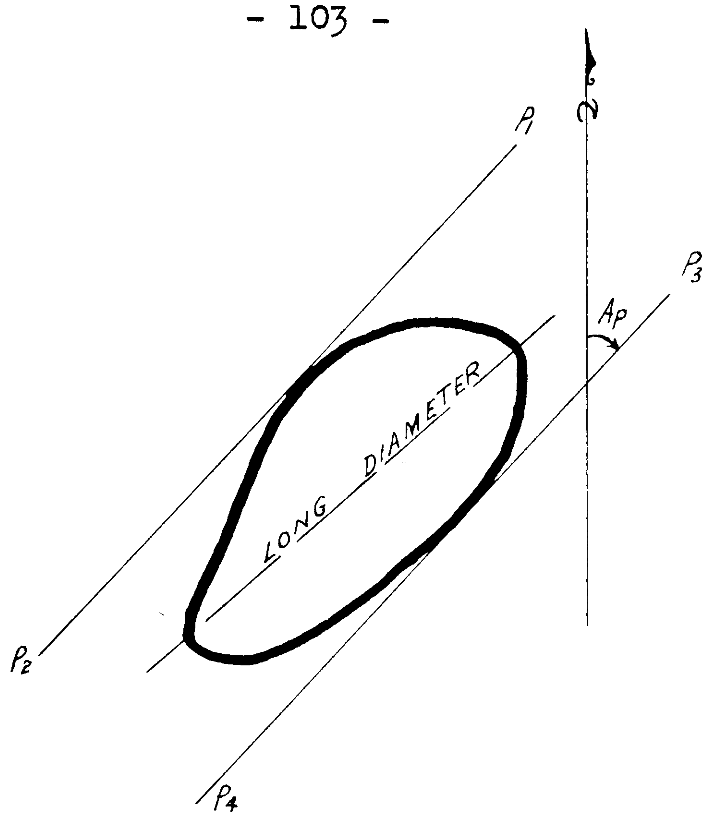


Fig. 13 Least projection measure of elongation azimuth.
P1P2, P3P4, least projection tangents. Ap, least projection azimuth

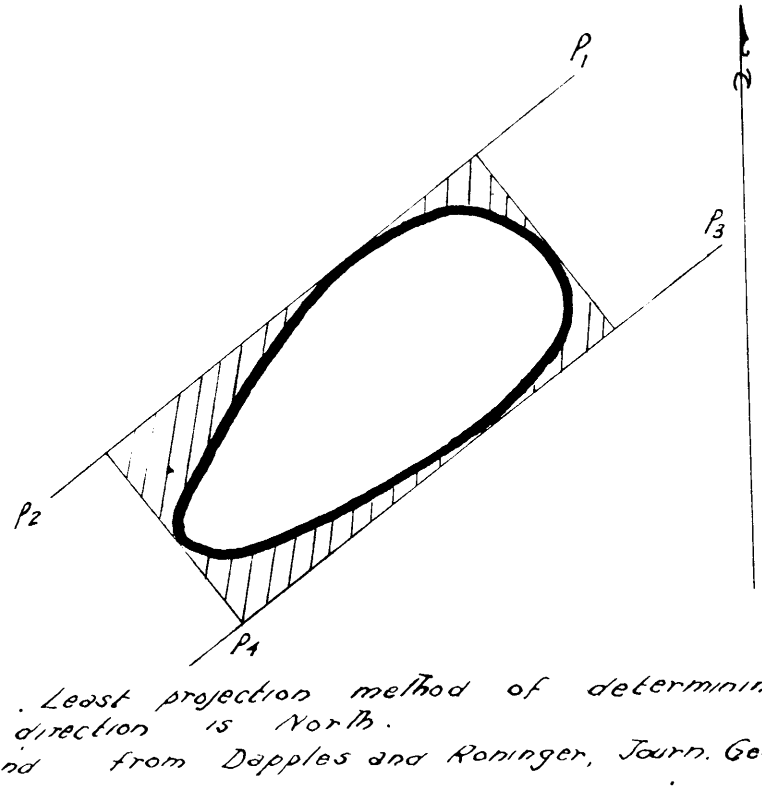


Fig. 14 . Least projection method of determining area direction.
Area direction is North.
(Fig and from Dapples and Rominger, Journ. Geol. Vol. 53, 1945, figs 1 and 2)

axis ("area direction") is evidently the projection equivalent of end position.

Dapples and Rominger (1945) have devised a method which provides a reliable visual measure of end position. In this method the least projection rectangle (rectangle formed by the least projection tangents to the grain projection and the perpendicular pair of tangents) is constructed around each grain (Fig. 14). The end of the grain having the greater area may then be determined by visual estimation of the half of the least projection rectangle having the least area outside of the grain projection. Grains to which the visual method cannot be applied with certainty may be omitted without harm.

Area direction data for 200 grains probably could be considered as sufficient to yield reliable results of this type of distribution.

Both elongation direction and end position (area direction) data may be represented graphically by means of histograms.

(7) SUGGESTED PROCEDURE FOR DETERMINING THE SOURCE AND DIRECTION OF SOURCE OF CLASTIC SEDIMENTS

In a detailed petrographic determination of the source and direction of source of a clastic sediment both crushed samples and oriented thin sections should be examined. From the crushed samples information regarding mineral composition may be obtained while the thin sections may be used for the determination of size, sphericity, and roundness, and orientation of the detrital grains as outlined in the previous section.

The securing of a representative sample of the stratum is obviously the first step in the investigation. This is accomplished best by collecting several samples from a known outcrop and averaging their results. About 3 samples within a linear limit of ± 10 ft. along the strike of a stratum and at a known elevation above some marker horizon would be taken. At each of the points sampled an oriented specimen would also be cut from which a thin section would be prepared.

From what has been stated above the mineral composition of a sediment, which is indicative of source rock, is determined from an examination of crushed samples while the direction of source is determined principally from an examination of the oriented thin sections. However, lateral variations in minerals of a particular grade size also provide valuable information as regards source direction. Cogen (1935) has suggested a method that makes quantitative variations of the heavy mineral crop readily apparent. In detail the method is as follows: The samples taken would be screened and each sample split into constituent grade sizes. The heavy minerals would be separated from a given grade classified as to species and counted. A count of all the heavy mineral grains that had been separated from a given grade would not be necessary. By the use of a miniature sample splitter a known fraction of the heavy crop suitable for counting could be secured. The grain counts in every case would be reduced mathematically to represent the number of grains in a given weight of graded material, e.g. 10, 25, or 100 grams. An average of the 3 samples would be taken as the standard for further comparisons. The average number of grains of each mineral species secured in this fashion would then be assumed to equal 100 per cent for each of the species represented. All future comparisons would be made with the type sample, and the percentages of the various heavy minerals would be functions of the quantities present in the type sample.

The scheme is best made clear by an illustration. Let the sample which will serve as a standard possess in a 20 gram portion of a particular grade size a heavy mineral crop constituted as follows: 150 grains of A, 200 of B, 50 of C, 25 of D, and 100 of E. Let there be four samples, taken at the same elevation above the marker horizon, which show respectively, an increase of the entire crop (No 1 in Table 8), a shrinkage of the entire crop (No 2), little

TABLE 8

Percentage Method of Comparing the Number of Mineral Grains in a Series of Samples

No. of grains in 20 gms. of __ mm. grade size

						Other Minerals	
Sample No.	A	B	C	D	E	F	G
Reference Sample	150	200	50	25	100		
1	305	435	100	55	210		
2	100	140	35	16	66		
3	145	210	50	27	98		
4	155	204	125	28	95		
5	a	b	c	d	e	f	g
			Per Cent by No. of grains				
R.S.	100	100	100	100	100		
1	203	218	200	220	210		
2	67	70	70	64	66		
3	97	105	100	108	98		
4	103	102	150	112	95		
5	$100 \cdot \frac{a}{150}$	$100 \cdot \frac{b}{200}$	$100 \cdot \frac{c}{50}$	$100 \cdot \frac{d}{25}$	$100 \cdot \frac{e}{100}$	$100 \cdot \frac{f}{k}$	$100 \cdot \frac{g}{k}$

$P = 100 . \frac{n}{t}$ where

P = Per Cent

n = number of grains of a mineral species in a given amount of a selected grade size

t = number of grains of a mineral species in the same amount of a selected grade size from the reference specimen.

k = any arbitrarily selected constant

deviation from the reference sample (No. 3), and a strong fluctuation in the quantity of only one mineral species (No. 4).

The table shows that when the proportions between the constituents of a sample are comparable to the proportions which exist in the reference specimen, the effect is to give percentages that are nearly alike for all five components. A general mass increase of the crop produces a percentage ranging over 100 per cent, while a diminution in the crop is indicated by percentages less than 100 per cent. A fluctuation in the quantity of a single component is immediately recognisable by a percentage which differs widely from that of the other constituents.

Further, this scheme lends itself conveniently to graphical representation thus making lateral variations in mineral content obvious at a glance.

(8) EXAMPLES OF SOURCE ROCK DETERMINATIONS

The general nature of the problems involved, and the methods used in petrographic determinations of source and direction of source of clastic sediments has been outlined above. In conclusion a few characteristic examples may be reviewed. For further examples references may be made to P.G.H. Boswell, Mineralogy of Sedimentary Rocks (London, Murby 1933), Chapter V, on minerals as clues to the source of sediments, pages 47-59.

According to Boswell (1933) one of the earliest efforts, perhaps the earliest systematic attempt, to trace to their source the minerals of an ancient sediment, was that of H.H. Thomas (1902) in the case of the Bunter Pebble-Bed of Devon and Dorset. Of this investigation Boswell (1933 p. 51) says: "The investigation was marked by its thoroughness, and as a result, has become a classic paper for students of the petrology of sediments."

At Budleigh Salterton on the south coast of Devonshire the base of the Bunter is represented by a pebble-bed about 70 feet thick. The pebbles consist of:

(a) fossiliferous quartzites, having a fauna resembling that of the Grès de May and the Grès Armorican, and which presumably must have come from Armorica (either N.W. France or an ancient extension across what is now the Channel);

(b) other quartzites, grey, red, and purple;

(c) vein-quartz;

(d) feldspathic grits, arkose, and tourmalinised grits, also identified in Armorican formations;

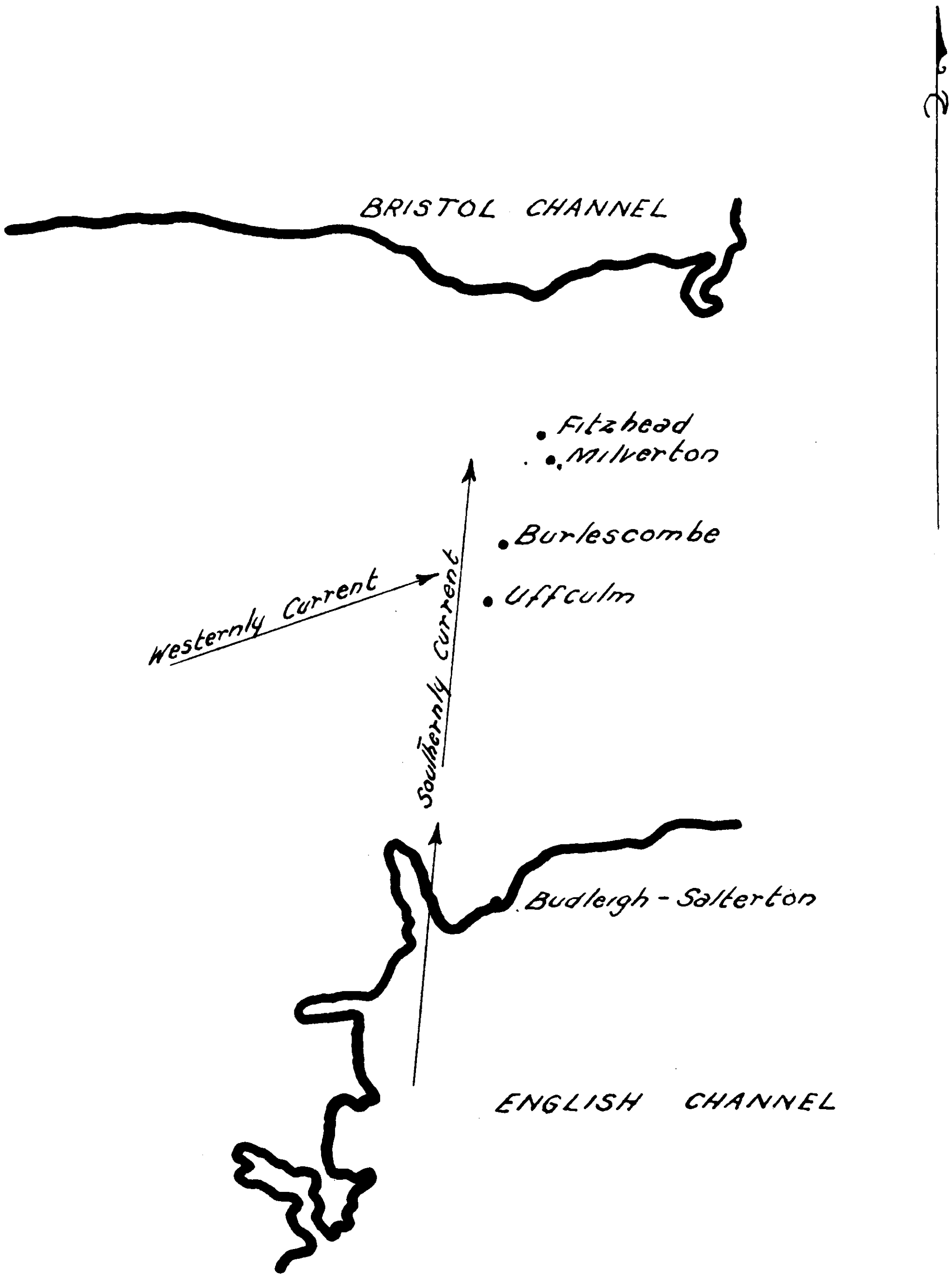
(e) various igneous rocks, including felsites and decomposed granite. Traced northwards towards Somerset the pebbles become smaller, and near Burlescombe pebbles of dolomitic carboniferous limestone appear in abundance, indicating a fresh influx of material from the west (Fig. 15).

The matrix at Budleigh Salterton is an incoherent sand, each grain being coated with red iron oxide. Beyond Burlescombe the latter material is less plentiful, its place being taken by a calcareous cement.

H.H. Thomas (1902) investigated the constituents of the sandy matrix and from the nature of the minerals and their distribution reached the following conclusions: "We may deduce the existence of a southernly main current, over the whole line from the southern coast of Devon to Fitzhead in Somerset, a distance of about 30 miles; and at the same time it will be seen that this main current was joined to the north of Uffculm by a minor current, probably from the west (Fig. 15). The probable source of much of the material was the Armorican massif of Triassic times, and the high land of Devon and Cornwall to the west, feeding the southernly and westernly currents respectively."

These conclusions are based on the following evidence:

(i) A gradual diminution of the percentage of heavy material (S.G. 2.58) from south to north, until in the neighbourhood of Burlescombe it begins to rise again pointing



SKETCH MAP OF PART OF
DEVON AND SOMERSET
SCALE: 1IN = 12 MILES

Fig. 15. Possible directions of sediment-bearing currents of the Bunter Pebble-Bed in the west of England (After H.H. Thomas, Q. J. G. S., Vol. 58, 1902)

to a fresh influx of material.

(ii) Staurolite, which is abundant in the extreme south, diminishes considerably in quantity in the more northernly part of the outcrop of the Pebble-Bed, while fluorspar does not extend northward further than about 4 or 5 miles from the coast.

(iii) Gradual diminution in the size of the rounded tourmaline grains from south to north.

(iv) Associated with the rise in percentage of the heavy material at Burlescombe and the other localities near, an assemblage of minerals occurs which differs markedly from that of the normal, more southerly type.

(v) The occurrence of minerals such as staurolite, kyanite, sillimanite, microcline, and probably cordierite, and the prevalence of "shimmer aggregates" suggests some great metamorphic area as the source of much of the material. The probable land area to the south capable of supplying the staurolite, and many of the other heavy minerals associated with it appears to be the Armorican massif or its northern extension in Triassic times.

(vi) Evidence obtained from a study of the nature and distribution of the pebbles is in agreement with the above conclusions.

A. Gilligan (1919) made a detailed study of the petrology of the Yorkshire Millstone Grit.

The dominant pebbles were found to be of quartz, and microscopic examination showed that they had been derived from mylonitised and gneissose rocks, and from sheared vein-quartz. Pebbles of remarkably fresh microcline, sometimes perthitic, and of pegmatite also occur, together with other types of igneous rocks, the chief of which are granites and porphyries. The latter include a variety of rhomb-porphyry, which may have come from the Christiana or Kebnekaise districts, and is therefore suggestive of a Scandinavian origin. The metamorphic rocks represented include gneisses and garnetiferous schists (which also contain tourmaline), and one type was identified with the "Black Schist" of Blair Athol. Cherts also occur, one type of which is oolitic and resembles certain chert pebbles from the Torridonian.

The general deduction from the above assemblage was that the material was mainly derived from a complex of metamorphic and granitic rocks. This was borne out by the nature of the finer material. Quartz grains showed undulose extinction and crenulate and mylonitised textures, and the inclusions in order of abundance were of regular, irregular and acicular types.

Among the heavy minerals, garnet, ilmenite, tourmaline and monazite (in order of abundance) were found most abundantly -- and in the case of ilmenite and monazite exclusively -- in the coarser grits and sandstones, while in the finer sandstones and shales zircon and rutile were found to take first place.

The occurrence of monazite is particularly interesting in view of the fact that Mackie found that mineral in 43 granites of the North of Scotland out of 52 examined, while in the granites of Cornwall and the Lake District monazite occurs but sparingly. Thus a northern source is again strongly indicated.

The Belleforte Sandstone of Centre County, Pennsylvania, investigated by Krynine and Tuttle in 1938 (Krynine, 1946), may be taken as a final example. This sandstone proved to be made of reworked detritus produced by the erosion of the upper Cambrian Gatesburg formation, which normally is stratigraphically located more than 3,500 ft. below the Belleforte Sandstone. This conclusion was based on the following evidence:

(i) Both formations contain almost identical percentages of the same thirteen varieties of rounded tourmaline. The possibilities of both formations being derived from a hypothetical common source are untenable on petrologic and statistical grounds.

(ii) The rounded tourmalines in the Gatesburg formation have developed after their deposition, striking authigenic overgrowths of colourless sedimentary tourmaline. The rounded tourmalines in the Belleforte sandstone also have overgrowths but these are abraded and worn.

(iii) Certain rock fragments within the Belleforte (such as some types of siliceous oolites) can be traced to the Gatesburg formation.

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