PROVENANCE OF DETRITAL MINERALS FROM PRE-BELTIAN AREAS, MONTANA

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Submitted in partial fulfillment of the requirements for the degree of Master of Science in Geology at the University of Michigan, 1949

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ILLUSTRATIONS

ABSTRACT

A series of four stream sediments were examined from two areas in southwestern Montana. The samples are from streams draining the Cherry Creek series of pre-Beltian age. Heavy mineral separations were made and the results were studied. A relationship between distributive province and derived sediment is established. A general discussion of provenance is presented. A survey of British and American literature on the subject was made and the selected bibliography is included.

PROVENANCE OF DETRITAL MINERALS FROM PRE-BELTIAN AREAS, MONTANA

INTRODUCTION

Problem

This thesis describes the heavy minerals found in sediments from four streams draining the Cherry Creek series in Madison and Beaverhead Counties, Montana. These findings are then to be related to the general problem of sedimentary provenance. This investigation was made during the school year, 1948-1949, and submitted in partial fulfillment of the requirements for the degree of Master of Science in Geology at the University of Michigan.

Acknowledgments

The writer wishes to express his appreciation to Dr. E. Wm. Heinrich, of the University of Michigan, who suggested the problem and whose help and guidance made this report possible. The writer also wishes to express his thanks to Dr. Walter F. Hunt and Dr. George V. Cohee for various constructive criticisms and to Mr. M. V. Denny who helped the writer in many ways, especially with the photomicrographs.

Special thanks are due to Messrs. Wallace Griffitts, William Gillespie, Russell Brant and Nixon C. Elmer, fellow classmates who contributed help and criticism to the completion of this report.

Location and Access

All the detritals studied were collected by Dr. E. Wm. Heinrich during the field season of 1948 from streams draining the Cherry Creek series of southwestern Montana. Carter Creek and Proffitt Gulch, from which two of the four samples were obtained, are ten to twelve miles southeast of Dillon, Montana, in Madison and Beaverhead Counties respectively. Both deposits are in the foothills in the southern end of the Ruby Range. These localities are easily accessible from Dillon by road (Fig. 1).

The two remaining samples were gathered some twenty-five miles to the east and north of the first area (Fig. 1) in Madison County. The California Gulch detritals were secured from gold placer gravels at a point five miles upstream from the mouth of the gulch in the foothills on the west side of the Tobacco Root Mountains. This area is easily reached over a road from the town of Laurin.

The fourth sample was collected from a gulch twelve miles south of Ennis (Fig. 1). This area is also accessible by road and is in the foothills of the Gravelly Range.

General Geology

The sediments that contributed to the formation of the detritals studied are of pre-Beltian age and form part of the Cherry Creek series (Peal, 1847). These pre-Cambrian rocks crop out over large areas in southwestern Montana, being well exposed along the flanks of the Tobacco Root, Gravelly and Ruby Ranges. The type section consists of quartz-feldspar gneiss, quartz-mica schist, marble, quartzite and hornblende-biotite schist, all of which are unquestionably metasediments (Tansley, Schafer, and Hart, 1933).

INDEX MAP

After E. Riasz

Fig. 1. Location of samples:

- 1. Keystone Talc Area
- 2. Proffitt Gulch
- 3. California Gulch
- 4. Ennis Kyanite Area

The pre-Beltian rocks of this part of Montana are being studied by the Montana Bureau of Mines and Geology (E. Wm. Heinrich, 1942). Below, in summary form, is the sequence of geologic events which has been worked out.[1]

1. Formation of the Pony series.
2. Deposition of the Cherry Creek sediments.
3. Intrusion of the Pony and Cherry Creek series by mafic and ultramafic sills.
4. Regional metamorphism.
5. Intrusion of the Blacktail granite.
6. Continued regional metamorphism.
7. Unconformity.
8. Belt series deposited.
9. Paleozoic-Mesozoic sequence deposited.
10. Laramide disturbance.
11. Boulder batholith intruded with accompaning pegmatites.
12. Later ultramafic bodies emplaced.

Faulting and subsequent vigorous erosion in the late Tertiary has exposed these pre-Beltian metasediments along the flanks of many of the mountain ranges of southwestern Montana.

Carter Creek drains to the northwest and is transverse to the northeast strike of the Cherry Creek series over which it runs. In this area the section that contributes material to Carter Creek is as follows: amphibolite, hornblende gneiss with local anthophyllite and garnetiferous facies, cherty dolomitic marble, granitic gneiss and peridotite.

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1. Dr. E. Wm. Heinrich, per. comm.

Proffitt Gulch is a strike valley, which trends northeast and has been cut into a thick biotite schist layer with local garnet and sillimanite facies. Pods of a massive sillimanite rock have also been exposed and the area as a whole is cut by some pegmatites. Tributary streams drain areas where dolomitic marble, granite gneiss and hornblende gneiss are exposed. These rocks again are all, with the exception of the pegmatite, of Cherry Creek age.

California Creek drains to the southwest and is a tributary to the main Ruby River. It has incised a gulch transverse to the sediments which trend northwest along the flanks of the Tobacco Root Mountains. The rocks contributing the detritals carried by the stream are all Cherry Creek in age and consist of the following members (Tansley, Schafer, and Hart, 1933): quartz-feldspar, garnetiferous gneiss, hornblende-biotite schist, quartzite and contact metamorphosed marble. The layers dip to the west off the flank of the Tobacco Root batholith.

The Ennis Kyanite Area (Heinrich, 1948) is drained by several streams which empty into the Madison River. The one from which the sample was obtained drains to the northeast, cutting obliquely across the east-trending beds of the Cherry Creek series. The pre-Cambrian rocks here exposed are rather sharply folded, intruded in places by pegmatites, and all layers dip to the south. The sequence from north to south that has contributed to the formation of the sample are: dolomitic marble, mica garnet gneiss, dolomitic marble, hornblende schist, dolomitic marble, mica gneiss, dolomitic marble and mica gneiss.

TECHNIQUE

Method of Separation

The unsorted detritals were first panned with water to free the mineral grains from silt and clays. Next, after drying, the heavy fraction was obtained by means of a separatory flask and bromoform. Separatory operations were facilitated by the use of several similar sets of aparatus as is illustrated in Figure 2.

A separatory flask was filled about three-fourths full with bromoform and a thin layer of detritals was scattered onto the top of the bromoform. Care was exercised not to put too much sample in at one time. A layer not exceeding .05 inch was found to be most practical and efficient. This was then agitated with a stirring rod to keep the light fraction from hindering the downward passage of the heavy fraction. The process was repeated, with alternating periods of agitation and settling, until the separation was believed complete.

At this point the petcock was opened to allow the heavy fraction to be carried down to the filter paper and funnel below. The process was repeated until the top of the bromoform and light fraction had reached a point about 1.5 to 2 inches above the stopcock. Then the separatory flask was removed, drained, and washed out with acetone; the lighter residue was caught on another filter paper. The heavy fraction on the first filter paper was allowed to drain, and the bromoform collected in a flask. After the heavy residue had finished draining, it was washed with acetone several times. The resulting filtrate of acetone and bromoform drained into another flask and was

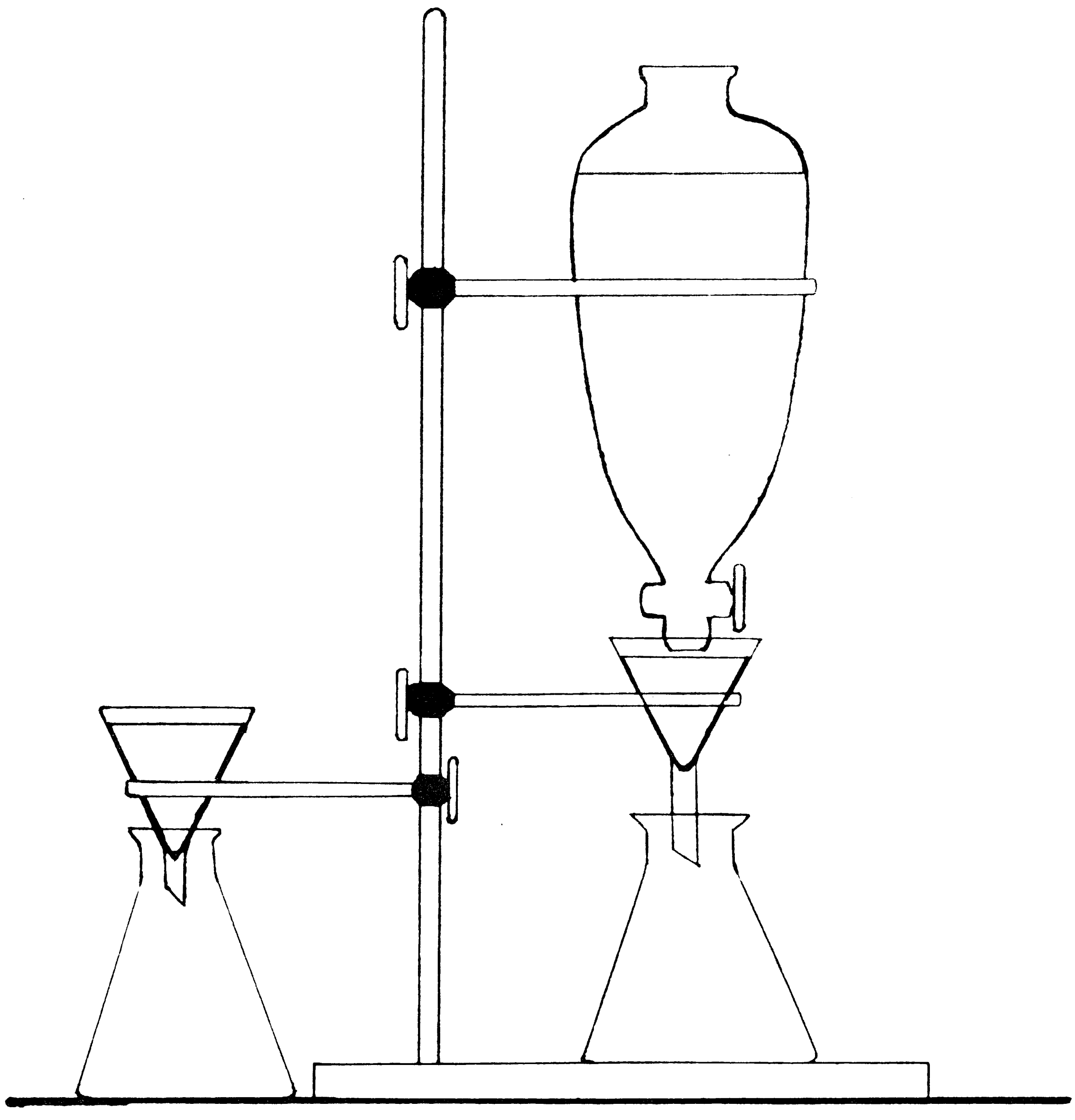


Fig. 2. Sketch of separatory apparatus.

stored until enough had been accumulated to be refined for its bromoform content.

After both light and heavy fractions were dried, by allowing the acetone to evaporate from the grains and filter paper, they were stored for examination.

Methods of Identification

The assemblage from each locality was studied first with the aid of a binocular microscope. This proved to be rather effective, for the grain size of all the samples is very coarse. Here were noted such things as shape, size, relative degrees of rounding, and alteration as well as any affinities or antipathies of occurrence exhibited.

After this preliminary study, the magnetic fraction was removed with a hand magnet. Then in each assemblage the individual minerals were isolated by hand picking, using a steel needle moistened with oil. These isolated grains were then studied individually in immersion media under a petrographic microscope.

Next each sample was put through a sixty-mesh screen and permanent slides of the detritals were mounted in canada balsum. Three slides of each sample were made, one of unscreened detritals and two of material that passed through the sixty-mesh screen. These slides were then studied to obtain frequency data and as a cross check on the data previously obtained.

Finally each assemblage was examined under flourescent light in order to pick up any of the rarer flourescent minerals which might be present.

Description of Samples

Keystone Talc Area (Carter Creek): This sample (Plate 1) is characterized by its high content of anthophyllite which is a reflection of the presence of anthophyllitic hornblende gneiss over which the stream runs. Garnet, brown and green hornblende, biotite, tremolite and actinolite are common. Magnetite, sillimanite, diopside, epidote, zircon and tourmaline also are present in smaller amounts with apatite, ilmenite and leucoxene very rare.

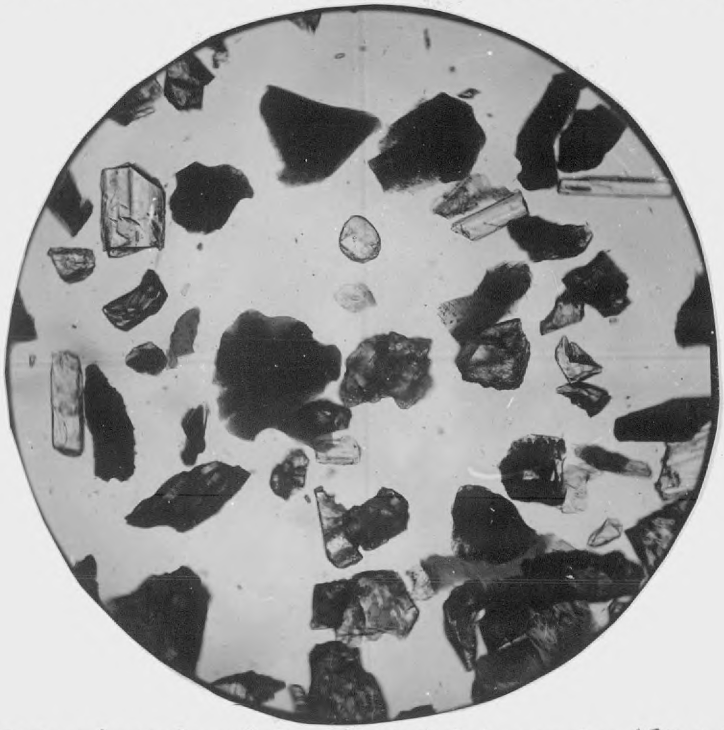
Proffitt Gulch: The distinguishing characteristic of this sample is its high content of sillimanite (Plate 1). These minerals are derived from the sillimanite biotite schists which are peculiar to the area drained by Proffitt Creek. Garnet and biotite are very abundant, with hornblende, muscovite and calcite common. Actinolite, magnetite, tourmaline, zircon, epidote, rutile, diopside and augite appear uncommonly.

California Gulch: With the exception of some rare andalusite and apatite, and the absence of tourmaline this sample is similar to the others (Plate 2). Garnet and biotite are most plentiful, with hornblende, actinolite, tremolite and muscovite very common. Magnetite, augite, sphene, orthoclase, sillimanite, zircon, epidote, rutile, andalusite and apatite appear very infrequently. Fergusonite has been reported by Cooke and Perry (1945), but was not recognized in this study.

Ennis Kyanite Area: Very abundant kyanite in large coarse crystals along with abundant anthophyllite distinguishes this sediment from the others (Plate 2). Muscovite, tremolite, biotite and garnet

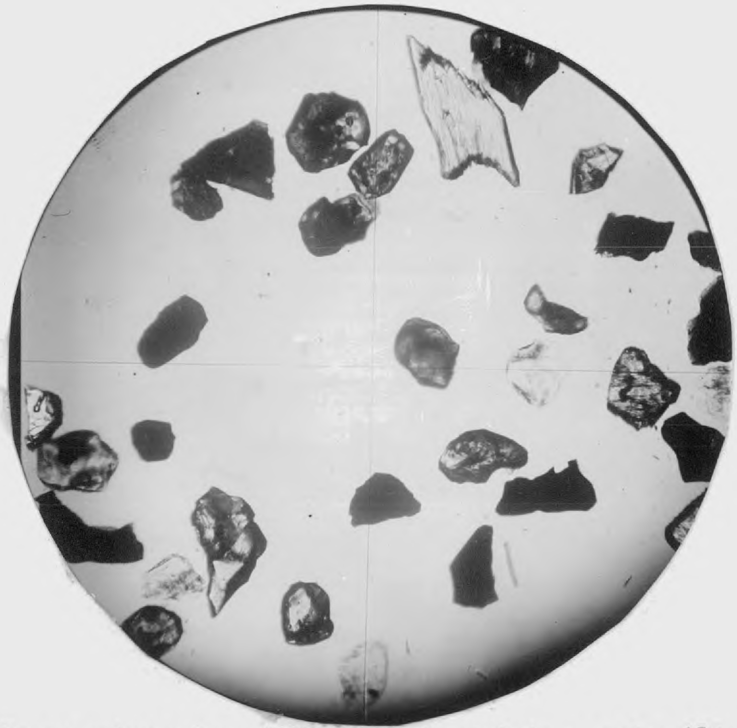
Plate 1

a. Heavy minerals of Keystone Talc sample (50 d.)

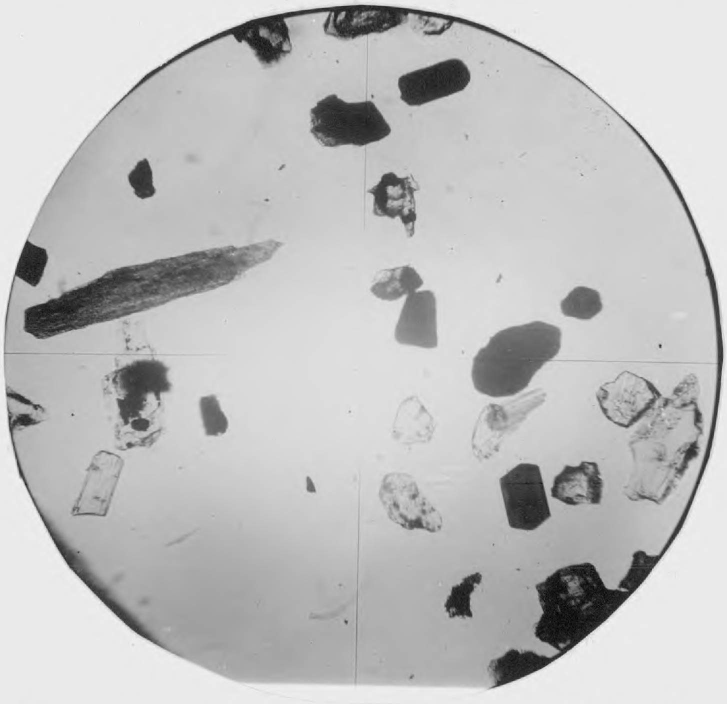


b. Heavy minerals of Proffitt Gulch sample (50 d.)

Plate 2



a. Heavy minerals of California Gulch sample (50 d.)



b. Heavy minerals of Ennis Kyanite sample (50 d.)

are also very common. Less common are apatite, magnetite, rutile, spinel and diopside.

In comparing the distribution and frequency of the various minerals that appear in the samples (Table 1) several common relationships can be discerned. Garnet, hornblende, actinolite, biotite, sillimanite and magnetite are common to all samples. This is expectable as the source rocks from which these detritals were derived contain these minerals in abundance. Secondly, these minerals show a frequency which matches very well with the frequency of these constituents in the source rocks. There is also a group of minerals which, although almost ubiquitous in their occurrence, are present in minor amounts. They include such minerals as tremolite, muscovite, tourmaline, apatite, augite, zircon, rutile, epidote and diopside. There remain, with the exception of dolomite, kyanite and anthophyllite which are locally abundant, andalusite, calcite, spinel, ilmenite and leucoxene, each one of which is both rare and appears in but one sample.

Many of the characters of the mineral assemblages in each sample are so similar that they will be discussed as a unit. All the minerals were found to be in a very fresh state with very little alteration evident. The grain size is very coarse, with fully one-tenth of the total sample being larger than .50mm. The Ennis Kyanite sample was exceptionally coarse due in part to very abundant large, bladed kyanite crystals. All the crystals were angular with the exception of some of the tourmaline, zircon and apatite crystals which were rounded to well rounded.

TABLE 1. Mineral Occurrence and Frequency

Mineral Name	Keystone Talc Area	Proffitt Gulch	*California Gulch	Ennis Kyanite Area
Garnet	VA	VA	VA	VA
Hornblende	A	C	C	C
Actinolite	C	R	C	C
Biotite	C	VA	A	VA
Magnetite	R	R	R	R
Sillimanite	R	A	R	C
Tremolite	A		C	A
Tourmaline	R	R		C
Zircon	R	R	R	
Epidote	R	R	R	
Muscovite	C	C		A
Rutile		R	R	R
Diopside	R	R		R
Apatite	VR		VR	VR
Anthophyllite	VA			A
Augite		R	VR	
Ilmenite	VR			
Leucoxene	VR			
Spinel				VR
Dolomite				C
Calcite		C		
Kyanite				VR
Andalusite, Sphene and Orthoclase			VR	

VA- very abundant, A- abundant, C- common, R- rare, VR- very rare

*Fergusonite has been reported from the sands of this area (Cooke and Perry, 1945).

Description of Individual Minerals

Actinolite (Plate 3). Commonly found in clear, pale green, elongate prisms and cleavage fragments with striations parallel to cleavage very common on the larger crystals. The extinction angles vary from 3° to 10°. Values for γ 1.645 and β 1.630.

Andalusite. Very rare and found as irregular, colorless, anhedral grains with many inclusions of opaque material and lacking pleochroism. The indices measured were γ 1.637, β 1.635.

Anthophyllite (Plate 3). Commonly found as light brown elongate prisms, deeply striated parallel to the elongation. Easily distinguished from the other amphiboles by its color and parallel extinction. Pleochroic from colorless to light brown parallel to the c-axis. Indices measured are γ 1.665, β 1.650 with large 2V of 80-85°.

Apatite. The few crystals identified as apatite were colorless, rounded prisms. The parallel extinction, low birefringence and flash figure obtained on the prism face identified this mineral as apatite.

Augite. Found in small equidimensional grains in shades of dark green and brown. Pleochroic from yellowish green to dark green. Angular blocky crystals with poor cleavage common. Extinction angle 40°, β 1.70, α 1.68.

Biotite (Plate 4). Large basal cleavage flakes are common with numerous inclusions of sillimanite needles. Frequently having a bleached appearance due to chloritic alteration. 2V varies from 5°- 10° with values of 1.645 for γ and 1.640 for β.

Calcite. Appears as many small anhedral grains in the Proffitt Gulch slides. The grains are irregularly shaped with few cleavage flakes making their appearance.

Diopside. This mineral is in short bladed crystals. The grains were colorless to gray with good cleavage and high extinction angles varying from 37°- 42°.

Dolomite. Characteristically appears as cleavage rhombs with high double refraction found only in the Ennis Kyanite samples.

Epidote (Plate 4). Commonly as sub-angular to rounded grains of pale greenish yellow color. Frequently showing a centered optic axis interference figure.

Garnet (Plate 5). Ranges in color from pale pink through a reddish brown. Varying from clear angular fragments to those very turbid with inclusions of magnetite.

Hornblende (Plate 5). Both dark brown and dark green varieties are found with the green variety being much more abundant and characteristic. The cleavage fragments and crystals are striated parallel to the elongation. Both varieties are pleochroic from green or brown parallel to [illegible] and a pale green or brown at right angles to this direction. Extinction angle is 15°, 2V over 80°, γ 1.685, β 1.675.

Ilmenite. Found as patches in otherwise well altered fragments. Alteration is to creamy white leucoxene.

Kyanite (Plate 6). Large bladed crystals with prominent cross fractures common. Many crystal fragments have numerous inclusions of magnetite which impart a cloudy appearance to the otherwise light blue to colorless crystals. Extinction angle is high, 33°. 2V is very large with γ 1.725 and β 1.720.

Leucoxene. As previously stated, it appears as a powdery white alteration product on ilmenite grains.

Magnetite. Occurs as small irregularly-shaped crystals which appear bluish in reflected light. Often the grains are mottled with limonite stains.

Muscovite (Plate 6). This mineral is very distinctive having many inclusions of sillimanite needles and magnetite grains. Irregular basal cleavage flakes is the common habit exhibited. 2V varies from 35° to 40°, β 1.590, γ 1.595.

Rutile. Prismatic, acicular grains common with polysynthetic twinning parallel to the (101) face. The grains have the typical "foxy-red" color and high birefringence.

Sillimanite (Plate 7). Commonly found in bundles of fibrous crystals. Many single crystals are present as long slender colorless prisms. Indices measured were γ 1.683 and β 1.660.

Spinel. Only one light green, pitted grain positively identified, but there may be more which were not distinguished from colorless garnet.

Tourmaline (Plate 7). Found principally in euhedral prisms of light brown color. Some rounded crystal fragments were found. Pleochroic, from light brown to dark brown with maximum adsorption at right angles to the lower nicols prism.

Tremolite (Plate 8). Euhedral, prismatic, colorless crystals commonly having an extinction angle of from 0 to 13°, 2V 80°- 90°, β 1.635, γ 1.645. The larger crystals are striated parallel to the elongation.

Zircon (Plate 8). Excellent euhedral, prismatic crystals with pyramidal terminations common containing numerous inclusions. Also some rounded to anhedral grains are present. Color varies from colorless, which were most numerous, to a mauve.

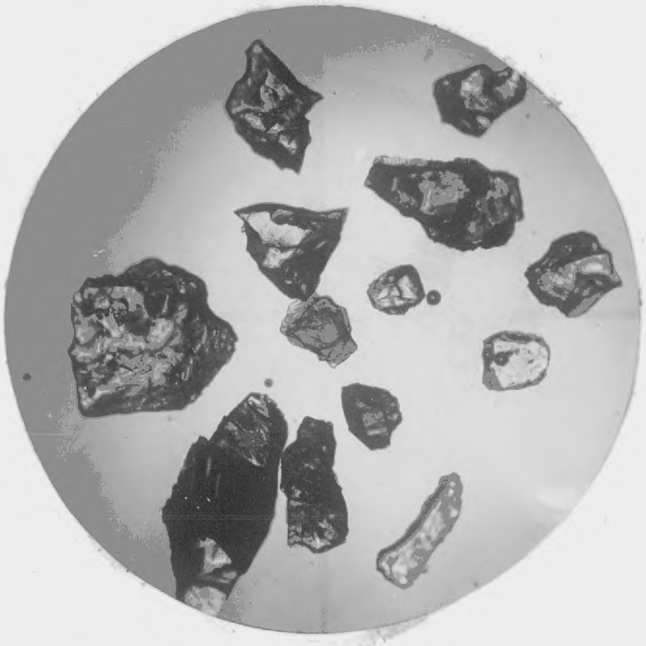
Plate 3

a. Actinolite (20 d.)

b. Anthophyllite (20 d.)

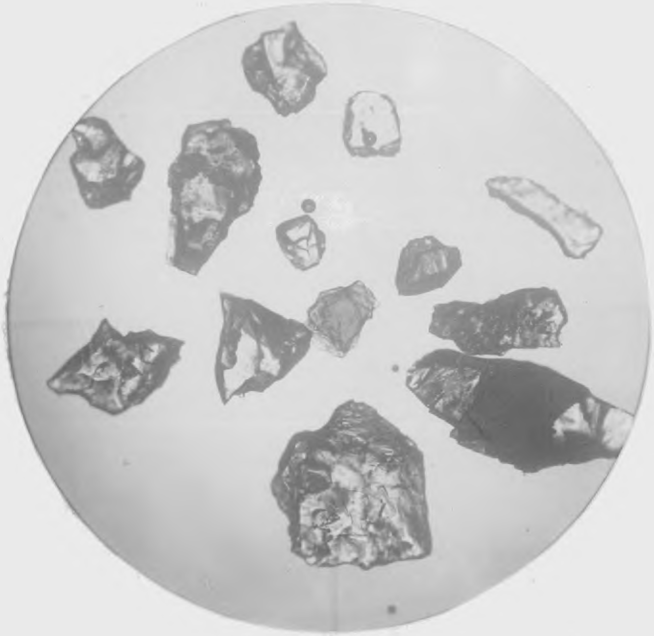
Plate 4

a. Biotite (20 d.)

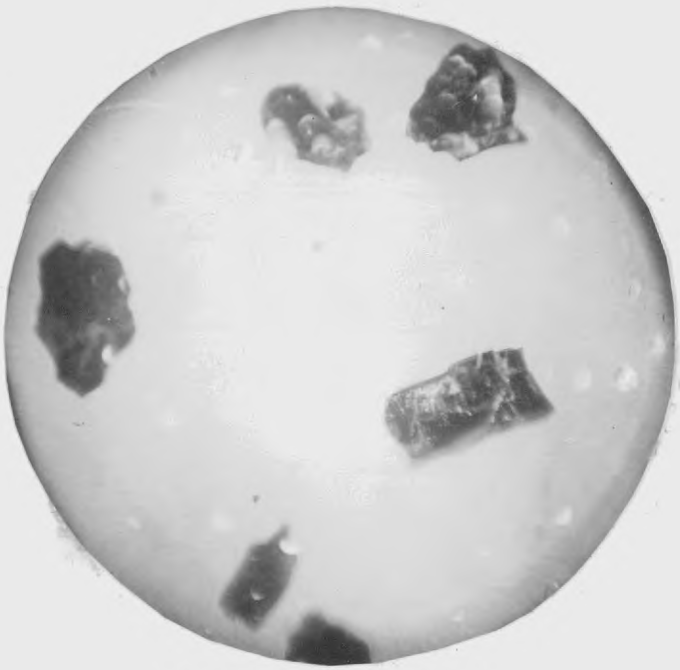


b. Epidote (20 d.)
(Central grain epidote, surrounded by garnet.)

Plate 5



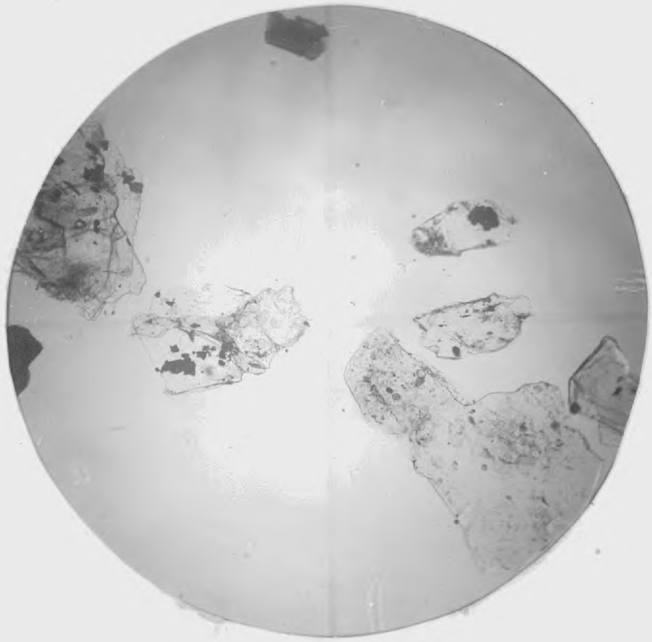
a. Garnet (20 d.)



b. Hornblende (20 d.)

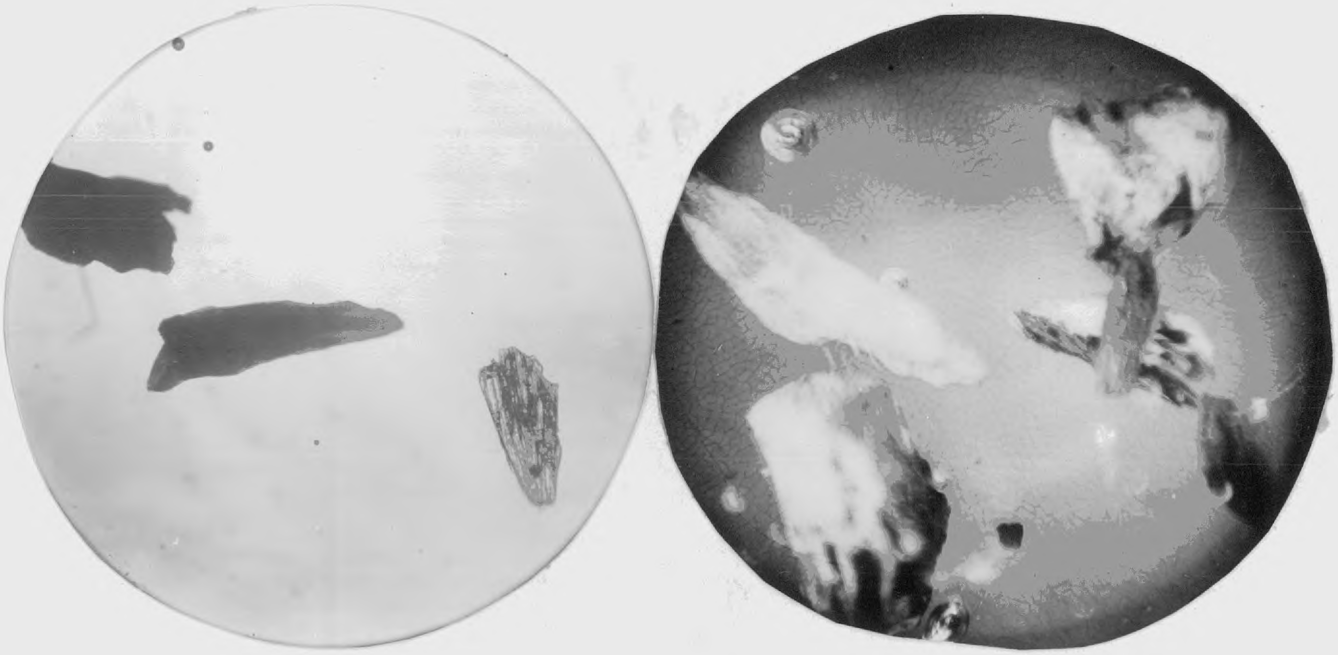
Plate 6

a. Kyanite (20 d.)

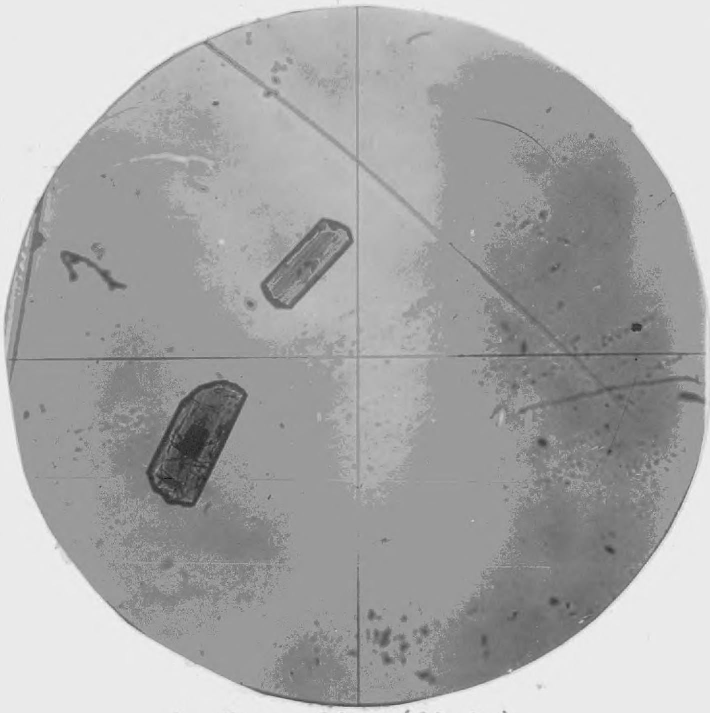


b. Muscovite (20 d.)

Plate 7

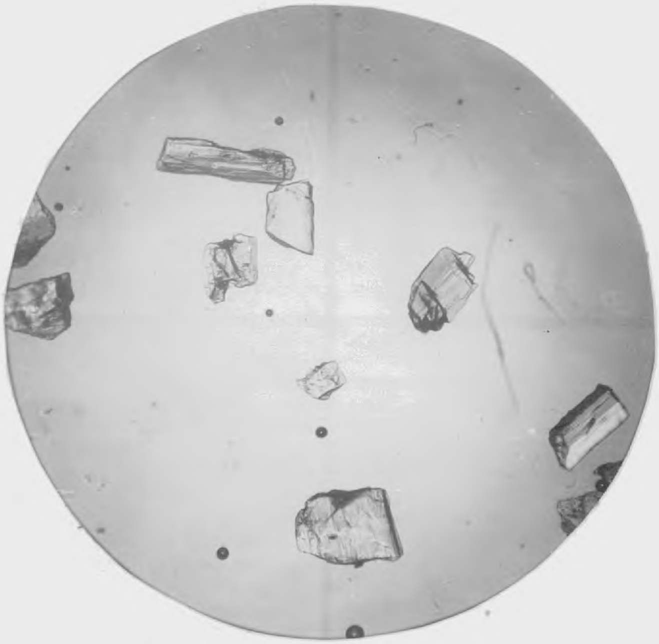


a. Sillimanite (20 d.)



b. Tourmaline (20 d.)

Plate 8



a. Tremolite (20 d.)

b. Zircon (20 d.)

DISCUSSION OF PROVENANCE

General

Any discussion of provenance based on heavy mineral studies is predicated upon the assumptions, first, that the concept of an alternation of orogenic and geosynclinal phases of earth history is a reality and, second, that this being so, the products of degradation derived from these cyclic changes will, with due recognition of the forces acting on them, be indicative both of their source areas and their depositional environments.

Weathering

The rate of weathering of a rock depends upon three things, the mineral composition of the rock involved, the relief, and the climate of the area. Goldich (1938) has compared mineral stability to weathering and concludes that in a normal igneous rock the minerals which formed first will be the first to decompose. He calls this a "Mineral Stability Series".

TABLE 2. Mineral Stability Series (After Goldich)

Increasing Stability ↓	Olivine	Calcic Plagioclase
	Augite	Calcic-alkalic Plagioclase
	Hornblende	Alkali-calcic Plagioclase
	Biotite	Alkalic Plagioclase
	Potash Feldspar	
	Muscovite	
	Quartz	

This seems to be an entirely logical condition, for the earliest formed minerals are in greater disequilibrium than the later formed ones. From this chart it also follows that the rocks richest in the more stable minerals, granites, etc., will decompose at a slower rate than those with a greater percentage of unstable minerals such as gabbros.

One of the few studies of comparative rates of weathering of common heavy minerals was conducted by L. D. and C. Dryden (1946) in a Pennsylvania - Maryland Area. They compared the heavy minerals in fresh rocks with their weathered products and arrived at the following conclusions as summarized in Table 3 below:

TABLE 3. Stability of Common Heavy Minerals

Mineral	Index of Stability
Zircon	100
Tourmaline	80*
Sillimanite	40
Monazite	40
Chloritoid	20*
Kyanite	7
Hornblende	5
Staurolite	3
Garnet	1
Hypersthene	1*

*Estimated, no data available
Index based on garnet which is taken as 1
(Table after Dryden)

In a recent interesting paper (Allen, 1948) similar results were obtained in studying the weathering of glacial deposits. In this paper the seeming inconsistency of garnet in sediments was pointed out and related to two factors, the chemical composition of the garnet involved and the type of weathering to which it is subjected. In general, if garnets can be liberated by rapid erosion before they are decomposed chemically, they are much more likely to appear in sediments. Some garnets, particularly the pegmatitic manganese garnet, spessartite, weather very rapidly. Intrastratal solution, however, may be expected to be equally effective in decomposing garnet after deposition.

Van der Marel (1948), studying residual soils developed from extrusive rocks, found that the percentage of various heavy minerals in these soils could be used to identify the stage of weathering to which the soils had progressed. One of his charts is presented below.

TABLE 4.

Rhyolite Tuff	Minerals				
Stage of Weathering	Opaque	Hypersthene	Amphibole	Allanite	Zircon
Fresh Rhyolite tuff	43%	5%	42%	4%	6%
Slightly weathered soil	53	2	32	5	8
Moderately " "	62	1	14	10	13
Strongly " "	36	trace	5	28	31
Very " " "	20	"	absent	40	40

After Van der Marel

The effect of climate and relief upon sediments are summarized by Pettijohn (1949, p. 385) in the following manner.

"A composition that suggests maturity, such as high quartz-to-feldspar and high alumina-to-soda ratios most likely is the product of a warm humid climate in an area of low relief. Mixtures of stable and unstable materials such as feldspathic sandstone associated with high alumina and low soda shales, suggest a warm humid climate in regions of high relief with youthful topography. The coarse, relatively fresh debris of the canyons is mingled with the finer maturely weathered materials of the interstream regions, If the sediment contains only immature products, the area of provenance either is very high in relief with a mature topography or is a region of rigorous climate. In the former case the sands and silts will contain numerous bits of carbonized wood. In general, according to Barrell (1908), the character of the fine fluviatile or wash detritus in the region of its origin may be taken as an index of the climate. The size or abundance of the coarser materials, on the other hand, is a measure of the rapidity of erosion, and hence a measure of the topographic relief".

Transportation

The effects of transportation upon sedimentary particles is very thoroughly treated in articles in "Recent Marine Sediments" by R. Dana Russell and Filip Hjulstrom and in "Sedimentary Rocks" by F. J. Pettijohn. Most of the following information was obtained from these sources. The principal processes of transportation affecting sediments are abrasion and sorting. Since the effects of these two may, depending upon the conditions, either reinforce or mitigate one another they will be treated separately.

Sorting may be either "local" or "progressive" as stated by Russell, and the factors involved are size, shape and specific gravity of the sedimentary particles and the velocity, turbulence, specific gravity and viscosity of the transporting medium. Local sorting refers to the degree of sorting at one locality or site of deposition as represented by the various beds of a sediment. The degree to which local sorting has been developed is an indication of the agent and conditions of deposition, and is of prime importance. However, local sorting represents but a static portion of the dynamic process of progressive sorting. Thus to understand the agent involved and the conditions of deposition of any sediment the process as a whole must be understood.

Progressive sorting is the process by which sedimentary particles change size, shape and mineral composition, as they proceed toward the basin of deposition. Change in grain size may be due to a gradual decrease in competency or to fluctuations in competency, which cause the larger particles to lag behind.

The average shape of the particles may change progressively due to several interrelated factors. When grains are moved by suspension the more spherical grains will tend to be deposited first. The least spherical, as the micas, will travel the longest distance under this mode of travel. In cases where the dominant mode of transportation of bed load is by rolling, just the reverse is true and the most spherical grains travel farther than the less spherical ones. In other cases, where saltation is the primary method of transport, these two methods are brought into play jointly, resulting in little progressive change in shape downstream.

Minerals will also be progressively sorted according to specific gravity, the minerals of lower density outrunning those of higher density, but this effect will be modified by the size and shape factors. The progressive sorting of sedimentary particles according to size tends to increase the amounts of initially smaller minerals found in sediments in the direction of transport. Thus, zircon, apatite, tourmaline, magnetite and other accessory minerals tend to become more abundant toward the basin of deposition. Progressive sorting according to shape, as previously stated, depends on the method of transport. The micas and kyanite, for example, are usually transported a greater distance than other minerals of similar size and specific gravity, where the mode of transport is suspension, due to their flakey habit. If rolling is the dominant mode of transport, minerals of the highest sphericity, as garnet, quartz, zircon, iron ores, etc., will become relatively more abundant in the direction of transport.

According to Pettijohn (1949) the dominant process that controls the composition of any river sand is progressive sorting. He asserts that abrasion is a subordinate factor to sorting in effecting changes in grain size and shape in sediments in their direction of travel. The major effects of abrasion seem to be modification of surface textures and rounding. Few comparative studies of abrasion and decrease in grain size have been conducted and those that have (R. D. Russell and R. E. Taylor, 1937) suggest that abrasion is not a very effective agent for reducing the grain size of sand-size particles but is the dominant process in pebble-size particles (G. A. Theil, 1940).

The process of abrasion is intimately associated with that of sorting and depends on many other factors, all of which are listed below in chart form (after Pettijohn, 1949).

I. Original size, shape and roundness
II. Compositional factors
  A. Mechanical
    1. Hardness
    2. Cleavage
    3. Toughness
  B. Chemical - solubility
III. Transportational factors
  A. Distance of transport
  B. Manner of transport
    1. Rigor of action
    2. Nature of motion
      a. Sliding
      b. Rolling
      c. Saltation
      d. Suspension
    3. Agent of transport
      a. Wind
      b. Water

Laboratory experiments (G. A. Theil, 1940) have proved that, whereas abrasion does tend to reduce in size the more brittle and softer minerals in the direction of transport, the amount of such abrasion produces only minor effects. Confirmation of this may be seen when the order of abrasion resistance is compared (Table 5) with the order of persistence (Table 6). This comparison shows that there is only a partial relationship between the two, for resistance to abrasion depends on physical properties, whereas, the order of persistence depends primarily upon chemical stability of the minerals involved.

TABLE 5. Order of Resistance to Abrasion

(After Theil, 1945)		(After Friese, 1921)
Barite	↓	Monazite
Siderite		Orthoclase
Fluorite		Diopside
Goethite		Andalusite
Enstatite		Kyanite
Kyanite		Apatite
Bronzite		Olivine
Hematite	Increasing Resistance to Abrasion	Epidote
Augite		Ilmenite
Apatite		Garnet
Spodumene		Magnetite
Hypersthene		Topaz
Diallage		Augite
Rutile		Staurolite
Hornblende		Cordierite
Zircon		Pyrite
Epidote		Tourmaline
Garnet		
Titanite		
Staurolite		
Microcline		
Tourmaline		
Quartz	↓	

These experiments and the work of Russell (1937) and Pettijohn and Ridge (1933) have invalidated the old notion that certain minerals, notably the pyroxenes, feldspars and amphiboles are rapidly eliminated in transport. Therefore, the absence of these minerals from sediments can only be explained by deep weathering of the source rocks, with their elimination there, by post-depositional intrastratal solution, or by their original absence in the rocks.

Stability

There is an apparent increase in complexity of heavy mineral suits with decreasing age. This has been noted by many workers in the field, as early as 1913 (Thoulet). This fact had also been noted by Boswell (1923) who hypothesized that this increase in complexity was due to two causes: an increase in complexity of terrane with decrease in geologic age, and disappearence of the less stable minerals through intrastratal solution.

Pettijohn (1941) reviewed this problem recently and by means of a search through the literature on heavy mineral studies he was able to set up an order of persistence (Table 6) for heavy minerals. He believes that intrastratal solution is the primary cause for the disappearance of the less stable minerals in deposits of increasing geologic age. In confirmation of this he sites studies by Stow (1938) and Cogen (1940), in which they attribute the changes in heavy mineral content to changes in provenance. Pettijohn points out that these studies and others made in widely separate areas agree so well

TABLE 6. Relative Order of Persistence Throughout Geologic Age

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

(After Pettijohn) The numbers are only relative, with zircon being arbitrarily chosen as 1. The negative numbers indicate these minerals to be commonly authigenic as well as allogenic.

on certain mineral changes that some general principle must underlie them all. In all these examples the order of appearance of heavy minerals follows his "Mineral Persistence Chart", so he concludes that intrastratal solution, rather than the greater complexity of modern terranes, accounts most readily for the apparent increase in complexity of heavy minerals with decreasing geologic age. Russell (1937) in his study of the Mississippi River sediments stated that, although pyroxenes and amphiboles withstood abrasion well and appear in younger sediments, they are absent in older sediments. He therefore concludes that their loss subsequent to deposition is due to intrastratal solution. Smithson (1941) in a study of detrital minerals arrived independently at a conclusion similar to that of Pettijohn. The stability relationships he found are tabulated in Table 7 and conform rather closely to Pettijohn's stability series.

TABLE 7. Stability Series

Stable	Somewhat Stable	Unstable	Very Bnstable
Zircon Rutile Tourmaline Apatite	Monazite	Garnet Staurolite Kyanite	Ferro-Magnesium Minerals

(After Smithson)

Authigenic Minerals

No study of heavy minerals and their relation to provenance would be complete without mention of the authigenic character of some minerals. The list of authigenic minerals includes; quartz, chalcedony, feldspars (orthoclase, rarely microcline and albite), calcite, dolomite, siderite, clay micas (illite and sericite), chamosite, chlorite, analcite, glaucophane, gypsum, anhydrite, barite, marcasite, pyrite, rutile, anatase, brookite, hornblende, tourmaline and zircon (Boswell, 1933 and Pettijohn, 1949).

These minerals may form in sediments with or without nuclei but they are formed more commonly as secondary growth upon allogenic grains. Often, as in the case of authigenic quartz, the optical orientation is similar in allogenic and authigenic portions of the crystal, making identification of its component parts difficult to impossible. However, in many cases the secondary growth is separated from the primary grain by an iron oxide film or as in the case of feldspars or quartz, by different optical orientation, as most outgrowths on feldspars are orthoclase regardless of the composition of the allogenic grain, or by a difference in color, as in tourmaline. Another indication of secondary growth is the almost perfect development of crystal faces and form that are shown by some of the detritals subject to authigenic growth.

It has been noted by Pettijohn (1949) and others that "secondary enlargement is a self evident criterion of stability, just as etched surfaces and the like are criteria of instability". Thus, quartz, the alkali feldspars, tourmaline and zircon all exhibit secondary growth and confirm this criterion.

PROVENANCE OF SAMPLES STUDIED

General

The four areas sampled in this study have, with due allowance for minor local variations, identical source rocks, climate, vegitation and transportational factors. The following is a summary of these factors and how they were derived from this study.

Source Rocks

The abundant biotite, garnet and amphiboles with smaller but ubiquitous amounts of sillimanite, rutile, epidote, tourmaline and zircon are significant and seem to indicate for their common source of origin medium-grade metamorphic rocks such as garnet-biotite-amphibole schists and gneisses. The diopside, tremolite, andalusite and carbonates seem to indicate the presence of metamorphosed calcareous members. Locally there seems to be an abundance of kyanite, sillimanite and anthophyllite. These minerals could represent local facies of the above mentioned rocks enriched in these particular minerals.

Climate and Relief

As previously stated the relative abundance, size and degree of weathering of the fine and coarse minerals indicate, respectively, the climate and relief of the source area. The finer materials of this study were not very much altered and they constitute a minor portion of the total. The coarse minerals are very fresh and dominate the assemblages. Thus, the climate of the distributive province is rigorous and the relief high with consequent rapid and vigorous erosion.

Transportation

The presence of such a rich suite of dissimilar minerals is in itself indicative of freshness of sediment and the short journey it must have traveled. The angularity, lack of sorting and unweathered character of the component grains supplements this conclusion.

Persistence and Stability

Apparently all the minerals stable enough to resist decomposition during the time necessary for the disintegration of the parent rock appear in these very fresh and recent sediments. From the great abundance of garnet and the amphiboles it appears that the dominant form of weathering was mechanical rather than chemical.

Conclusions

1. The source rocks were garnet-biotite-amphibole schists and gneisses with subordinate metamorphic calcareous members.

2. The climate is rigorous and the relief high.

3. The sediments were derived under conditions of mechanical disintegration and have traveled for a short distance only.

BIBLIOGRAPHY

General Texts

Boswell, P. G. H., (1933) Mineralogy of Sedimentary Rocks , Thomas Murby & Co., London. Contains annotated bibliography of 1025 papers.

Krumbein, W. C. and Pettijohn, F. J., (1938) Manual of Sedimentary Petrography, Appleton-Century-Crofts Inc.

Milner, H. B., (1940) Sedimentary Petrography, 3rd ed., Thomas Murby & Co., London.

Pettijohn, F. J., (1949) Sedimentary Rocks, Harper and Bros., N.Y.

Raeburn, C. and Milner, H. B., (1927) Alluvial Prospecting, Thomas Murby & Co., London.

Technique

Boswell, P. G. H., (1923) Notes on Petrographic Methods, Geol. Mag., vol. 60, pp. 165-168.

Brammall, A., (1928) Dartmoor Detritals: A Study in Provenance, Proc. Geol. Assoc., vol. 39, pp. 27-48.

Cogen, W. M., (1935) Some Suggestions for Heavy Mineral Investigations of Sediments, Jour. Sed. Petrol., vol. 5, pp. 3-8.

Cooke, S. R. B., and Perry, E. S., (1945) Columbium and Cerium and Minerals in Montana, Amer. Min., vol. 30, pp. 623-628.

Edison, F. C., (1932) Heavy Minerals as a Guide in Stratigraphy Studies, Amer. Min., vol. 17, pp. 429-436.

Tyler, S. A., and Marsden, R. W., (1938) Heavy Mineral Methods applied to the Pre-Cambrian rocks of the south shore of Lake Superior, Amer. Min., vol. 23, p. 180. (abs)

Weathering and Persistence

Allen, Victor T., (1948) Weathering and Heavy Minerals, Jour. Sed. Petrol., vol. 18, no. 1, pp. 38-42.

BIBLIOGRAPHY

Weathering and Persistence

Dryden, L. D. and C., (1946) Comparative Rates of Weathering of Some Common Heavy Minerals, Jour. Sed. Petrol., vol. 16, pp. 91-96.

Goldich, Samuel S., (1938) A Study in Rock Weathering , Jour. Geol., vol. 46, pp. 17-58.

Pettijohn, F. J., (1941) Persistence of Heavy Minerals and Geologic Age, Jour. Geol., vol. 49, pp. 610-625.

Russell, R. D., (1937) Mineral Composition of Mississippi River Sands, Bul. G. S. A., vol. 49.

Smithson, F., (1941) The Alteration of Detrital Minerals in the Mesozoic Rocks of Yorkshire, Geol. Mag., vol. 78, pp. 97-112.

Van der Marel, H. W., (1948) Volcanic Glass, Allanite and Zircon as Typical Minerals of the Toba Rhyolite at Sumatra's East Coast, Jour. Sed. Petrol., vol. 18, no. 1, pp. 24-29.

Transportation

Krumbein, W. C., (1942) Flood Deposits of Arroyo Seco, Los Angeles County, California, G. S. A. Bul., vol. 53, p. 1381.

Pettijohn, F. J., and Ridge, J. D., (1932) A Textural Variation Series of Beach Sands from Cedar Point, Ohio, Jour. Sed. Petrol., vol. 2, pp. 76-88.

Russell, R. D., (1937) Mineral Composition of Mississippi River Sands, Bul. G. S. A., vol. 49.

Russell, R. D., and Taylor, R. E., (1937) Roundness and Shape of Mississippi River Sands, Jour. Geol., vol. 45, pp. 225-267.

Theil, G. A., (1945) Mechanical Effects of Stream Transportation on Mineral Grains of Sand Size, G. S. A. Bul., Abstract, vol. 56, p. 1207.

Wadell, H., (1932) Volume Shape and Roundness of Rock Particles, Jour. Geol., vol. 40, pp. 443-451.

BIBLIOGRAPHY

Provenance

Armstrong, P., (1922) Zircon as Criterion of Igneous or Sedimentary Metamorphics, Amer. Jour. Sc., 5th Series, vol. 4, p. 391.

Barrell, J., (1908) Relations Between Climate and Terrestrial Deposits, Jour. Geol., vol. 16, p. 183.

Boswell, P. G. H., (1924) Purple Zircon in British Sedimentary Rocks, Min. Mag., vol. 21, pp. 310-317.

Brammall, A., (1928) Dartmoor Detritals: A Study in Provenance, Proc. Geol. Assoc., vol. 39, pp. 27-48.

Brammall, A. and Harwood, H. F., (1923) The Occurrence of Rutile Brookite and Anatase on Dartmoor, Min. Mag., vol. 20, pp. 20-26.

(1923) Occurrences of Zircon in Dartmoor Granite, Min. Mag., vol. 20, pp. 27-31.

Butterfield, J. A., (1939) Brookite in Millstone Grit, Geol. Mag., vol. 76, pp. 220-228.

Chatterjee, M., (1929) The Accessory Mineral Assemblage of the Bodin Moor Granite, Proc. Geol. Assoc., vol. 40, pp. 147-152.

Gogen, W. M., (1940) Heavy Mineral Zones of Lousiana and Texas Gulf Coast Sediments, A. A. P. G. Bul., vol. 24, pp. 2069f.

Davies, G. M., (1915) Detrital Andalusite in Cretaceous and Eocene Sands, Min. Mag., vol. 17, pp. 218-220.

Ghosh, P. K., (1928) The Mineral Assemblage of the Falmouth Granite, Proc. Geol. Assoc., vol. 39, pp. 332-338.

Groves, A. W., (1930) The Granites of Brittany and Normandy, Geol. Mag., vol. 67, pp. 218-240.

(1930) The Heavy Mineral Suites and Correlation of the Granites of Brittany and the Channel Islands, Geol. Mag., vol. 67, pp. 218-240.

(1931) The Unroofing of the Dartmoor Granite, Quart. Jour. Geol. Soc. of London, vol. 87, pp. 62-96.

Krynine, Paul, (1946) The Tourmaline Group in Sediments, Jour. Geol., vol. 54, pp. 65-87.

BIBLIOGRAPHY

Provenance

Leech, J. G. C., (1929) St. Austell Detritals, Proc. Geol. Assoc., vol. 40, pp. 139-146.

Miller, Roswell, (1945) The Heavy Mineral Content of Recent Dune Sands in Florida, Amer. Min., vol. 30, pp. 64-67.

Rastall, R. H., (1939) Rutile in the Dogger, Geol. Mag., vol. 76, pp. 109-115.

Reed, J. C., (1937) The Study of Accessory Minerals in Igneous and Metamorphic Rocks, Amer. Min., vol. 22, pp. 73-84.

Scrivenor, J. B., (1903) Anatase and Magnetite Occurrences, Min. Mag., vol. 13, pp. 348-352.

Stow, M. H., (1938) Dating Cretaceous-Eocene Tectonic Movements in the Big Horn Basin by Heavy Minerals, G. S. A. Bul., vol. 49, pp. 731-762.

(1939) Reflection of Provenance in Heavy Minerals of the James River, Virginia, Jour. Sed. Petrol., vol. 9, no. 2, pp. 86-91.

Tyler, S. A., (1936) Heavy Minerals of the St. Peter Sandstone in Wisconsin, Jour. of Sed. Petrol., vol. 6, pp. 55-84.

Unclassified

Alty, S. W., (1933) Some Properties of Authigenic Tourmaline, Amer. Min., vol. 18, pp. 351-355.

Heinrich, E. Wm., (1948) Deposits of the Sillimanite Group of Minerals South of Ennis, Madison County, With Notes on Other Occurrences in Montana, Mont. Bureau of Mines and Geol., Misc. Contributions no. 10.

(1949) Pre-Beltian Rocks Near Dillon, Montana, (Abstr.) Amer. Min., vol. 34, p. 278.

Peal, A. C., (1847) Three Forks Folio, U. S. Geol. Survey Geol. Atlas, no. 24.

Tansley, W., Schafer, P. and Hart, L., (1933) A Geologic Reconnaissance of the Tobacco Root Mountains, Madison County, Montana, Mont. Bureau of Mines and Geol., Memoir no. 9.

Tickell, F. G., (1939) The Examination of Fragmental Rocks, Stanford University Press, California.

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