EXERCISE 5
HEAVY-MINERAL ANALYSIS AND PROVENANCE

Introduction

In Exercise 1 we were concerned with gross mineralogical composition of sediments from the standpoint of sediment classification. Often, by studying the mineralogy in more detail we can learn much more about the history of a sediment. Specifically we can determine which rock type or types served as the parent or source material of the sediment. The source material or source area is known as provenance. It should be apparent that this is true only for detrital sediments and sedimentary rocks.

To achieve the objective of determining provenance, it is necessary to study all the minerals present in a sediment, not just the most abundant ones. Indeed it is often the least common accessory minerals that tell us most about a given sediment's provenance. Different igneous, sedimentary and metamorphic rocks have different, and often distinct or even unique, groups of accessory minerals. This laboratory will be concerned with (1) methods of separating out these accessory minerals to facilitate their identification and study and (2) consideration of questions of provenance.

Heavy Minerals

One of the more common separation methods used is based on the different specific gravities of different minerals. The more common minerals: quartz, feldspars, and calcite have low specific gravities (~ 2.7) and are known as "light minerals" or "lights." By putting a sediment sample in a liquid of high specific gravity, the common minerals will float, while the less abundant accessory minerals will sink. Since these minerals have higher specific gravities (> 2.9), they are often referred to as "heavy minerals" or "heavies."

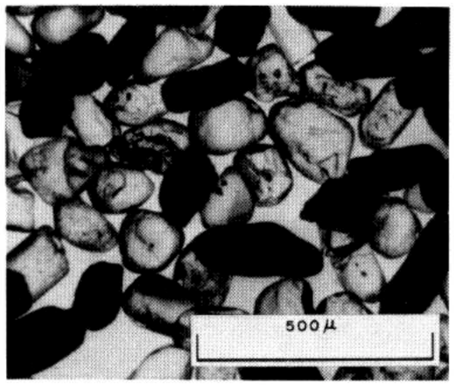
Heavy minerals include many kinds of opaque and transparent minerals. The opaque group consists of oxides, sulfides, and other so-called ore minerals. Typically the opaque minerals predominate. The transparent group consists mostly of rock-making silicates. Table 5-1 is a list of some heavy minerals and the rocks from which they are derived.

Heavy Minerals	Parent Rocks: Igneous – Mafic	Igneous – Felsic	Hydrothermal (veins, pegmatites)	Metamorphic – High-rank	Metamorphic – Low-rank	Sedimentary
Anatase	x					
Augite	x					
Brookite	x					
Chromite	x					
Hypersthene	x					
Ilmenite	x	x				
Leucoxene	x	x				
Magnetite	x	x		x		
Olivine	x					
Rutile	x					
Serpentine	x					
Apatite		x				
Biotite		x	x	x		
Hornblende		x	x	x Blue-green variety		
Monazite		x	x			
Sphene		x				
Tourmaline		x Small pink euhedra	x Typically blue (indicolite)		x Small pale-brown euhedra, carbonaceous inclusions	
Zircon		x				
Fluorite			x			
Garnet			x	x		
Topaz			x			
Andalusite				x		
Epidote				x	x	
Kyanite				x		
Sillimanite				x		
Staurolite				x		
Zoisite				x		
Barite			x			x

SOURCE: After F. J. Pettijohn, 1975, Table 13-1, p. 487.

Some Heavy Minerals and Their Parent Rocks (Friedman and Sanders, 1978)
Table 5-1

Because they transmit polarized light, the rock-making silicates can be studied routinely as grain mounts using a binocular or petrographic microscope (Fig. 5-1). Some particles of rock-making silicate minerals have



Opaque heavy minerals, including rutile and leucoxene, not distinguishable in this view (black), and transparent heavy minerals (light), all zircons. Some zircons contain many inclusions. Concentrate from Pleistocene sand attained in commercial operation by various separation techniques, viewed through binocular microscope. North Stradbrooke Island, Queensland, Australia. (Minsands Exploration Pty., Ltd., in Friedman and Sanders, 1978, Fig. 2-8, p. 37.)

Figure 5-1

been so thoroughly altered or coated that their mounted grains are no longer transparent. In rapid, routine examination of grain mounts using a petrographic microscope, the opaque minerals have been generally ignored and have been counted together under the single heading, "opaques."

Caution

The liquids used in heavy-mineral analysis are DANGEROUS! The liquids and their fumes are TOXIC, and you should carefully follow your instructor's directions. An excellent reference on the handling of these liquids is: Hauf, P. L.; and Airey, J., 1980, The handling, hazards, and maintenance of heavy liquids in the geologic laboratory: U.S. Geological Survey Circular 827, 24 p.

References Dealing with Heavy-Mineral Analysis

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Equipment and Materials

Heavy liquid - tetrabromoethane ($C_2H_2Br_4$), about 10 ml per sample

Acetone

Hand magnet, for removal of magnetic mineral particles

Separatory funnels and ring stand

Sieves

Analytical balance

Microscopes - binocular and petrographic

Index oils

Glass slides and cover glasses

Filter paper

Magnetic-separator apparatus

Bottles for collecting used heavy liquid and fluid waste

Watch glass to cover separatory funnel

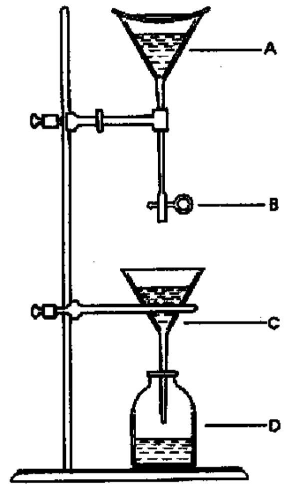
Separation of Heavy Minerals

Heavy minerals may be separated from minerals of lower density by (1) gravity methods, (2) magnetic methods, or (3) centrifuge methods. In this exercise you will carry out procedures that will introduce you to the principles of gravity separation and magnetic separation.

Separation of heavy-mineral particles by gravity is accomplished using a so-called heavy liquid and two superposed separatory funnels. The technique is reliable and particularly useful where large amounts of sediment must be processed. It suffers, however, from the disadvantage that complete separations normally require from one to three hours. A typical arrangement of apparatus for gravity separation of heavy minerals is shown in Figure 5-2.

In order to serve as a suitable medium for gravity separation of heavy-mineral particles, a heavy liquid, in addition to having a high specific gravity, must be: liquid at room temperature, of low-viscosity, transparent, chemically inert, readily available, chemically stable, easily handled and recovered, inexpensive and non-poisonous. Unfortunately, heavy liquids having the last two properties are not common.

You should keep in mind at all times that THE LIQUID THAT YOU WILL BE USING IS HIGHLY TOXIC AND THAT THE FUMES ARE TOXIC AS WELL. ALL



Simple Apparatus for Heavy-Mineral Separation by Gravity Method

A. Separatory funnel containing heavy liquid

B. Rubber tube with pinch-cock

C. Funnel with filter-paper lining

D. Bottle for collecting used heavy liquid

(Krumbein and Pettijohn, 1938, Fig. 153, p. 335.)

Figure 5-2

PROCEDURES MUST BE CARRIED OUT UNDER A WELL-VENTILATED HOOD! You will use tetrabromoethane ($C_2H_2Br_4$), which has a specific gravity at 20°C of 2.96; bromoform ($CHBr_3$) is also commonly used as a heavy liquid. Although for this exercise you will perform only one separation, you should be aware that using different liquids or mixtures of liquids of proper densities one can separate heavies into smaller and smaller classes of differing specific gravity.

Procedure I: Separation of Heavy-Mineral Particles by the Gravity Method

1. If necessary, sieve sample in order to obtain material in 1 to 4ϕ (1/2-1/16 mm) range.

2. Weigh sample - about 25 g is sufficient. Record sample weight, heavy liquid and liquid specific gravity on Form 5-1.

3. Pour tetrabromoethane into upper (separatory) funnel (see Fig. 5-2). The funnel should be about 1/2 full. CARRY OUT THIS AND ALL FOLLOWING OPERATIONS UNDER A WELL-VENTILATED

HOOD. THE HEAVY LIQUID AND ITS FUMES ARE TOXIC!

4. Pour sample into tetrabromoethane and stir thoroughly in order to wet all particles and disperse air bubbles.

5. Allow particles to settle; stir periodically so that particles will not adhere to funnel wall. Cover funnel with watch glass to reduce heavy-liquid evaporation loss.

6. When heavy minerals have settled to bottom of separatory funnel, open pinch-cock and allow heavy-mineral particles to drop onto filter paper in lower funnel. Close pinch-cock so that minerals floating in remaining heavy liquid will remain in the separatory funnel.

7. After heavy liquid has drained from filter paper into used heavy-liquid bottle below, remove paper and place upside down in porcelain dish or large watch glass containing acetone. If necessary, use plastic squeeze bottle containing acetone to wash into the dish any particles which adhere to the filter paper; decant excess acetone into fluid waste container.

8. Dry heavy-mineral fraction, record weight on Form 5-1, and label and retain fraction for compositional determination and provenance analysis.

9. Using the same apparatus set-up as before, drain the remaining heavy liquid through filter paper in the lower funnel and into the used heavy-liquid bottle below. The light minerals will collect on the filter paper. It may be necessary to use a squeeze bottle containing acetone to wash particles that adhere to the side of the separatory funnel. If this is necessary, it is important during the washing process to replace the bottle used for collection of undiluted used heavy liquid with one used for collection of fluid waste (i.e., a mixture of acetone and heavy liquid).

10. Using the same procedure as that outlined in Steps 7 through 9, collect, dry, record weight and retain the light-mineral fraction for compositional determination.

HEAVY-MINERAL SEPARATION BY GRAVITY METHOD

Sample weight ______________________________

Type of heavy liquid ________________________

Heavy liquid specific gravity _________________

Weight of heavy-mineral fraction _______________

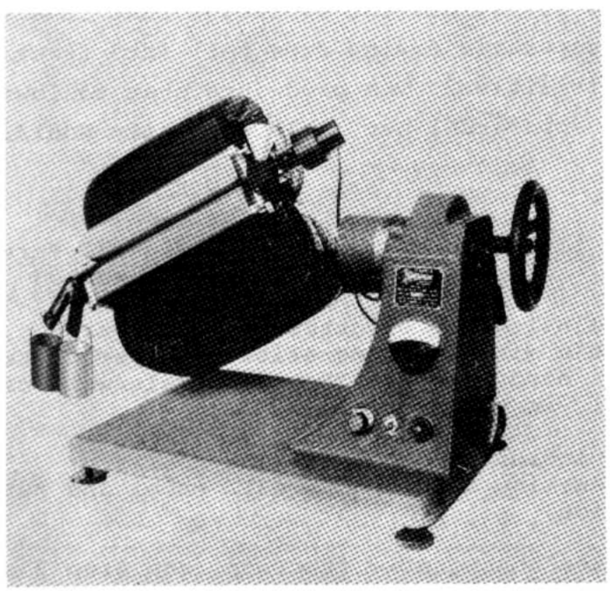
Weight of light-mineral fraction _______________

Form 5-1

Magnetic separation of mineral particles depends on the magnetic susceptibility of the minerals to be separated. This is a complex phenomenon which is a function of chemical composition, especially minor amounts of iron or manganese, and atomic-lattice structure.

The simplest form of magnetic separation is by hand magnet, a procedure which works for only one common detrital mineral - magnetite. Other minerals having magnetic susceptibility are separated by using apparatus which generate strong electromagnetic fields. Companies which market electromagnetic separators suitable for mineralogic work are: S. G. Frantz Co., Trenton, New Jersey; Chas. W. Cook & Sons, Ltd., Birmingham, England; and R. Eisenblaetter, Lingolsheim (Bas-Rhin), France.

The Frantz separator (Fig. 5-3) incorporates an electromagnet with two elongate pole pieces arranged so that the space between the poles is much wider on one side than the other. A vibrating metal chute parallels the pole pieces. Mineral particles are introduced into the upper end of the chute and slide toward the lower end. Those with higher magnetic susceptibility move toward the side of the chute where the pole gap is



Frantz Isodynamic Magnetic Separator
(inclined position)
(Müller, 1967)

Figure 5-3

narrow and the magnetic flux the greatest. The separator is mounted so that it can be rotated both in the direction of grain movement (slope) and in a direction normal to the direction of grain movement (tilt). The way in which mineral particles separate as they move along the length of the chute depends on (1) the tilt of the chute, (2) the amperage applied to the electromagnet and, to some extent, (3) the slope and rate of feed to the chute. At the lower end of the chute the particles are separated into two streams, one consisting of grains of higher susceptibility than that corresponding to the amperage setting used, the other consisting of grains of lower susceptibility.

Inasmuch as there is wide variation in magnetic susceptibility of mineral particles of a given species, it is common practice to set the Frantz separator slope at 10 to 30° (20° is more or less standard), the tilt at 5 to 20° (5° for minerals of low susceptibility, 15° for those of moderate to high susceptibility) and then determine the most effective amperage by trial and error.

The magnetic separator manufactured by Chas. W. Cook & Sons is very similar to the Frantz separator; the Eisenblaetter separator, developed in the early 1960s, has the advantage that in a single operation sample material is separated during free fall into fractions having different mass susceptibilities. The procedure that follows is designed for use with the Frantz apparatus, but could be easily modified for use with the Cook separator.

Procedure II: Separation of Heavy-Mineral Particles by the Magnetic-Susceptibility Method

1. Before using the electromagnetic separator, remove ferromagnetic minerals (magnetite and pyrrhotite) from the sample with a hand magnet. These minerals will clog the apparatus if left in the sample.

2. Using a side slope of 20° and a tilt of 25°, run the sample at a setting of 0.4 amperes. Label and retain the magnetic fraction.

3. Take the nonmagnetic fraction from Step 2 and run it at a setting of 0.8 amperes. Label and retain the magnetic fraction.

4. Take the nonmagnetic fraction from Step 3 and run it at a setting of 1.5 amperes. Label and retain the magnetic fraction and the nonmagnetic fraction.

5. Refer to Table 5-2 for a listing of those heavy minerals which are magnetic at 0.4, 0.8, and 1.5 amperes.

Magnetic at 0.4	Magnetic at 0.8	Magnetic at 1.5	Nonmagnetic at 1.5
Garnet	Biotite	Muscovite	Zircon
Ilmenite	Hornblende	Spinel	Rutile
Chromite	Hypersthene	Enstatite	Sphene
Chloritoid	Augite	Tourmaline	Leucoxene
Olivine	Actinolite	Clinozoisite	Apatite
	Staurolite	Diopside	Corundum
	Epidote	Tremolite	Barite
	Chlorite		Fluorite
			Sillimanite
			Kyanite

Minerals which are magentic at 0.4, 0.8, and 1.5 amperes settings (side slope 20°, tilt 25°) on the Frantz Isodynamic Magnetic Separator

Table 5-2

Determination of Provenance

Based on their physical and chemical nature, heavy minerals may be divided into four groups: opaques, micas, ultra-stables and meta-stables (Folk, 1974, p. 96).

Opaque minerals, inasmuch as they have a relatively high iron content, generally have a very high specific gravity. They include magnetite, ilmenite, pyrite, hematite, limonite, and leucoxene. Most researchers lump the opaques together and do not attempt to differentiate them. However, for purposes of this exercise you should attempt differentiation.

Micas vary in specific gravity due to compositional variation and in hydraulic behavior due to variation in particle shape. In addition, mica particles sometimes do not sink in bromoform. It is understandable that the micas are commonly not counted in heavy-mineral analyses.

The ultra-stable group includes zircon, tourmaline and rutile. Zircon and tourmaline are chemically inert and very hard and are therefore able to survive numerous cycles of erosion and transport. They are also polyvarietal and thus excellent indicators of provenance. Euhedral zircon is an indicator of volcanism.

The metastable group includes olivine, apatite, amphibole, pyroxene, garnet, epidote, clinozoisite, zoisite, kyanite, sillimanite, andalusite, staurolite, and many other minerals.

Table 5-3 is a summary of the characteristics and mode of occurrence of the more important heavy minerals. It will be useful in Procedure III: Identification of Heavy Mineral Particles. For detailed information on identification of both heavy minerals and light minerals, refer to Krumbein and Pettijohn (1938, p. 412-464), or Milner (1962).

Procedure III: Determination of Heavy-Mineral Composition

1. Under the binocular microscope, study the composition of the heavy-mineral fraction that you saved from Procedure I: Separation of Heavy-Mineral Particles by the Gravity Method.

2. Estimate particle-type percentages and record data on Form 5-2.

3. Using the fractions that you saved from Procedure II: Separation of Heavy-Mineral Particles by the Magnetic Susceptibility Method, estimate particle-type percentages and record data on Form 5-2.

4. Diagram your estimates of the percentages of various particle-types on Form 5-2.

The data that you have recorded in Procedure III will be used in Procedure IV: Interpretation of Provenance.

In order to interpret the nature of the source rock from which sediment was derived, it is necessary to group heavy minerals into genetic suites such as (1) reworked sedimentary, (2) low- and high-rank metamorphic, (3) sialic and mafic igneous, (4) pegmatitic, and (5) authigenic (Hubert, 1971, p. 462). The relative importance of each suite is then evaluated and inferences made about provenance. Table 5-4 outlines suites of heavy minerals derived from various source rocks.

Table 5-3

Characteristics and Mode of Occurrence of Important Heavy Minerals
(After Krumbein and Pettijohn, 1938)

Mineral	G	H	Form	Colors	Luster	Miscellaneous	Provenance
<u>Opaques</u>:							
Magnetite (Fe_3O_4)	5.17	6	Isometric, octahedra	Bluish black in reflected light	Metallic	Angular and well rounded particles abundant; marked by strong magnetic character and crystal form; distinguished from ilmenite with difficulty; may alter to hematite or limonite	Mafic igneous and high-rank metamorphic rocks
Ilmenite ($FeTiO_3$)	4.6-4.9	5-6	Orthorhombic	Brownish to purplish black in reflected light	Metallic	Common in sediments as irregular to well-rounded grains; often in part altered to leucoxene; nonmagnetic	Igneous and high-rank metamorphic rocks
Pyrite (FeS_2)	5.02	6	Isometric, cubes and pyritohedra, often striated; conchoidal fracture	Pale brass-yellow in reflected light, readily tarnished	Metallic	Nearly always authigenic; occurs in sediments as globular to irregular aggregates or as nodules and small concretions	Ubiquitous

Table 5-3 (continued)

Mineral	G	H	Form	Colors	Luster	Miscellaneous	Provenance
Hematite (Fe_2O_3)	5.2	6	Hexagonal-rhombohedral	Indian red to black in reflected light	Metallic to earthy	Usually alteration product but may be detrital	Ubiquitous
Limonite Hydrous iron oxide	3.8	5-6	Amorphous	Ochre yellow, brown to brownish black in reflected light	Earthy to metallic	Occurs as rounded granules or as powdery aggregates and coatings, usually as a decomposition product of pyrite, marcasite and glauconite; sometimes detrital	Ubiquitous
Leucoxene	3.5-4.5		An aggregate of extremely fine-grained sphene, rutile or anatase	Dead white in reflected light	Dull	Forms an alteration product usually after ilmenite; appears as rounded grains, sometimes with mat surface minutely pitted	Authigenic
Micas:						Do not always sink in bromoform; percentages unreliable because of unpredictable hydraulic behavior	

Table 5-3 (continued)

Mineral	G	H	Form	Colors	Luster	Miscellaneous	Provenance
Ultra-stables:							
Zircon ($ZrSiO_4$)	4.6–4.7	7½	Tetragonal, short prisms with pyramids; cleavage rare	Usually colorless, some particles are mauve, yellow to brown	Adamantine	Particles often show euhedral form with well-marked crystal faces; well-worn particles usually elongate, elliptical or globular; contain large mineral, liquid or gas inclusions; many particles show well-defined zoning; particles can survive many reworkings	Sialic to intermediate igneous rocks
Tourmaline	3.0–3.3	7–7½	Hexagonal-rhombohedral; striated prismatic; cleavage lacking or poor	Yellow-brown, dark brown, indigo to black		Particles occur as elongate prisms, irregular fractured pieces and well-rounded ovals; inclusions are common. Particles can survive many reworkings	Pneumatolytic rocks, pegmatites, schists, gneisses, marbles
Rutile (TiO_2)	4.24	6–6½	Tetragonal, often striated	Yellow, reddish brown, red	Adamantine	Particles irregular, generally elongate, prismatic with rounded pyramidal ends common; inclusions abundant. Characterized by form, very high bire-	Sialic igneous and crystalline metamorphic rocks

Table 5-3 (continued)

Mineral	G	H	Form	Colors	Luster	Miscellaneous	Provenance
Rutile (continued)						fringence, high relief, deep color and striae	
<u>Metastables</u>:							
Olivine $(Mg, Fe)_2SiO_4$	3.5	6½-7	Orthorhombic, cleavage good	Colorless, pale yellow	Glassy	Occurs in sediments as irregular, much-fractured particles; particles colorless, with bright interference colors and showing traces of decomposition; rare as a detrital occurring only in dry climates with rapid erosion	Basic and ultrabasic igneous rocks
Apatite $Ca_5(F, Cl)(PO_4)_3$	3.16-3.22	5	Hexagonal, long to short prismatic, terminated by base or pyramid; imperfect basal cleavage	Green or brown, also blue violet or colorless	Vitreous to subresinous	Particles oval to nearly circular to slightly worn elongate prismatic form; frequently contain inclusions in planes or rows; characterized by detrital form, low birefringence	Acid igneous rocks and pegmatites

Table 5-3 (continued)

Mineral	G	H	Form	Colors	Luster	Miscellaneous	Provenance
Amphibole (Hornblende, Actinolite, Tremolite)	2.9-3.5	5-6	Long, blade-like prisms; cleavage-two oblique	Hornblende-dark brown and green to black; Actinolite-dusky yellow green to dusky yellowish green; Tremolite-white to colorless	Satiny, glassy, pearly	Particles elongate, prismatic, with longitudinal cleavage and marked diagonal cross-fractures; may occur as irregular fractured particles; hornblendes often nearly opaque and appear translucent just on thin edges	Igneous and metamorphic rocks
Pyroxene (Augite, diopside)	3.2-3.4	5-6	Monoclinic; cleavage-perfect prismatic at about 90°	Augite-pale brownish gray or pale grayish green; Diopside-very pale green or colorless	Vitreous	Particles usually elongate, worn cleavage fragments, sometimes with dentate ends; irregular or poorly rounded; diopside more resistant than augite, particles moderately well-rounded	Augite-intermediate and basic igneous rocks; Diopside-metamorphic contact rocks and schists
Garnet	3.5-4.3	7	Isometric, dodecahedra, trapezohedra; fracture-conchoidal	Colorless, pale pink, orange, red, apricot-yellow, amber	Glassy	Characterized by color, conchoidal fracture, isotropism and high relief	Igneous and metamorphic rocks; high abundance indicates metamorphic source

Table 5-3 (continued)

Mineral	G	H	Form	Colors	Luster	Miscellaneous	Provenance
Epidote $Ca_2(Al,Fe)$ $Al_2(Si_2O_7)$ $(SiO_4)O(OH)$	3.36	6	Monoclinic; cleavage-present but not visible in particles	Pale greenish yellow to lemon yellow	Glassy to dull	Particles greenish yellow, equidimensional, sharply angular to subrounded	Metamorphosed igneous rocks
Clinozoisite (Complex calcium aluminum silicate)	3.25-3.37	6-6½	Monoclinic; prismatic	Grayish white, green and pink; Lighter in color than epidote	Vitreous	Zoisite is a relatively rare member of the epidote group	Crystalline schists and metamorphosed basic rocks
Kyanite (Al_2SiO_5)	3.6	5-7	Triclinic; bladed; cleavage-2 at 90°	Usually colorless, rarely pale blue	Vitreous to pearly	Particles are elongate and of marked rectangular outline to short, moderately rounded and elliptical; carbonaceous inclusions common; particles may alter along edges to "mica"	Schists and gneisses
Sillimanite Al_2SiO_4	3.23	6-7	Orthorhombic; cleavage - one direction, perfect	Colorless	Vitreous	Particles irregular to short prismatic, split longitudinally and have striae parallel to length	Metamorphosed argillaceous rocks

Table 5-3 (continued)

Mineral	G	H	Form	Colors	Luster	Miscellaneous	Provenance
Staurolite $(Fe,Mg)_2(Al,Fe)_9O_6(SiO_4)_4(O,OH)_2$	3.7	7-7½	Orthorhombic; short prisms, cruciform twins	Yellow, gold, brown	When altered, dull to earthy; when fresh, resinous to vitreous	Particles irregular, somewhat platy with hackly to subconchoidal fracture; inclusions numerous; bright interference colors	Crystalline schists, slates and sometimes gneisses
Andalusite (Al_2SiO_5)	3.15	7½	Orthorhombic; nearly square prisms; cleavage-good prismatic at about 90°	Colorless to pink	Dull to vitreous	Particles are elongate worn or broken prisms to irregular in shape showing only conchoidal fracture; inclusions common	Contact metamorphic zones in shaly rock

DETERMINATION OF HEAVY-MINERAL COMPOSITION - Gravity separated fraction and magnetically separated fraction

Exercise 5
Name ______________________
Laboratory Section ______________
Date ______________________

Estimated Percentage of Total Particles

Particle-type	Gravity-separated	Magnetically-separated
Magnetite		
Ilmenite		
Pyrite		
Hematite		
Limonite		
Leucoxene		
Total Opaques		
Total Micas		
Zircon		
Tourmaline		
Rutile		
Total Ultra-Stables		
Olivine		
Apatite		
Amphiboles		
Pyroxenes		
Garnet		
Epidote		
Clinozoisite		
Kyanite		
Sillimanite		
Staurolite		
Andalusite		
Total Metastables		
Total Particles	100%	100%
Pie Diagrams (3.6° of arc = 1% composition)	Heavy mineral composition	Heavy mineral composition

Form 5-2

Reworked sediments	Well-rounded grains of rutile, tourmaline, zircon.
Low-rank metamorphic	Biotite, chlorite, spessartite garnet, tourmaline (especially small, euhedral, brown crystals with graphite inclusions).
High-rank metamorphic	Actinolite, andalusite, apatite, almandine garnet, biotite, diopside, epidote, clinozoisite, glaucophane, hornblende (including blue-green varieties), ilmenite, kyanite, magnetite, sillimanite, sphene, staurolite, tourmaline, tremolite, zircon.
Sialic igneous	Apatite, biotite, hornblende, ilmenite, monazite, muscovite, rutile, sphene, tourmaline, zircon.
Mafic igneous	Augite, diopside, epidote, hornblende, hypersthene, ilmenite, magnetite, olivine, oxyhornblende, pyrope garnet, serpentine.
Pegmatites	Apatite, biotite, cassiterite, garnet, monazite, muscovite, rutile, tourmaline (especially indicolite).
Ash falls	Euhedral crystals of apatite, augite, biotite, hornblende, and zircon.
Authigenic	Hematite, leucoxene, limonite, tourmaline, zircon; euhedral crystals of anatase, brookite, pyrite, rutile, and sphene.

Provenance of Some Common Heavy Minerals
(Hubert, 1971, p. 462)

Table 5-4

Procedure IV: Interpretation of Provenance

The data on Form 5-2 provide a basis for interpretation of provenance for (1) the gravity-separated heavy-mineral fractions, and (2) the magnetically-separated heavy-mineral fraction. In the space below, outline your interpretations and the reasoning that led you to them: