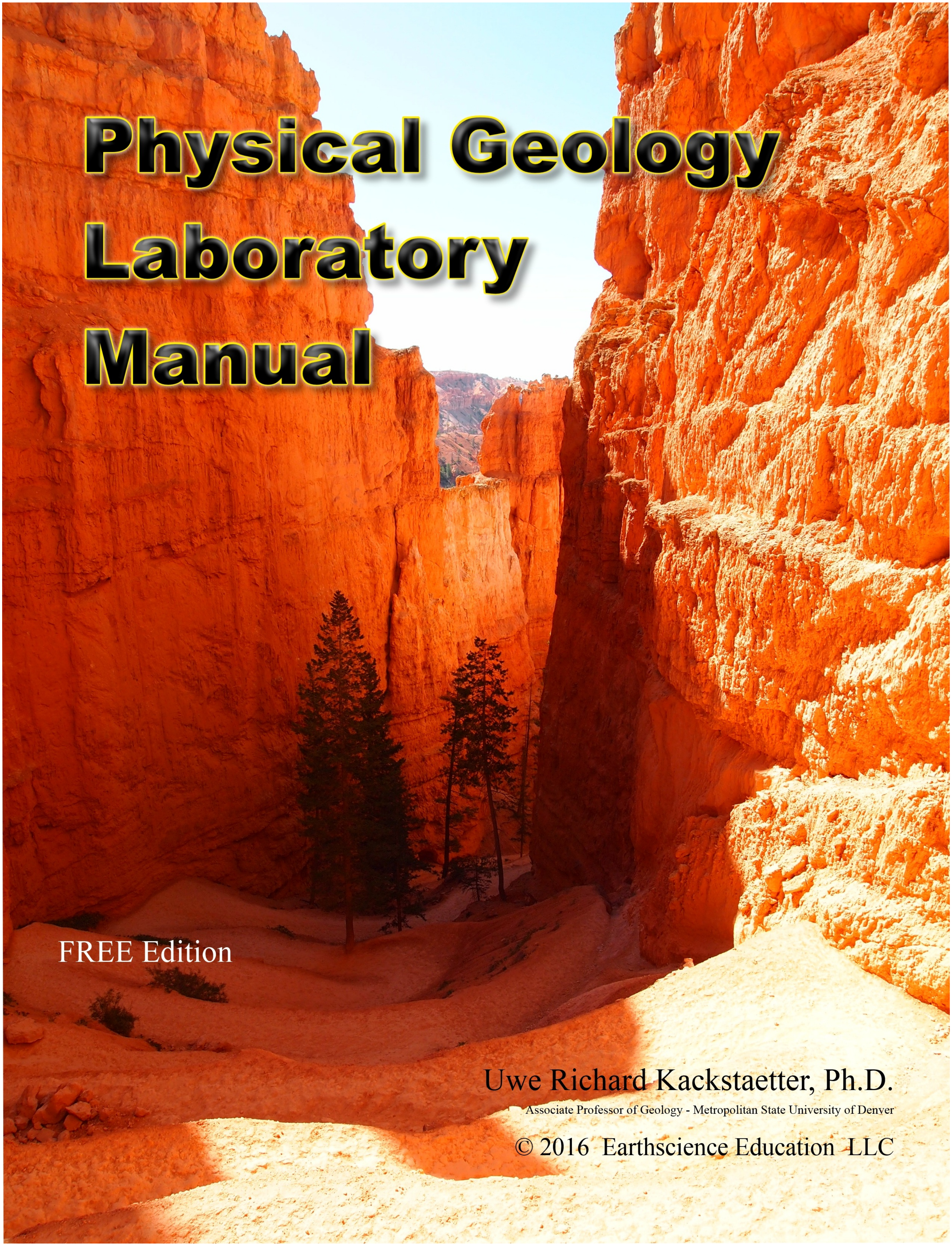
Physical Geology Laboratory Manual



FREE Edition

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LAB EXERCISES

Quick links to all Laboratory exercises in this manual.

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Professional Rock / Mineral ID Kit

You will need a mineral - rock study kit in conjunction with this text containing the following materials:

- ☐ 9 Mohs Hardness minerals: Talc, Gypsum, Calcite, Fluorite, Apatite, Orthoclase, Quartz (crystal), Topaz, Corundum
- ☐ Hardness testing: Thick glass plate; a piece of copper; steel nail
- ☐ 9 Igneous Rock Chips for study: Andesite, Basalt, Diorite, Gabbro, Granite, Obsidian, Pumice, Rhyolite, Tuff
- ☐ lab grade dark and light streak plates
- ☐ small magnet
- ☐ 19 additional Mineral Chips for study: Augite, Barite, Biotite, Chalcopyrite, Chlorite, Dolomite, Galena, Halite, Hematite, Hornblende, Kaolinite, Limonite, Magnetite, Muscovite, Olivine, Plagioclase (light & dark), Pyrite, Quartz (milky),
- ☐ 6 Metamorphic Rock Chips for study: Gneiss, Marble, Quartzite, Schist, Skarn, Slate
- ☐ bottle with dilute laboratory grade HCl for rock and mineral testing (or vinegar)
- ☐ Densimeter field system for accurate determination of material densities consisting of: electronic scale with a minimum of 100g x 0.01g resolution, calibration weight, small cup, nylon string (use in class set or purchase your own)
- ☐ 8 Sedimentary Rock Chips for study: Arkose, Chert, Coal, Conglomerate, Gypsum, Limestone, Sandstone, Shale
- ☐ precision glass/metal handlense (10x)

This kit with the exception of the density system is freely available when sign up for a geology course at Metropolitan State University of Denver.

For those interested in a career or hobby of the geologic sciences, a mineral identification step-by-step hands-on field and laboratory approach for the novice, professional, prospector, geoscientist and mineral laboratories for use in practical mineralogy and mineral identification is available at rapidmineralid.com. In addition, more sophisticated testing methods and equipment for field and laboratory is also available.

1 MINERALS

Minerals are the building blocks of geologic materials. They do not need to be beautiful crystals, but can occur as aggregates or masses. Over 5000 mineral species have been described and more than 100 new minerals are added every year. However, most of these 5000 minerals are rare. Only about 200 are common enough to make up macroscopic rocks and of these, the most abundant 50 make up 99.9% of the Earth's crust.

In order for a geologic material to qualify as a mineral, it must meet the following four definitions:

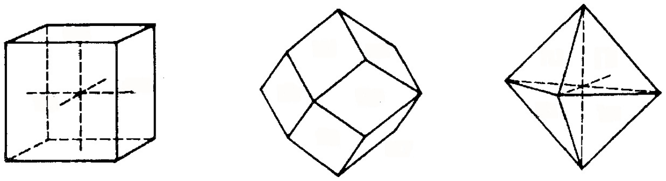
1. A mineral forms and occurs naturally
2. A mineral is a homogenous solid (alas with two exceptions:)
    a. Mercury (Hg) Water (H_2O)
3. A mineral has a definite chemical composition
4. A mineral has an ordered atomic arrangement or crystal structure (with very few exceptions: e.g., opal).

1.1 MINERAL CRYSTAL STRUCTURES

Many minerals occur in nature with definite and characteristic external geometric forms. These we call crystals. The outward shapes are an expression of an orderly internal atomic arrangement of the elements which compose the crystals. The possible number of crystal patterns is limited by geometric consideration. As a result, all crystals can be classified within one of six possible crystal systems:

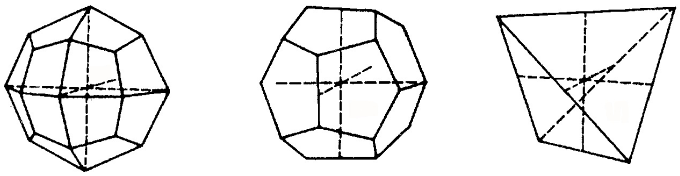
1.1.1 ISOMETRIC CRYSTAL SYSTEM

In the **Isometric system** three axes are at right angles to each other and are of equal length (Iso = equal, metron = measure). The Isometric crystal system has many forms and shapes and high order symmetry. It must always have, however, three equal length imaginary axes at right angles to each other. Some crystal forms of the Isometric system are shown In figure 1.1. Three imaginary crystal axes are sketched in all but one of the crystals. Visualize where they would be in this rhombododecohedron model.



Cubic Rhombododecohedron Octahedron

Some typical isometric minerals: diamond, gold, platinum, copper, argentite, chromite, magnetite, fluorite, sphalerite galena, halite, tetrahedrite, and others.



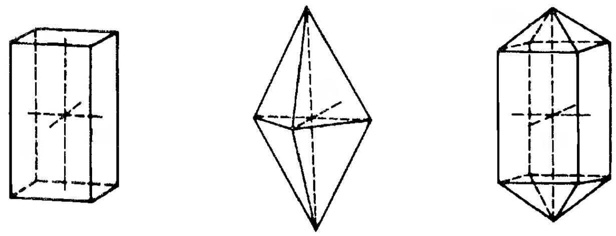
Trapezohedron Pyritohedron Tetrahedron

Some other isometric minerals: garnet, spinel, cuprite, pyrite, bornite, cobaltite, uraninite and others with extended crystal face intersections.

Figure 1.1 - Examples of the Isometric crystal system. Mineral forms and common mineral axes in the system shown by dashed lines.

1.1.2 TETRAGONAL CRYSTAL SYSTEM

The **Tetragonal System** (Tetra = four; gonon = angle) has also three imaginary crystal axes at right angles to each other. However, while the two horizontal axes are of equal length, the vertical axis is longer or shorter than the other two. Zircon, for example, crystallizes in the tetragonal system. A common crystal form is a 4-sided pyramid which may have vertical sides or prismatic faces, and an upside down pyramid. Figure 1.2 shows three crystal forms in the tetragonal system and gives a short list of some common tetragonal minerals. This crystal system contains the fewest of all minerals.



Tetragonal Prism Bipyramidal Bipyramidal Prismatic

Common tetragonal minerals include: cassiterite, chalcopyrite, rutile, scheelite, thorite, idocrase, wulfenite, zircon and others.

Figure 1.2 - Some crystal forms in the Tetragonal crystal system.

1.1.3 ORTHORHOMBIC CRYSTAL SYSTEM

The **Orthorhombic System** (orthos = straight) has again three imaginary crystal axes at right angles to each other. However, each one has a different length. In the realm of man-made objects, a brick or shoe box would belong to the orthorhombic system for example. In the world of minerals, the common mineral barite crystallizes in the system. Figure 1.3 shows some typical crystal forms in the system, inclusive a brief list of some common orthorhombic minerals.

1.1.4 MONOCLINIC CRYSTAL SYSTEM

The **Monoclinic System** (mono = single, cline = inclined) has three crystal axes of unequal length, as is the case in the orthorhombic system as well. While two of the axises in the monoclinic system intersect at right angles to each other, the third axis does not, but intersects the other two obliquely. The gypsum crystal exhibits these characteristics as well as crystal forms of biotite and muscovite micas. It should be noted that the oblique angle of the third axis in monoclinic minerals can be very small, as low as 1 ° in muscovite mica. Common crystal forms and minerals in the system are shown in figure 1.4.

1.1.5 TRICLINIC CRYSTAL SYSTEM

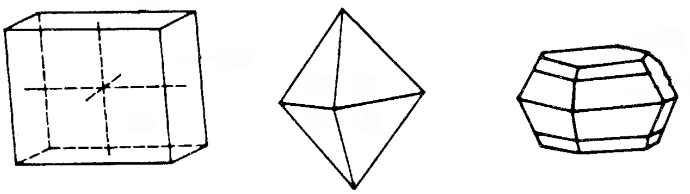
The **Triclinic System** (tri = three, cline = inclined) has three crystal axises of varying length and all three intersect not at right angles but obliquely to each other. Graphically, this makes this crystal system a challenge to represent in form of a drawing. Kyanite, plagioclase and rhodonite crystallize within this system. Some crystal forms in the triclinic system are shown in figure 1.5 together with a list of some common minerals.

1.2.6 HEXAGONAL CRYSTAL SYSTEM

Interestingly enough, the **Hexagonal System** (hexa = six; gonon = angle) has four crystal axes instead of the usual three. However, three of the axes in this system are equal in length and in a horizontal plane, intersecting in angles of 60 degrees to each other. The fourth axis is of different length and at right angles to the others and In the vertical plane of the crystal. The common mineral quartz shows the distinctive characteristics of the hexagonal system (figure 1.6).

Note that hexagonal first order and second order prisms differ. In first order prisms three equal length axes intersect the crystal faces at their edges. In second order prisms intersection of crystal axes occurs at the central part of the crystal faces.

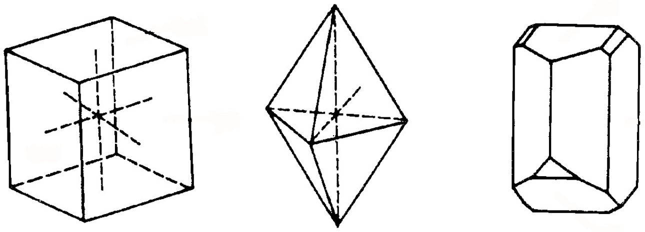
An odd branch of the hexagonal system is the rhombohedral class (figure 1.7). At first glance a simple rhombohedron locks like a triclinic crystal. Calcite, which displays rhombohedral hexagonal characteristics is indeed often mistaken for such a



Macro-, Brachy- & Basal Pinacoids | Pyramid | Pyramids, Domes & Basal Pinacoid

Common minerals in the system include: aragonite, azurite, barite, brochantite, cerussite, columbite, enargite, staurolite, stibnite, strontianite, marcasite, olivine, topaz and others.

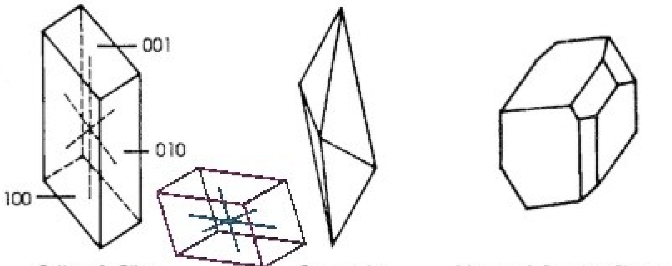
Figure 1.3 - Some crystal forms In the orthorhombic crystal system.



Ortho-, Clino- & Basal Pinacoids | Pyramids | Orthodomes, b-Pinacoid, Prisms

Augite, biotite, crocoite, gypsum, hornblende, malachite, monazite, muscovite, orthoclase, tenorite, titanite, wolframite and numerous others are examples.

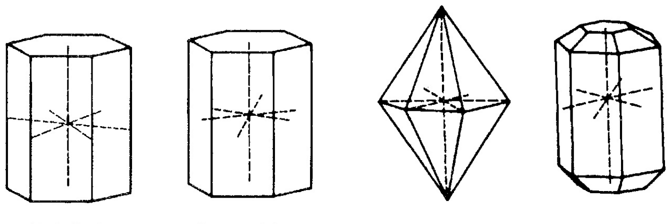
Figure 1.4 - Common mineral forms in the monoclinic system. Drawings are shown with very small oblique angle of the third axis.



Ortho- & Clino Pinacoids & Base | Pyramids | Macro- & Brachy- Pinacoids, Prism, Pyramid & Base

Plagioclase, kyanite, rhodonite, turquoise, ulexite and axinite are common minerals in system.

Figure 1.5 - Some crystal forms in the triclinic system.



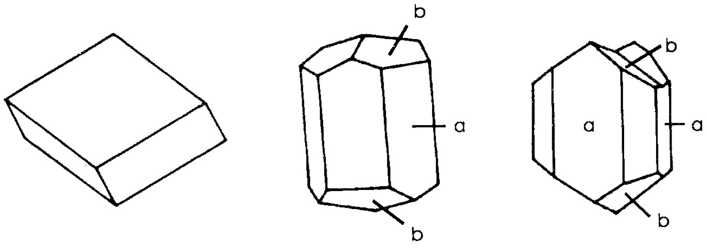
First Order Prism | Second Order Prism | First Order Pyramid | Prism; Bipyramid and Basal Pinacoid

Common hexagonal minerals are: apatite, beryl, molybdenite, niccolite, pyrrhotite, quartz and zincite.

Figure 1.6 - Hexagonal crystal forms with crystal axes.

triclinic geometrical form. However, when extending the main or c-axis through the most opposite corners of a rhombohedron, rotation around this c-axis will reveal perfect 6-folded rotation symmetry. Some famous gemstones such as emeralds (beryl), rubies and sapphires (corundum), and tourmaline belongs to the rhombohedral hexagonal crystal class.

The crystal forms illustrated are only a few of the very large number possible and known in nature. Yet, these can be very useful guides as you study and try to identify various natural crystals. The minerals pyrite and garnet and their various crystal forms exemplify some of the numerous possibilities. Pyrite may develop cubic, pyramidal or pyritohedral forms. In some cases the different crystal forms may be intermixed In the same mineral deposits.



Rhombohedron a. Prisms & b., Pyramids a. Prisms & b. Pyramids

Some common minerals in the class: chabazite, brucite, beryl, alunite, calcite, dolomite, tourmaline, rhodochrosite, siderite, corundum, hematite, cinnabar

Figure 1.7 - Examples of crystals of the rhombohedral class of the hexagonal system.

LAB EXERCISE 1 - CRYSTAL SYSTEMS

Name:	Course ID:

The attached sheet contains buildable paper models of the crystal systems discussed. Complete the table below by building each paper model. Indicate a short description of each crystal class and list mineral samples studied in class with their correct crystal system.

ISOMETRIC (Paste paper model here!)	Short description of crystal class:	Mineral(s) from study kit belonging to this class:
TETRAGONAL (Paste paper model here!)	Short description of crystal class:	Mineral(s) from study kit belonging to this class:
ORTHORHOMBIC (Paste paper model here!)	Short description of crystal class:	Mineral(s) from study kit belonging to this class:
MONOCLINIC (Paste paper model here!)	Short description of crystal class:	Mineral(s) from study kit belonging to this class:
TRICLINIC (Paste paper model here!)	Short description of crystal class:	Mineral(s) from study kit belonging to this class:
HEXAGONAL (Paste paper model here!)	Short description of crystal class:	Mineral(s) from study kit belonging to this class:
HEXAGONAL - RHOMBOHEDRAL (Paste paper model here!)	Short description of crystal class:	Mineral(s) from study kit belonging to this class:

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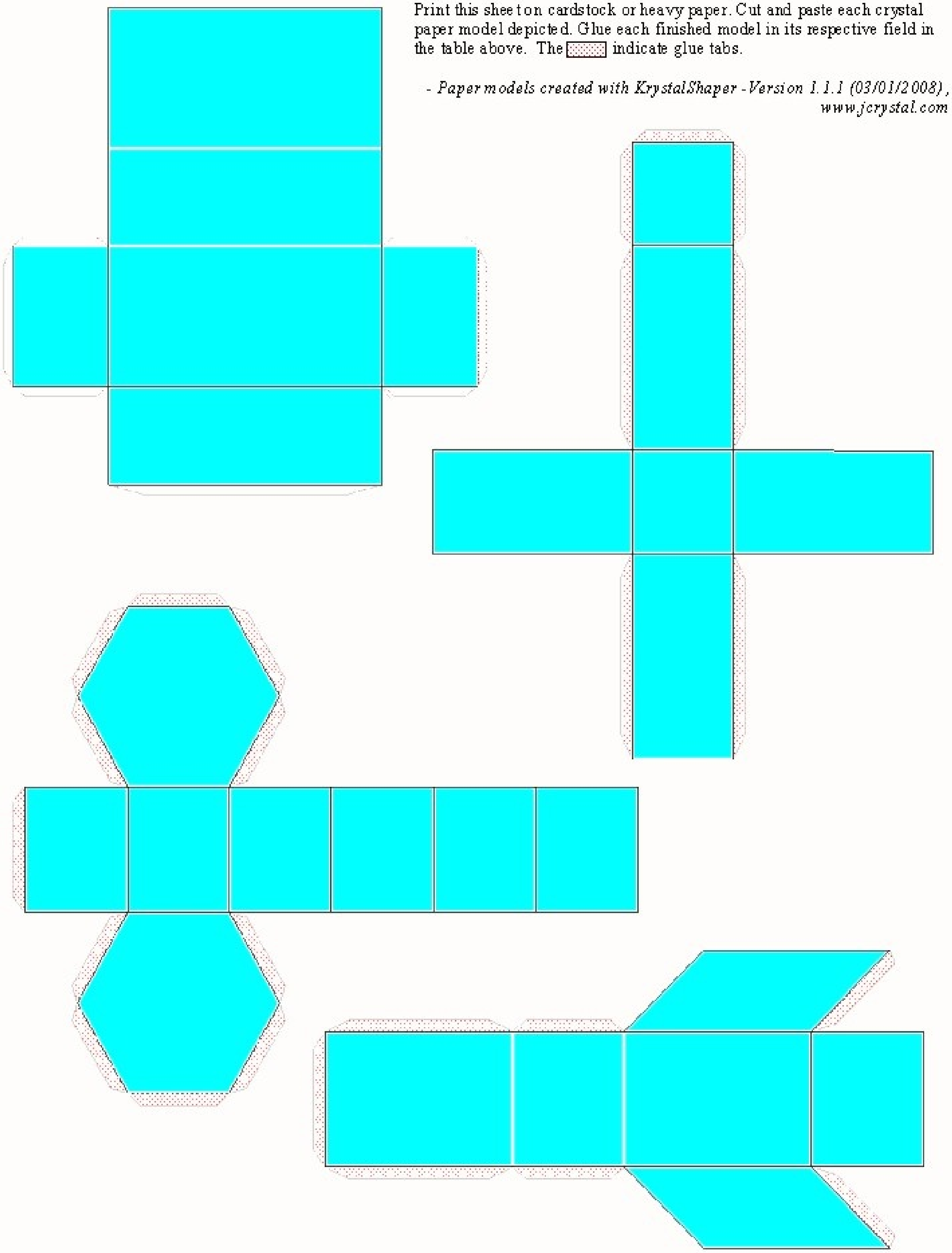

Print this sheet on cardstock or heavy paper. Cut and paste each crystal paper model depicted. Glue each finished model in its respective field in the table above. The ▨ indicate glue tabs.

- *Paper models created with KrystalShaper - Version 1.1.1 (03/01/2008), www.jcrystal.com*

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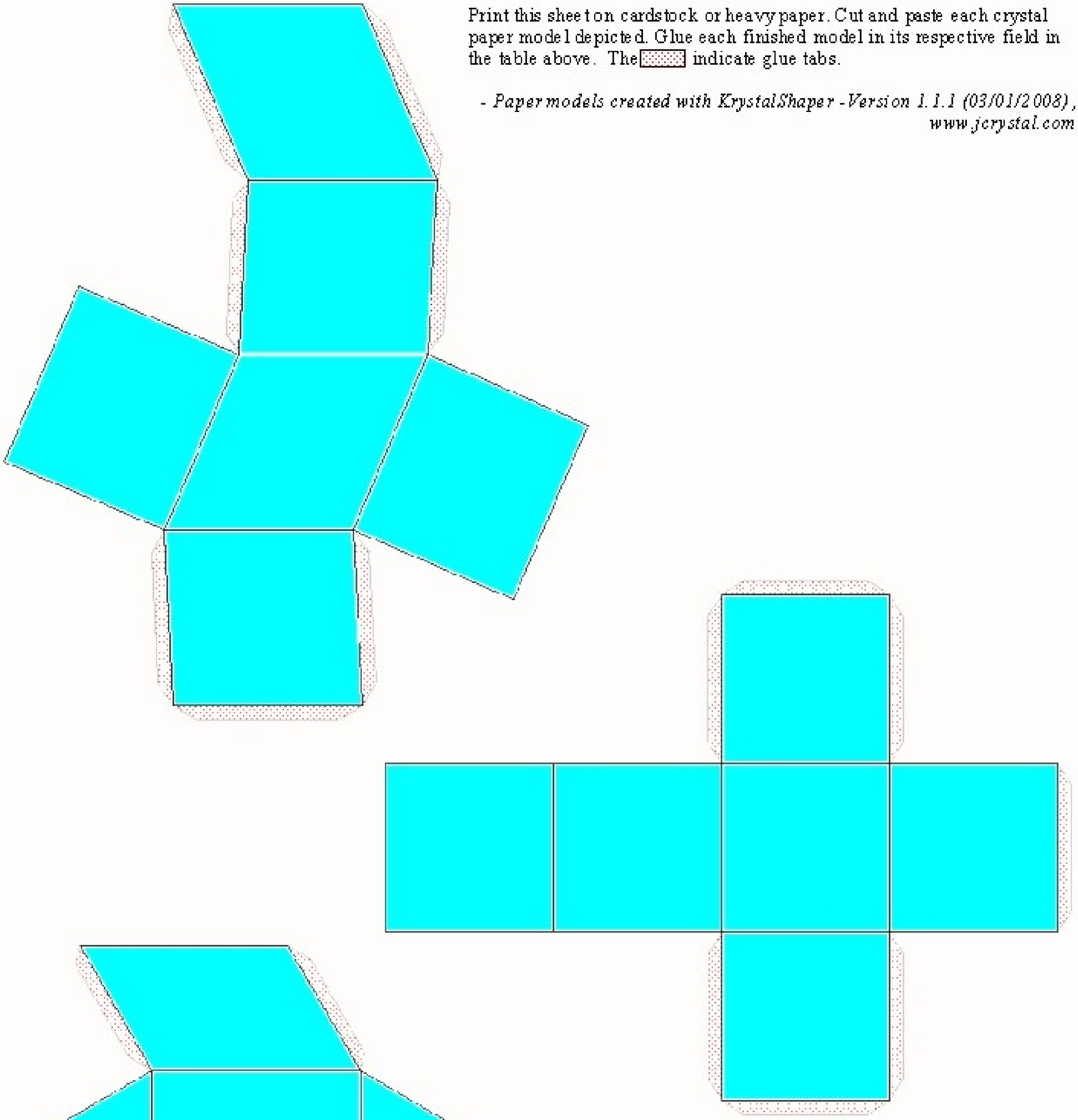

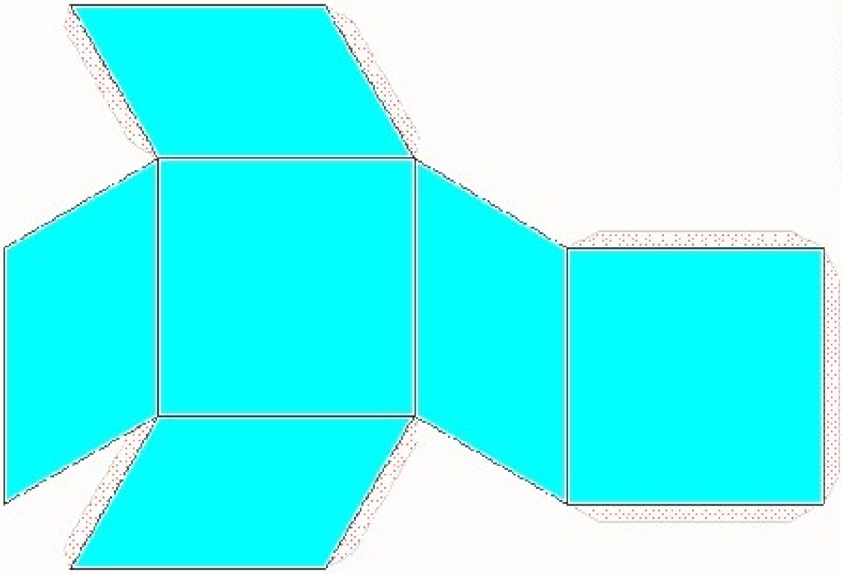

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1.2 MINERAL CHEMISTRY

All minerals are composed of atoms from those consisting of single atomic composition such as gold to those of complex composition involving several different types of atoms. The latter, based on electrical charge, are divided into ions. Atoms and molecules with a positive charge are called cations, while those with a negative charge are referred to as anions. While ions can consist of single elements, they often form charged clusters or ionic groups (polyatomic ions). In the Berzellan classification of minerals, chemical composition is the main basis. Minerals are placed in chemically related classes depending on the dominant anion (negative charged ion) or anionic group. Such an anionic group may consist of a combined C (carbon) plus 3 O (oxygen), creating the polyatomic anion $CO_3{}^{2-}$, which is the basis of the carbonate group.

Almost 200 years ago Dalton, an English chemist, after intensive research, proposed that all elements consist of very small particles called atoms. He further stated that for a given elemental substance the atoms are alike and exhibit identical chemical properties. Different elements have different chemical properties, and in an ordinary chemical reaction, no atom disappears or changes into another element. All 109 elements currently known to man are listed in a unique table called the "Periodic Table of Elements." Of those, only 92 are naturally occurring and only 77 of them are present in detectable average concentrations in the earth's crust and thus of importance in geology (see table 1.1).

Table 1.1 - Abundance of elements in the earth's crust in decreasing ppm (parts per million) or grams / metric tons, their valence or ionic charge and their ionic radius (IR) or size

Element	Abundance (ppm)	Valence	IR	Element	Abundance (ppm)	Valence	IR
O	445 000	-2	1.40	Pb	13	+2	1.19
Si	272 000	+4	0.40	B	9.0	+3	0.23
Al	83 000	+3	0.54	Th	8.1	+4	0.97
Fe	62 000	+2; +3	0.86; 0.65	Br	2.5	-1	1.96
Ca	46 600	+2	0.99	U	2.3	+4; +6	1.08; 0.52
Mg	27 640	+2	0.72	Sn	2.1	+4	0.69
Na	22 700	+1	1.02	Be	2.0	+2	0.35
K	18 400	+1	1.38	As	1.8	+5	0.58
Ti	6 320	+4	0.61	Mo	1.2	+4	0.65
P	1 120	+5	0.38	W	1.2	+4	0.62
Mn	1 060	+2	0.46	I	0.46	-1	2.2
F	544	-1	1.33	Sb	0.2	+5	0.76
Ba	390	+2	1.35	Cd	0.16	+2	0.97
Sr	384	+2	1.12	Ag	0.08	+1	1.26
S	340	-2	0.37	Hg	0.08	+2	1.02
Zr	162	+4	0.72	Se	0.05	+2	0.50
V	136	+3	0.59	Pt	0.01	+2	0.63
Cl	127	-1	1.81	Au	0.004	+1	0.85
Cr	122	+3	0.52	Ir	0.001	+4	0.63
Ni	99	+2	0.69	Ru	0.0001	+3	0.68
Zn	76	+2	0.74	Rh	0.0001	+2	0.68
Cu	68	+1; +2	0.9; 0.73	Common Polyatomic Ions:			
Co	29	+2	0.75	SO_4		-2	2.30
N	19	+5	0.13	CO_3		-2	1.50
Ga	19	+3	0.62				
Li	18	+1	0.76				

The different elements can react with each other and combine to form compounds according to chemical laws. A compound is a substance made of two or more elements combined in definite and constant amounts expressed as whole numbers or simple fractions. In water, for example, there are always two atoms of hydrogen (H) to one of oxygen (0), represented in the famous chemical formula H_2O, supporting the law of constant composition.

Minerals can be chemically classified as either compounds or pure elements (native minerals). Compounds (combined elements) are kept together by chemical bonds. These bonds between the elements can be divided into four principal bond types: ionic, covalent, metallic and van der Waals', with transitions among all types. In mineral genesis nature acts to form the best geometry of structural units in space combined with electrical neutrality and minimum lattice energy. These arrangements determine the physical and chemical properties of the mineral.

IONICALLY BONDED MINERAL PROPERTIES - Some properties of ionic-bonded crystals are moderate hardness, moderate specific gravity, fairly high melting and boiling points, and poor conductors of heat and electricity. Because of the uniformity of the electrostatic charge, the resultant crystal has high symmetry. Many ionically bonded minerals are also water soluble.

COVALENTLY BONDED MINERAL PROPERTIES - Electron sharing in atoms within minerals results in general insolubility, a greater stability and therefore hardness, very high melting and boiling points and non-conducting of electricity. The local and sharply directional bonds formed results in a lower symmetry for formed crystals than when ionic bonding occurs.

VAN DER WAALS' BONDED MINERAL PROPERTIES - The van der Waals' bond is most uncommon in minerals and if present, such as in graphite and mica, defines a zone of ready cleavage and low hardness.

METALLICALLY BONDED MINERAL PROPERTIES - The close metallic bonding results in high plasticity, ductility, tenacity, electrical conductivity, and low hardness. Melting and boiling points also relate directly to this bonding. Gold, silver, copper and a few other native metallic minerals have metallic bonding.

The individual type(s) of interatomic linkages or chemical bonds in minerals (metallic, ionic or polar, covalent and van der Waals) imparts characteristic properties of the matter in which it occurs. More than one type of chemical bond may be present in a single compound: 1. mixed and 2. like bonds. Several physical properties are the result of the mixed type such as hardness, melting point, and strength. Each physical characteristic is determined by the weakest bonds. These are direct1y affected by increased mechanical or thermal stress. Still, the classification of bonding is arbitrary and many compounds may have intermediate types. For example, silicate minerals are neither purely ionic nor covalent but intermediate. As earlier noted, the geometry assumed by any solid is such that the entire crystal lattice tends to form with minimum potential energy.

1.2.1 IONIC SUBSTITUTION

Substitution of an ion or ionic group of a different element may occur in a given structure. This is called ionic substitution and the extent to which it occurs depends on several factors. Most important is ionic size. Ions of two elements can substitute for each other if the ionic radii are smaller or differ by less than 15%. If more than this, substitution is rare. Temperature of mineral formation may also affect substitution within the above limits. The higher the temperature, the greater the thermal activity and the less rigorous the space requirements within the lattice structure of the mineral. Crystals formed at high temperatures may show extensive ionic substitution, which is not possible at lower temperatures. A similar valence or electrical charge favors substitution, but is not a requirement as long as electrical neutrality can be maintained by other ions.

Complete ionic substitution may take place in mineral groups of exactly equal structure (Isostructural). For example siderite, $FeCO_3$, can have Mg^{2+} enter the lattice structure of the mineral in any proportion, or Fe^{2+} may enter the lattice of magnesite, $MgCO_3$, in all proportions. The valence charge is the same. The most abundant mineral group in the world, the plagioclase feldspars, have a type of solid solution or substitution of Na and Ca from the calcite rich anorthite to the sodium rich albite, i.e., $NaAlSi_3O_8 \rightarrow CaAl_2Si_2O_8$.

1.3 MINERAL GROUPS

According to chemistry, minerals can be classified or subdivided into various mineral groups. The silicate minerals comprise the largest of the groups and are discussed under 1.4 below. Figure 1.8 summarizes the most common mineral groups according to major chemical composition.

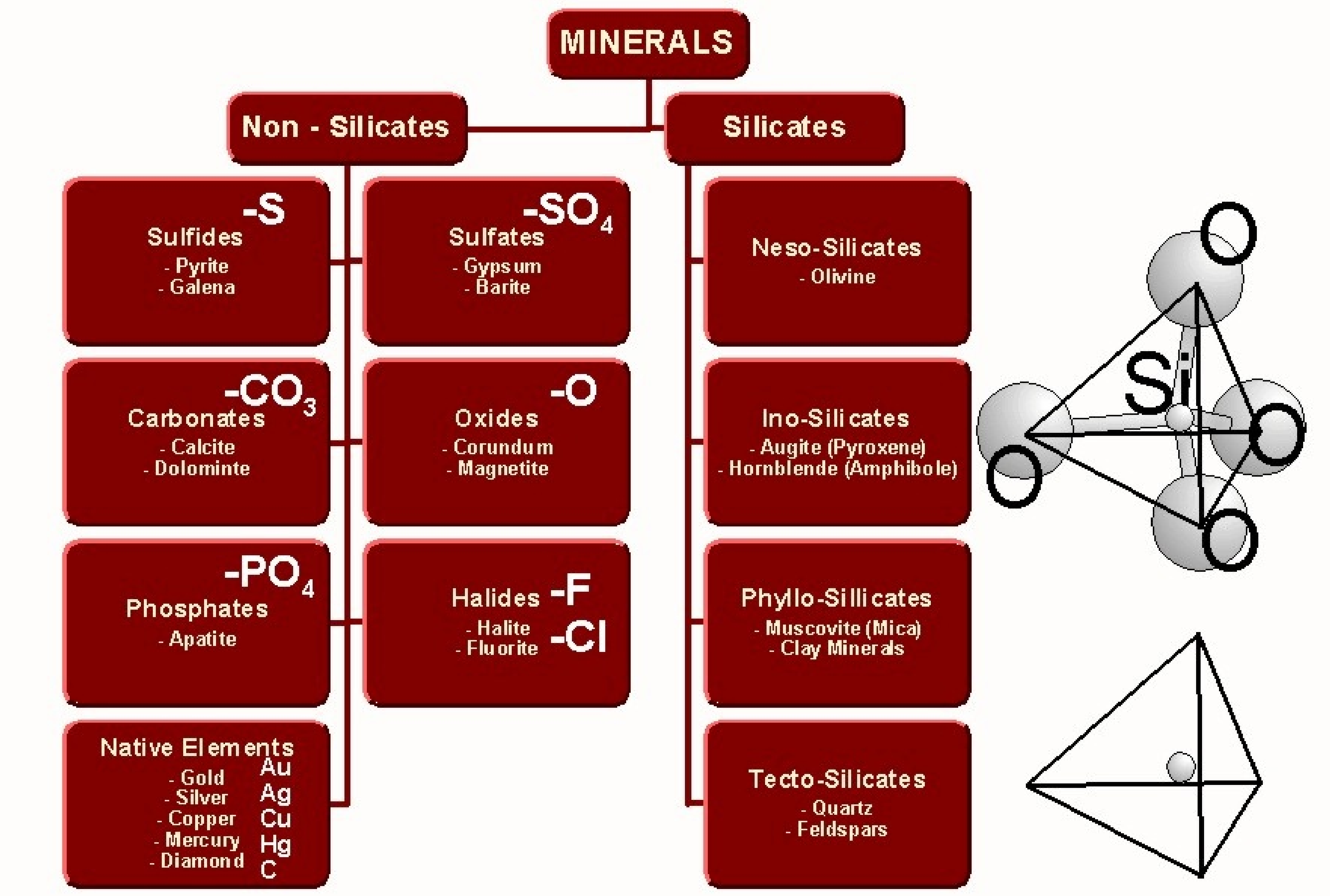


Figure 1.8 - Common mineral groups divided into silicates and nonsilicates according to chemical composition. Line with elemental symbol denotes major anion in group.

Non-silicate mineral groups consist predominantly of carbonates (containing CO_3 carbonate ion), sulfates (containing SO_4 sulfate ion), oxides (containing oxygen but NO silicon!), sulfides (containing sulfur), phosphates (containing PO_4 phosphate ion), halides (containing either fluorine, chlorine, iodine, or bromine ion), and the native elements as pure substances as listed above.

1.4 SILICATE MINERAL GROUP

In the silicates, the most abundant of all mineral types, silicon lies between four oxygen atoms. This structural block is universal in the silicates and is called the silica tetrahedron. The four oxygens always occur at the corners of a tetrahedron of almost constant size and regular shape (figure 1.9).

The different types of silicates result from the various ways in which the silicon-oxygen tetrahedra are linked to each other. These various linkages, or lack of, form several silicate structural types, namely *nesosilicates, sorosilicates, inosilicates, phyllosilicates*, and *tectosilicates*. These individual silicate groups and their respective minerals are discussed below.

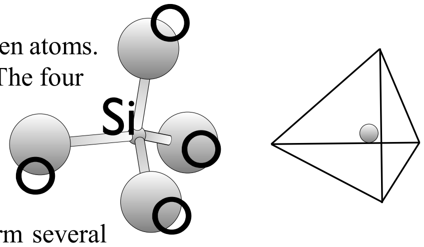


Figure 1.9- The silicate tetrahedron represented in "ball and stick" and "stylized tetrahedra format"

1.4.1 NESOSILICATES

Independent tetrahedral groups, or **nesosilicates***,* have the composition SiO_4 (Orthosilicate Ion: -4). Here the individual Si-tetrahedra do not touch each other, but are separated by other, usually metallic, ions. The mineral olivine, variety forsterite (Mg_2SiO_4), is typical of this group. Other common nesosilicates are the Al_2SiO_5 group *of* topaz, garnets, and zircon. Figure 1.10 shows individual silica tetrahedra separated by other large atoms or ions.

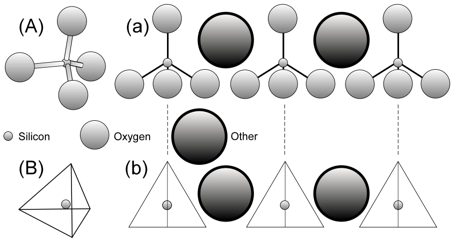


Figure 1.10 - Nesosilicates

1.4.2 SOROSILICATES

The **sorosilicates** are formed by two tetrahedra sharing a common oxygen between the ions. The composition is Si_2O_7 (Pyrosilicate Ion: -6) for this subclass. If more than two tetrahedra are linked and a closed or ring-like structure is formed, the composition will be Si_nO_{3n}. Three-linked tetrahedra include benitoite, $BaTiSi_3O_9$, and beryl with six-linked tetrahedra, $BeAl_2Si_6O_{18}$. The later is sometimes referred to as a cyclosilicate, because beryl will form a complete ring made out of Si-tetrahedra. The drawing (figure 1.11) displays two linked tetrahedra separated by large other atoms or ions.

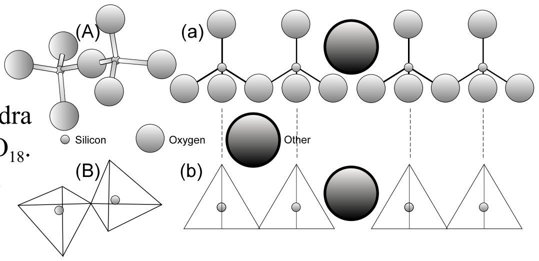


Figure 1.11 - Sorosilicates

1.4.3 INOSILICATES

You will recognize the possibility of the development of chainlike structures of two types and of indefinite extent: a) single chains, and b) double chains. These are called **inosilicates**. In the single chain each silica tetrahedron shares two oxygens with adjacent Si-tetrahedra and has an Si:O ratio = 1:3 (figure 1.12 (C)). The pyroxene mineral group with its common mineral member augite consists of such single silica chains. If alternate tetrahedra in two parallel single chains are linked, the Si:O ratio is 4:11. Here, every second tetrahedra in the chain shares three oxygens with adjoining neighbors (figure 1.12 (D)). This structure is characteristic of the well-known, and quite abundant amphibole group, such as hornblende. (Figure 1.12).

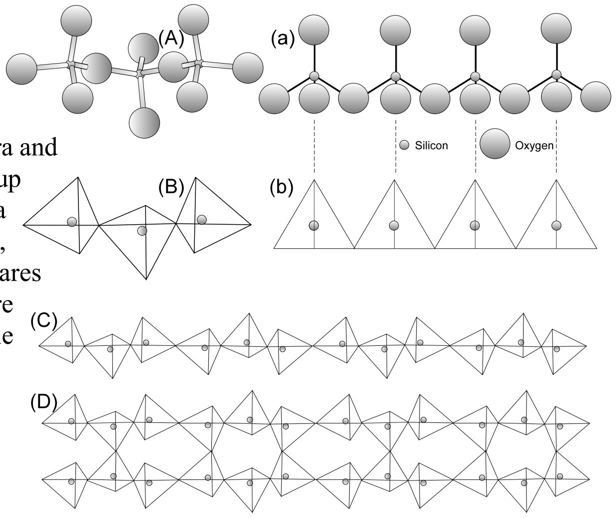


Figure 1.12 - Inosilicates

1.4.4 PHYLLOSILICATES

A sheet structure, known as the **phyllosilicates**, develops when three oxygen ions of each tetrahedron are shared with adjacent tetrahedra. This is basically the double-chain inosilicate structure extended indefinitely in two directions forming a sheet like structure. In more detail these sheets tend to have a hexagonal planar framework which results in a false hexagonal habit. Perfect basal cleavage occurs parallel to the plane of the sheet, where the sheets are interconnected by weak van der Waals bonds. Such linkage yields a ratio of Si:O of 2:5. All micas and clay structures are built on this basic unit, as well as talc. Figure 1.13 depicts the development of such a sheet from individual Si-tetrahedra.

1.4.5 TECTOSILICATES

The **tectosilicates** are a three dimensional or polymerized network with a SiO_4 tetrahedron sharing all its corners with other tetrahedra (figure 1.14). The Si:O ratio is 1 :2. Quartz and other silica forms have this structure. Because Al^{3+} may substitute for Si^{4+}, additional positive ions are required to maintain electrical neutrality. The very abundant feldspars and less abundant zeolites are examples.

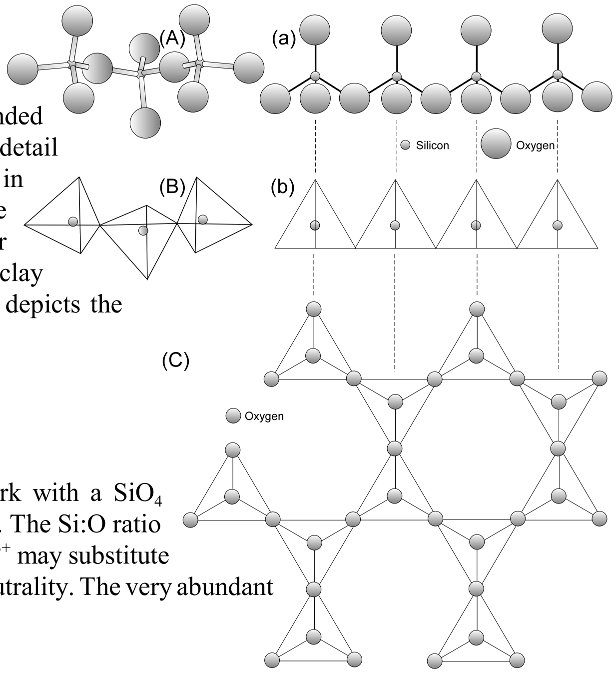


Figure 1.13 - Phyllosilicates

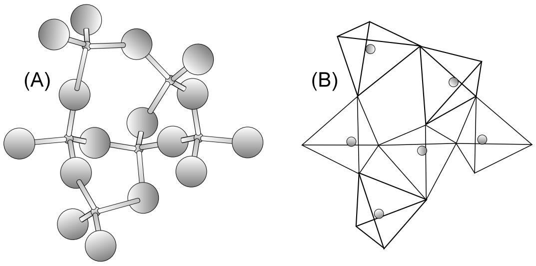


Figure 1.14 - Tectosilicate structures: quartz and Na - feldspar

1.5 BOWENS REACTION SERIES

Because of the extreme importance of the SiO_4 tetrahedral linkages or its type of polymerization during magma crystallization, a reaction series diagram may help to clarify the relationships of chemistry and geometry in the development of the very important silicate minerals from igneous melts.

Norman Levi Bowen (1887 - 1956) and his co-workers reported on productive research results on the characteristics of magmatic crystallization. They were able to show that the common minerals of igneous rocks, which are the most abundant in the mineral kingdom, can be arranged into two series:

1: a discontinuous reaction series made up of the ferromagnesian minerals, or minerals containing iron and magnesium
2: a continuous reaction series of the feldspars.

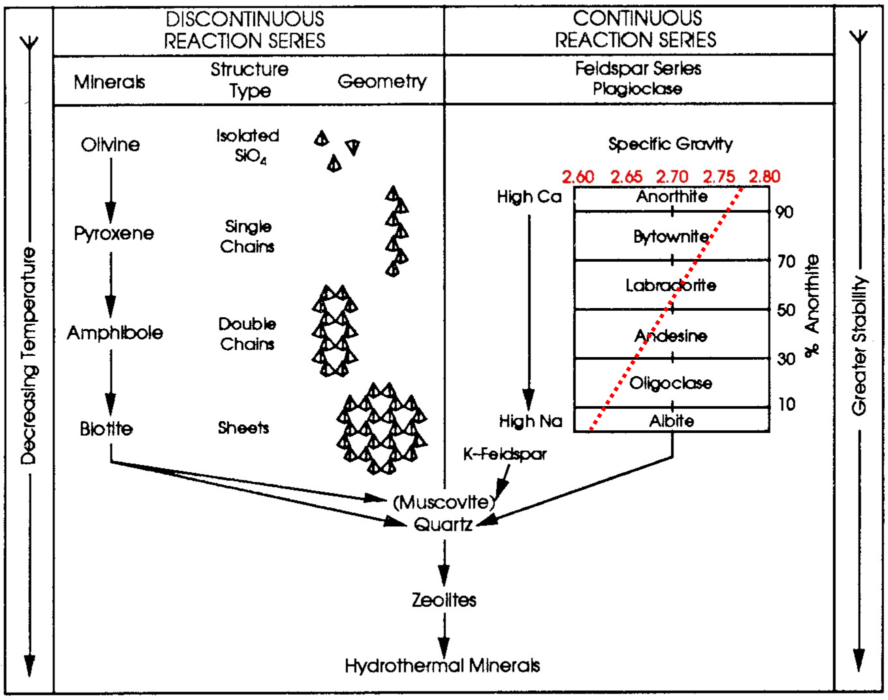


Figure 1.15 - Bowen's reaction series (modified)

Figure 1.15 illustrates this reaction series.

For the discontinuous series the crystallization begins at the highest temperature with olivine, one of the isolated SiO_4 tetrahedral groups, or nesosilicates. The temperature decreases and if still molten magma remains, the olivine completely reacts with the melt and gradually changes to pyroxene, the single chain tetrahedra of SiO_4. At the same time calcium rich feldspar continues to react with the melt and sodium becomes part of the feldspar composition. If some of the olivine and bytownite are removed from the crystallizing system, e.g., by settling of the olivine in the magma, or the floating of the less dense feldspar phenocrysts to the top of the magma chamber, then the reaction series continues to take place in the molten magma. Amphiboles and labradorite feldspar may crystallize. If complete crystallization takes place at this stage, a rock with the composition of amphibole-labradorite forms. The latter rock is an andesite or diorite depending on its cooling rate and the texture developed.

The longer the magma remains fluid, the more the reaction series proceeds. Granites, pegmatites and finally hydrothermal minerals may form, including the metallic ore minerals. Each of these is derived from the still molten mass or the residual fluids of the original magma. Pegmatites form as a result of residual high water content and other mineralized fluids in the late stage magma. These permit lower temperatures of crystallization, high mobility of the various ions or elements, and endow a greater fluidity to the end-stage magma to form rather large crystals. Sizes of several feet are common.

From olivine to quartz, all structural forms develop and may disappear. You will note the geometric progression from the isolated tetrahedra of SiO_4 first, then the single chains, double chains, sheets, and finally the three-dimensional networks or tectosilicates. This reaction series is a marvel of orderly development and geometric stability for the conditions extant at the time of the crystallization of the magma. Herein lies the secrets of not only structure of silicates minerals, but composition as well.

1.6 PHYSICAL PROPERTIES OF MINERALS

Minerals can be identified by using diagnostic physical properties. Such properties should be easy to determine and are therefore limited to the following: color, cleavage, hardness, luster, streak, specific gravity and tenacity. Tenacity includes sectility, malleability, brittleness, flexibility, and elasticity. Elasticity is a property common to all minerals but is optically visible in only a very few. A single physical property may not permit specific identification, but several such properties in combination will.

1.6.1 COLOR

Color: The color of a mineral depends upon the selective light absorption which it exerts upon the light reflected by it. If a mineral is green, for example, it reflects all the light waves except those which combined yield the sensation of green. Color is an important diagnostic property of each mineral. In studying the identification charts you will recognize that some individual minerals appear on several color charts. Such color variations may be present in the same outcrop, or in rare occasions in the same mineral specimen. Minerals with a color due to their specific composition have a predictable and constant color and are referred to as "self colored" or idiochromatic. Chemical or physical impurities can cause color varieties within the same mineral species. The influence on mineral coloration from impurities is complex. While the presence of chromium (Cr^{+3}) in corundum (Al_2O_3) produces the red gemstone ruby, the same chemical element in beryl ($Be_3Al_2Si_6O_{18}$) results in the green color of the emerald gem. The most common chemical elements responsible for color are the transition metals Co, Cr, Cu, Fe, Mn, Ni, Ti, and V. Minerals colored by such impurities are referred to as allochromatic (Other Colored).

1.6.2 CLEAVAGE & FRACTURE

Cleavage: Cleavage is the second major primary Identifier on the mineral identification charts. This physical property is the tendency of a mineral to break or cleave along crystallographic planes. Thus, cleavage is a more or less smooth surface of breaking in the mineral. The cleavage planes are reflections of possible crystal faces and, in turn, planes of the internal atomic structure of the mineral. These cleavage planes show minimum values of cohesion parallel to the cleavage surface.

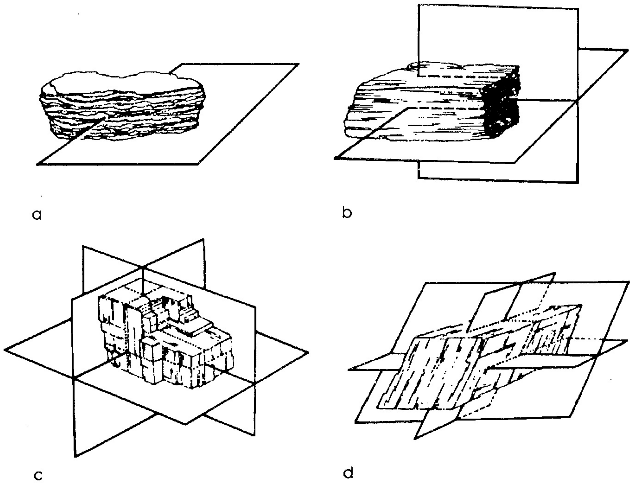


Figure 1.16 - Examples of mineral cleavage: a) one-direction. b) two direction. c) 3- direction at right angles. d) 3-direction not at right angles.

Cleavage is readily recognized by the mirror-like reflection of light from the mineral surface when it ss rotated in strong light. Keep in mind that cleavage is a broken surface of planar form in contrast to a primary crystal face. The mineral identification charts consider only the presence of distinct or indistinct cleavage in the mineral. Remember that several cleavage types are possible in various minerals. Some show one-direction cleavage, others two-direction at right angles, two directions not at right angles, and even three direction cubic, three direction rhombohedral, and others. Examples of some of the more common cleavages are shown in figure 1.16.

Each individual mineral description includes a comment on the character of, or lack of cleavage, for that specific mineral and the kind of cleavage to expect. For your practical use, however, the presence or absence of cleavage is generally sufficient for most mineral identifications.

1.6.3 LUSTER

Luster: In the identification tables METALLIC and NONMETALLIC properties of the mineral are used as a major identifier. The metallic luster is a reflectance characteristic of metals such as copper, iron, tin, and others. The nonmetallic luster includes several varieties such as adamantine, or that of the highly refractive index such as for diamond; vitreous luster, or that of broken glass or of the freshly fractured surface of the mineral quartz; resinous, greasy luster, like that of oiled glass; pearly luster and silky luster, or a reflectance similar to that of silk. The latter is generally related to a very fibrous mineral.

The explanation for the identification chart shows which minerals have metallic or nonmetallic luster. The length of this line or bar is also an indication of the hardness range of each mineral.

1.6.4 HARDNESS

Hardness: The resistance a mineral offers to scratching, or it's hardness, can be determined by scratching It with a material of known hardness, or a mineral of known hardness. For example, a mineral of known hardness will scratch one of lesser hardness. In making the hardness test remember that a scratch cannot be rubbed off. The powder formed in the hardness test may resemble a scratch, but if it can be rubbed away, and no scratch impression remains, the mineral has not been scratched. Simply check with your fingernail if a grove or scratch has occurred. If no scratch can be determined, the material used for the hardness test is softer than the tested or unknown material.

The hardness scale based on the relative hardness of certain minerals is known as the Mohs Scale of Hardness (Friedrich Mohs, 1773 -1839). It is the present standard for classifying the hardness of various minerals. While the scale is not quantitative in the absolute sense, it is most useful in identifying this special physical property of individual minerals. Ten minerals with different and progressively increasing hardness make up the scale. These include in order of increasing hardness: 1. Talc, 2. Gypsum, 3. Calcite, 4. Fluorite, 5. Apatite, 6. Feldspar, 7. Quartz, 8. Topaz, 9. Corundum, 10. Diamond. As a supplement to the Mohs Scale of Hardness, the fingernail has a hardness of 2.5, a copper penny 3.0, and glass or a pocket knife blade about 5.5. A good steel file is 7.0 on the scale. (See figure 1.17) Streak Plates have a Mohs hardness of approximately 6.5 to 7.5 depending on the ceramic material.

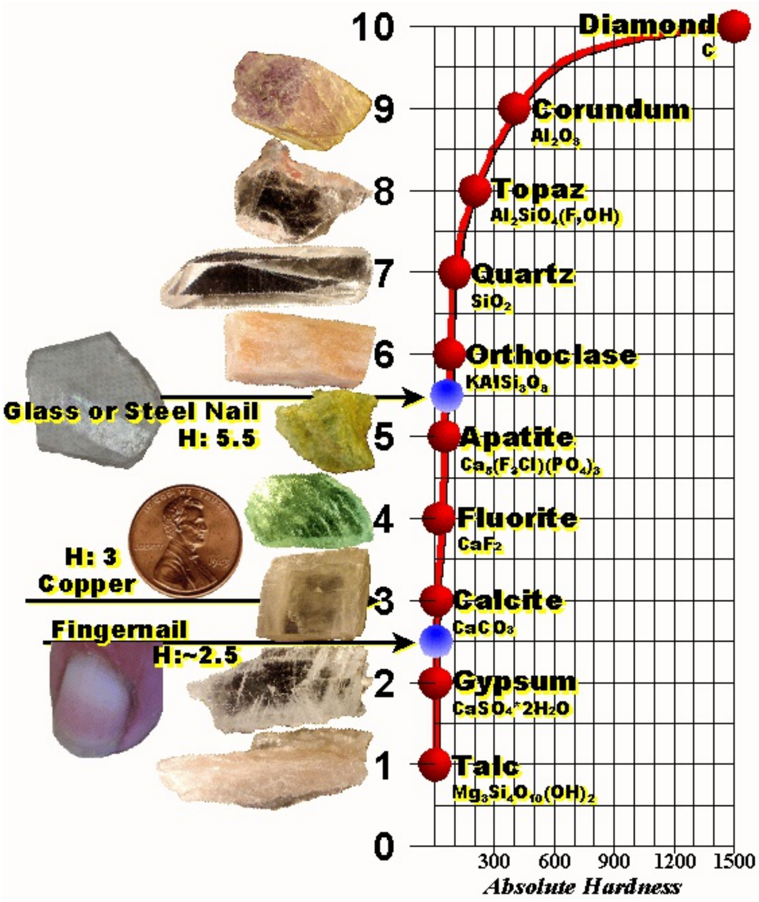


Figure 1.17a - Mohs Hardness Scale

The description of the individual minerals always includes the Mohs hardness number. Some minerals show different hardness numbers for the various cleavage faces. These variations relate to the internal atomic arrangement within the mineral. An example is kyanite. It has a hardness of 5 parallel to its length and 7 across the width of the crystal. Calcite is another example. It has a hardness of 3 on all surfaces except the base. The latter can be scratched by a fingernail of 2.5 hardness.

While a popular tool, the Mohs Hardness scale is more of an ordinal system than a referenced numerical scale. Modern technologies allow for measurement of Absolute Hardness with a Diamond hardness of 1500. Figure 1.17a shows Mohs hardness compared to absolute hardness, where Topaz is actually twice as hard as Quartz, Corundum twice as hard as Topaz, and Diamond is 3.5 times as hard as Corundum.

Figure 1.17b shows a hardness testing flow chart using the hardness tools included with the Professional Rock/Mineral ID kit.

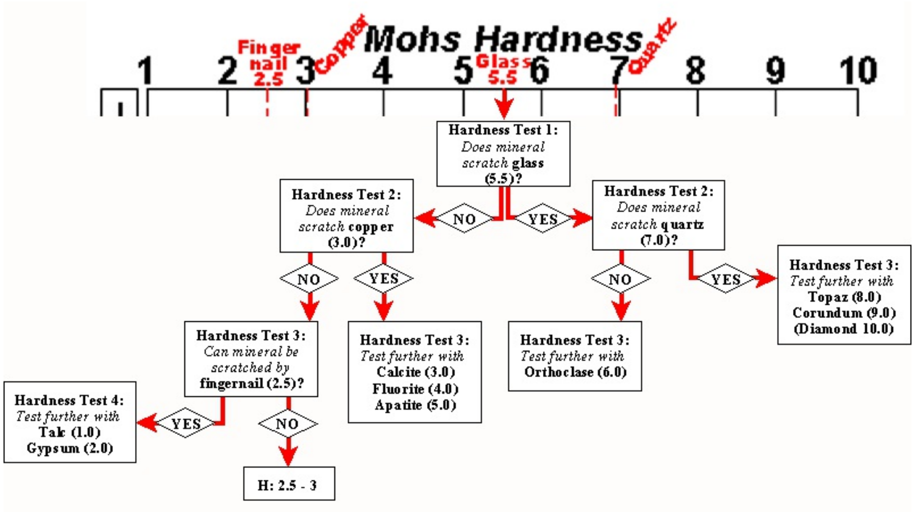


Figure 1.17b - Hardness Testing Flow Chart

1.6.5 SPECIFIC GRAVITY

Specific Gravity (S.G.): Specific Gravity(SG) or density is defined as the ratio of the mass (m) of an object compared to its volume (V). Mathematically this can be expressed as:

$$SG(\frac{g}{cm^3}) = \frac{m(g)}{V(cm^3)}$$

Mass (m) is measured in grams (g) and Volume (V) is measured in cubic centimeters (cm^3). Thus Specific Gravity becomes a ratio between the mass and volume of an object and the value is usually expressed in g/cm^3. This ratio of mass to volume of a specific material or compound never changes and is constant for that specific material, irregardless of the size of an object. Specific Gravity or Density can therefore be used as an excellent data point to determine and identify unknown materials, including metals and minerals.

Unfortunately, Specific Gravity determination as an added tool for mineral or rock identification in fieldwork has always been relegated to approximation by simply hefting a sample and identifying the density as either high, intermediate or low. The majority of geology texts use exactly this approach. If accurate densities are required, laboratory analysis is inevitable. Many introductory geoscience courses may point to the water displacement method in a graduate cylinder to determine the volume of a mineral sample in order to calculate mineral density. This method is highly inaccurate and hardly worth mentioning as a practical solution in a laboratory course where a certain amount of precision is anticipated. To date, simple and practical field portable devices to rapidly establish mineral or rock densities are virtually non-existent. The very few systems on the market are often cumbersome to use, are plagued with inherent inaccuracies, are expensive, and/or take time.

However, recently a rapid, simple and very practical system for specific gravity determination was developed (see *Kackstaetter, U.R., 2014, A Rapid, Inexpensive and Portable Field and Laboratory Method to Accurately Determine the Specific Gravity of Rocks and Minerals: The Professional Geologist Vol. 51:2, p.56 - 60*) and is called the SINGLE PAN HYDROSTATIC METHOD. This new, patent pending density measurement system is field-portable, highly accurate, amazingly precise and very rapid. Most results can be obtained in under 2 minutes, even by novice geologists. This is the first introductory geology text to present this method.

The development of the accurate portable SINGLE PAN HYDROSTATIC METHOD using a simple electronic single pan balance makes it easy to do rapid in-situ field density analysis of mineral samples. Such, the scale can not only be used to measure weight, but also the volume of a rock or mineral sample. While measurement of weight or mass on a balance is simple and straight forward, deriving the volume of an irregular shaped object with the same balance in only ONE simple direct measurement can be somewhat confusing. In order to understand how volume can be measured so simply (one measurement without calculation), we need to take a quick look at Archimedes' Principle and Newton's 3rd Law of Motion.

Archimedes' Principle: Have you every wondered why an object gets lighter when submersed in water? This was also a question that puzzled Archimedes (Archimedes of Syracuse; ~287 BC – ~212 BC). As he sat in a bathtub, he noted that the water level would rise by the displacement of water through his partially submersed body. Archimedes correctly correlated that the amount of water displaced equaled the volume of his submersed body, and that the force that made his body lighter, called the buoyant force, was proportional to the amount of displaced water. As indicated in figure 1.18, the volume of an immersed object in water is exactly equal to the volume amount of water displaced by the object which is directly proportional to the buoyant force experienced by the submersed object, something like:

$$V_{object} = V_{H2O_{displaced}} \propto F_{bouyancy}$$

If the exerted buoyant force on the object could be measured directly, the volume of the object can be easily ascertained without additional calculations. A look at Newton's 3rd Law of Motion will help to accomplis this task.

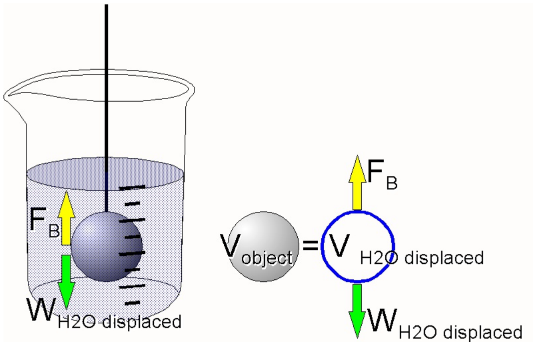


Figure 1.18 - The volume of a submersed object equals the volume of the amount of water displaced by the object. The weight of the displaced water is equal to the buoyant force acting on the object ($W_{H2O\ displaced} = F_B$). Because the buoyant force is omnidirectional, it also pushes downward and can be measured directly on the scale.

Newton's 3rd Law of Motion: This law of Newton basically states that if I exert any force on an object, and this object is not moving, than the object must push back against my force with an equal but opposite force (see figure 1.18). Any unbalanced forces that are not exactly the same and opposite will cause movement, or as Newton puts it "acceleration" in the direction of the weaker opposing force. For our problem, let us tie an object on a string and completely submerse it in water without touching the water container as shown in figure 1.18. It will displace the water in the amount of its volume, and the weight of the displaced water is equal to the buoyant force (F_B). All one has to do is to measure the "weight of the displaced water" and the volume of the object is found. Since F_B is omnidirectional, it will "push" downward as well, and if the water container is placed on a scale, this force or weight of displaced water is added to the weight of the container and the water and will register on the scale.

In short, specific gravity (SG) could be specified by determining the weight of the mineral in air (W_{air}), then obtaining the weight when the mineral is submerged in water (W_{water}). The difference between the two weights (W_{air} - W_{water}) is, of course, the weight of the volume of water equal to that displaced by the solid, which in turn is equal to the volume of the solid. Relating weight to volume when using water is easy since the density of water (SG_{H2O}) is considered to be 1.0 g/cm^3 for practical purposes. This means that 1g H_2O equals 1mL H_2O which in turn equals 1cm^3 H_2O.

Determining Specific Gravity with the SINGLE PAN HYDROSTATIC METHOD

By far the simplest, rapid, accurate practical approach in determining Specific Gravity of mineral and rock samples is the SINGLE PAN HYDROSTATIC METHOD. Only two measurements are needed and a simple mathematical division calculation will give you the answer.

Materials needed: Electronic Single Pan Scale, a small cup, string, water and your unknown sample. Calculator or nomograph for computing specific gravity.

Procedure:

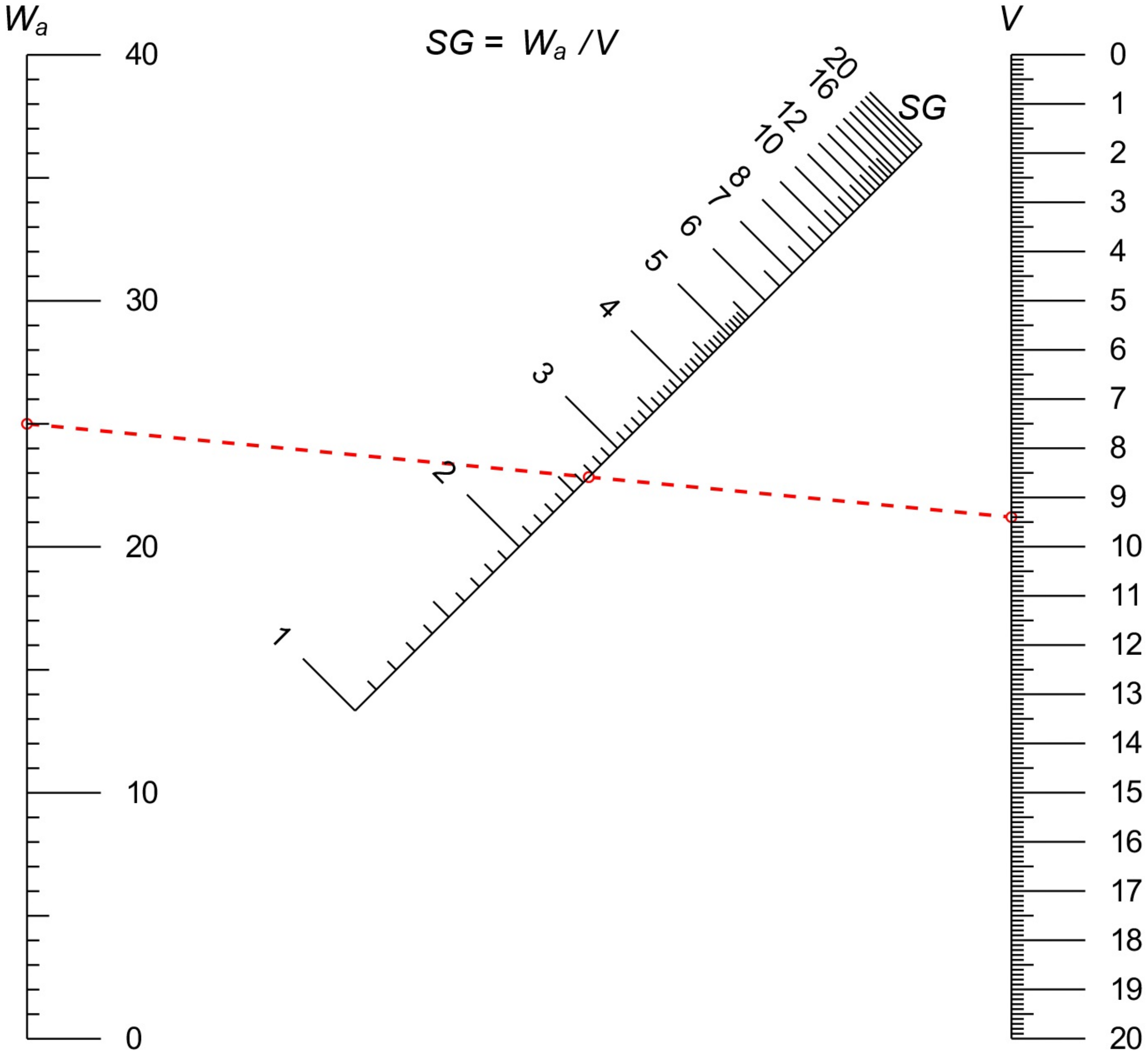
1. Turn on scale and calibrate according to manufacturers instruction
2. Weigh your unknown mineral sample in grams and record answer (m). Note: The larger the sample the smaller the error.
3. Using a slip knot, tie a string or thread on the sample.
4. Fill a small cup with enough water to completely submerse the sample. Place the cup on the scale and use the scale's tare function to reset the readout to zero (0).
5. While holding the string steady, submerse the sample completely into the plastic cup as indicated in figure 1.19. Neither the object nor string should touch the vessel while measuring and the sample must be completely immersed with NO air bubbles. The readout on the scale will be the weight of the displaced water or the volume of your sample (V). Record this number as cm^3 volume.

Using the specific gravity equation on the previous page, specific gravity or density can now be calculated by simply dividing the recorded volume (V) into the weight or mass (m) of your sample. If no calculator is available the pictured nomograph on the subsequent page can be used to rapidly compute the specific gravity of the sample, eliminating the necessity for electronic calculation devices.

Roughly Estimating Specific Gravity: The specific gravity of certain select minerals can be felt by hefting, indicating a fairly high mineral density. The mineral Barite feels somewhat heavy for its size. More obvious is the mineral Galena, a lead mineral with a very high specific gravity. Extremely high specific gravities, such as Gold or Platinum leave an indelible impression. However, this type of estimating densities by hefting a specimen usually works best when the sample is about the size of a grape or larger.

Specific gravity of very small samples: For very small samples or soils a special vessel called a pycnometer is used. A pycnometer is a calibrated device that measures volumes of air, water or other liquids or gases displaced by the sample. This method, however, is more appropriately discussed in advanced geoscience courses and not in introductory texts.

Figure 1.19 - Rapid measurement of sample volume by freely suspending and submersing specimen in a water-filled and tared plastic container. Balance readout is equivalent to volume of object in cm^3.



Using the above nomograph for specimen density calculations[1]

Plot the weight of a specimen (W) on the left vertical scale (W_a) of the nomograph, example shown 25.00 g. Mark the volume of specimen (V) obtained through buoyancy (specimen in water) measurements on the right vertical scale of the nomograph, example shown here 9.40 g. Connect both data plots with a straight line. The intersection of this line with the diagonal SG scale in the center gives the specific gravity, here 2.65 g/cm^3.

Note: When using this nomograph, heavier/larger specimens give better results.

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[1] Nomograph was generated using Python programming language scripting in conjunction with PyNomo Version 1.1 Release 0.2.2 software (Doerfler 2009)

1.6.6 STREAK

STREAK: Streak is the color of the mineral powder and can be an important diagnostic feature, especially for minerals with a metallic luster. This includes important ore minerals. The color of the powdered mineral is very much consistent, no matter what the color variation of the same mineral species in handsample might be. While it doesn't matter how the mineral is powered, most commonly a small tile of unglazed porcelain called a streak plate is employed for the test. Using such a streak plate is also least destructive to the mineral specimen. The mineral to be tested is rubbed against such an unglazed porcelain surface leaving small amounts of the mineral powder as a visible streak. Note that soft minerals tend to powder much more readily than harder minerals.

Determinative Table A includes the characteristic streak of many minerals as well as the hardness of the mineral. Colors of streak range from black to white and hardness refers to Mohs Scale. The colors of streak and hardness of a large number of minerals are included in the streak table. For best use of Determinative Table A, first identify the streak color, then check for hardness. Using color of the streak where it intersects the hardness column should give the mineral or minerals having these characteristics. Additional reference to the mineral descriptions may permit a specific identification by these two simple tests.

1.6.7 MAGNETIC RESPONSE

MAGNETIC RESPONSE: A strong hand magnet is very useful in identifying the four or five minerals which show sufficient magnetic response to be readily recognized. Suspending a small magnet on a thread or string and bringing the mineral close to it is the common magnetic test. The most magnetic mineral is magnetite (Fe_3O_4). Lodestone, the very magnetic variety of magnetite, was once used as a crude compass in ancient times. It is recognized in the field by the broken grains which line up parallel to the magnetic field of the mineral when struck by a hammer. Small particles of specular hematite (Fe_2O_3), are commonly affected by a strong magnet.

1.6.8 TASTE

TASTE: The sensation of taste can be determined only for those minerals which are easily soluble. Halite yields a salty taste, trona the taste of soda, epsomite a bitter taste, chalcanthite the taste of sulphuric acid and is nauseating. A cooling taste comes from niter and an astringent taste for alum. Glauberite has a bitter, salty taste, borates are salty, and borax-kernite has a sweet alkaline taste.

1.6.9 ODOR

ODOR: Except in rare cases minerals do not give off odors, yet if moistened with the breath, or in other cases rubbed or struck, some volatiles may escape and be detected by their odor. Some calcites, for example, when rubbed, and also some quartz, yield a very fetid odor, like rotten eggs. This may represent release of hydrogen sulfide which was originally trapped in small vacuoles in the minerals when they formed.

Kaolinite and other clay minerals give off an earthy odor when moistened with breath. If arsenopyrite is rubbed vigorously by a harder object, a garlic odor is produced. Likewise pyrite and other sulfides give off a sulphurous odor when rubbed vigorously by a hard object. Heat will produce sulphurous fumes from sulfides, horseradish odor from selenium-bearing ores, and garlic odor from arsenic containing compounds.

LAB EXERCISE 2 - MINERAL IDENTIFICATION

Name:	Course ID:

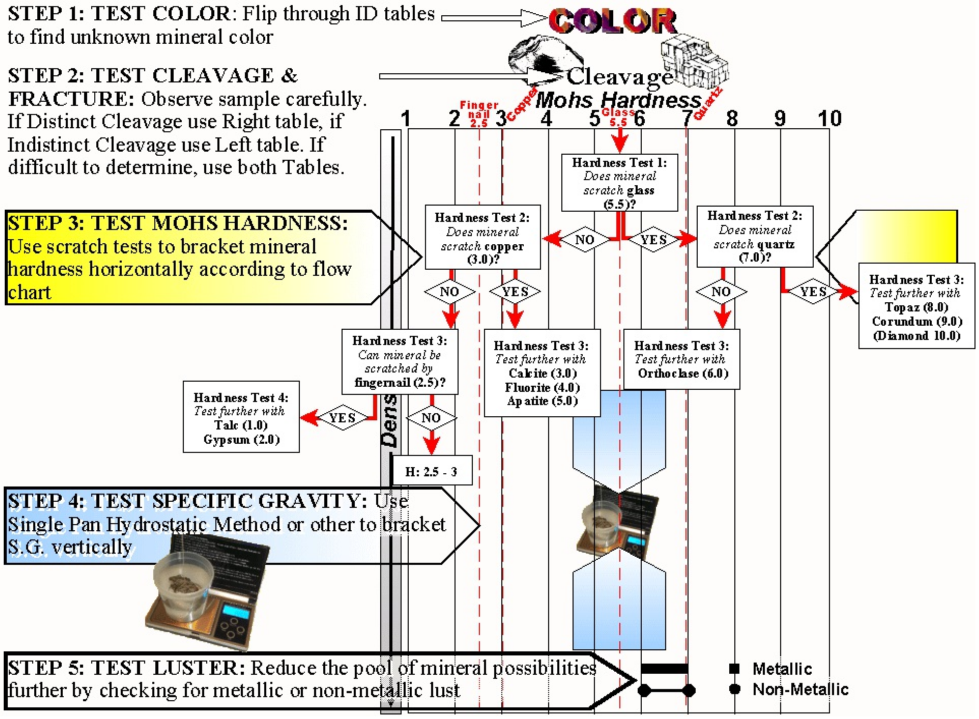
During this lab you are required to positively identify by name ALL minerals given to you in the attached determinative table. You will complete the provided blank Mineral ID Exercise Table in conjunction with your testing.

Materials needed:

- Professional Rock / Mineral Identification Kit *(See above for ordering information)*
- Set of Minerals included in the kit above (Mineral set as well as Mohs Hardness Minerals)
- MINERAL IDENTIFICATION TABLES
- other helpful determinative Mineral ID tables and mineral descriptions

Procedure:

1. Pick an unknown mineral sample (write down sample number or letter). Follow the outline given in the MINERAL IDENTIFICATION CHARTS. Write down the results in the blank Mineral ID Exercise Table as you go.
2. Use two colors to complete the table. Mark in blue all the values you have obtained by your own measurements or observations. Write in black everything you have researched, copied or otherwise obtained by looking it up.
3. MINERAL IDENTIFICATION: Use the Professional Rock/Mineral ID kit and the provided TABLES FOR THE DETERMINATION OF NON-METALLIC AND METALLIC MINERALS and follow the steps for mineral identification as outline to the right. Be sure to record your findings as you go in the Lab Answer Tables, such as *"color,"* *"cleavage,"* *"hardness,"* as well as *"streak,"* *"magnet,"* *"acid,"* and *"other"* using ONLY OWN OBSERVATIONS / MEASUREMENTS. Under *"other"* mark also the type of test or observational tool used to derive your answer, such as *taste,* or *smell* tests.



STEP 1: TEST COLOR: Flip through ID tables to find unknown mineral color

STEP 2: TEST CLEAVAGE & FRACTURE: Observe sample carefully. If Distinct Cleavage use Right table, if Indistinct Cleavage use Left table. If difficult to determine, use both Tables.

STEP 3: TEST MOHS HARDNESS: Use scratch tests to bracket mineral hardness horizontally according to flow chart

STEP 4: TEST SPECIFIC GRAVITY: Use Single Pan Hydrostatic Method or other to bracket S.G. vertically

STEP 5: TEST LUSTER: Reduce the pool of mineral possibilities further by checking for metallic or non-metallic lust

4. For the field *"MINERAL NAME"* write down your own identification first in blue. Mark also the correct identification from the key below your answer in "black."
5. The answers for all remaining fields should be meticulously researched. For *"formula"* look up the chemical formula of the mineral. *"Group"* should indicate the chemical group such as sulfate or phyllosilicate. *"Crystal sys"* should answer the crystal system as accurately as possible.

MINERAL ID EXERCISE TABLES **Name:**________________________________

*Complete using 2 colors. Mark your own measurements in **blue**. Mark researched or copied values in **black!***

	PASTE MINERAL SAMPLE from KIT HERE! *(Clear scotch tape)*							
	Luster:	☐ metallic ☐ Nonmetallic	☐ metallic ☐ Nonmetallic	☐ metallic ☐ Nonmetallic	☐ metallic ☐ Nonmetallic	☐ metallic ☐ Nonmetallic	☐ metallic ☐ Nonmetallic	☐ metallic ☐ Nonmetallic
	Hardness:							
	Color:							
	Other observations:							
Test	Cleavage:	☐ distinct ☐ indistinct	☐ distinct ☐ indistinct	☐ distinct ☐ indistinct	☐ distinct ☐ indistinct	☐ distinct ☐ indistinct	☐ distinct ☐ indistinct	☐ distinct ☐ indistinct
	Density: *Measure (see reverse side)*							
	Streak:							
	Acid:							
	Magnet:							
	Other:							
	MINERAL NAME:							
Research	Chemical Formula:							
	Mineral Group:							
	Crystal System:							

Make additional copies of this page if needed. Show all calculations on the next page:

*There is a tendency to just copy information from any source, This is completely acceptable for the area labeled RESEARCH. It is **NOT acceptable** for the fields indicated under TEST. You MUST actually perform tests and show YOUR results, not just copied references.*

MINERAL ID EXERCISE TABLES **Name:**______________________________________

DENSITY CALCULATIONS

	Sample:							
Density Test	Density calc.: *(see Lab 2b)*							
MINERAL NAME:								

Make additional copies of this page if needed.

*There is a tendency to just copy information from any source, This is completely acceptable for the area labeled RESEARCH. It is **NOT acceptable** for the fields indicated under TEST. You MUST actually perform tests and show YOUR results, not just copied references.*

MINERAL ID EXERCISE TABLES (cont'd) **Name:**______________________________________

*Complete using 2 colors. Mark your own measurements in **blue**. Mark researched or copied values in **black!***

	PASTE MINERAL SAMPLE from KIT HERE! *(Clear scotch tape)*							
	Luster:	☐ metallic ☐ Nonmetallic	☐ metallic ☐ Nonmetallic	☐ metallic ☐ Nonmetallic	☐ metallic ☐ Nonmetallic	☐ metallic ☐ Nonmetallic	☐ metallic ☐ Nonmetallic	☐ metallic ☐ Nonmetallic
	Hardness:							
	Color:							
	Other observations:							
Test	Cleavage:	☐ distinct ☐ indistinct	☐ distinct ☐ indistinct	☐ distinct ☐ indistinct	☐ distinct ☐ indistinct	☐ distinct ☐ indistinct	☐ distinct ☐ indistinct	☐ distinct ☐ indistinct
	Density: *Measure (see reverse side)*							
	Streak:							
	Acid:							
	Magnet:							
	Other:							
	MINERAL NAME:							
Research	Chemical Formula:							
	Mineral Group:							
	Crystal System:							

Make additional copies of this page if needed. Show all calculations on the next page:

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MINERAL ID EXERCISE TABLES (cont'd) **Name:**____

DENSITY CALCULATIONS

	Sample:							
Density Test	Density calc.: *(see Lab 2b)*							
	MINERAL NAME:							

Make additional copies of this page if needed.

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LAB EXERCISE 2b - DENSITY

Name:	Course ID:

This lab addendum is designed to give you practice and confidence using the SINGLE PAN HYDROSTATIC METHOD. Using a mineral of known density and trying to match the result will help you build skills of proper use with the system.

Materials needed:

- Minerals or materials of known density
- Single Pan Digital Scale
- Water
- Small cup and some thread or string
- Calculator or nomograph
- Other helpful determinative Mineral ID tables and mineral descriptions

Procedure:

1. Set the scale on a hard level surface. Turn it on and set readout to grams (g). Calibrate the scale according to manufacturers instruction.
2. Use a homogenous, dry mineral specimen and weigh in grams on balance. Record measurement as "m" (mass). Note: A minimum weight / size of >2 grams is recommended.
3. Tie your unknown mineral sample to the string with the slip knot. Fill a small cup with enough water to completely submerge the sample. Place the water filled cup on the scale and tare readout to zero (0).
4. Lower your tied-on mineral into the water. Neither the object nor string should touch the vessel while measuring and your mineral must be completely submerged. Make sure no major air bubbles are trapped on the sample or the string. Otherwise retrieve and submerse in rapid succession to dislodge air bubbles. Hold mineral on string steady and record the readout on the scale as "V" (volume).
5. Use the equation and a calculator or the associated nomograph in this text to compute specific gravity (SG).

Specimen Name	Measurements & Calculations	S.G.	% error
Quartz (SiO_2) S.G. = 2.65 g/cm^3	$SG(\frac{g}{cm^3}) = \frac{m\underline{\hspace{2cm}}g}{V\underline{\hspace{2cm}}cm^3}$	$\frac{\quad g}{cm^3}$	
Galena (PbS) S.G. ~ 7.40 g/cm^3	$SG(\frac{g}{cm^3}) = \frac{m\underline{\hspace{2cm}}g}{V\underline{\hspace{2cm}}cm^3}$	$\frac{\quad g}{cm^3}$	

What is the percent error of your measurement? You should be below ±5%. Use your measurement for quartz according to:

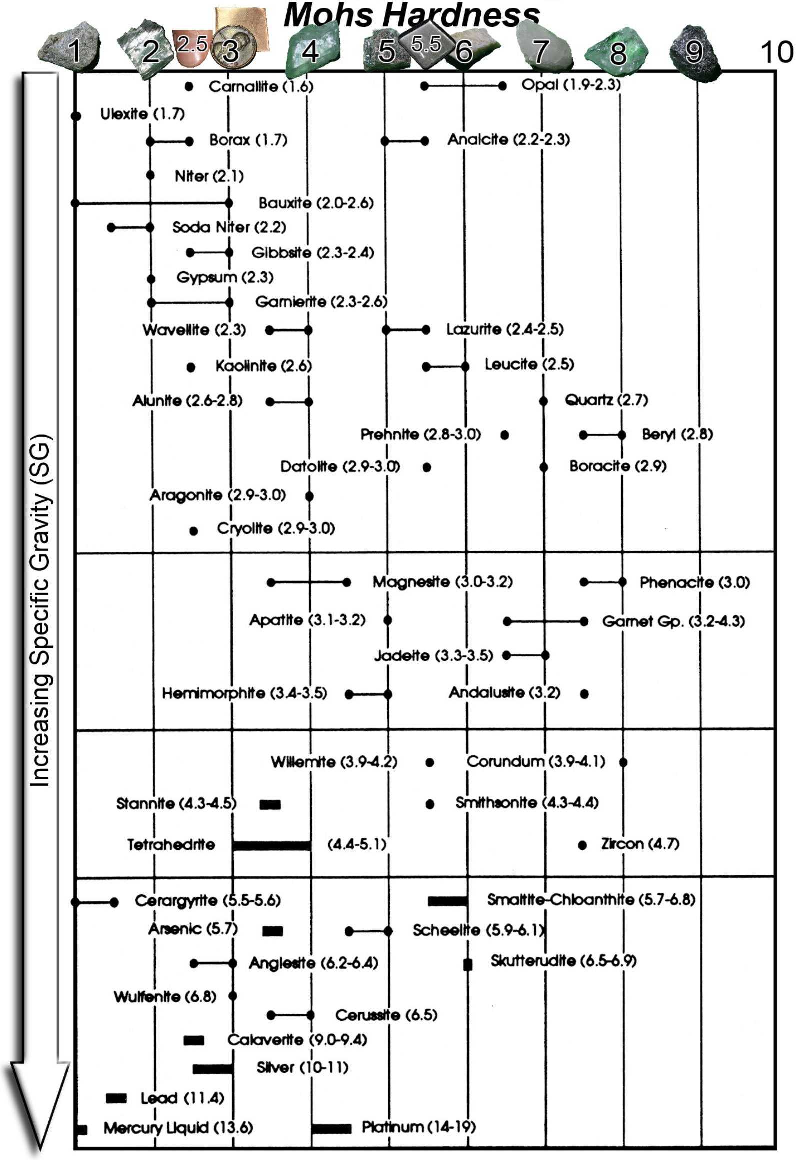
$$\%error_{quartz} = 100\% - (\frac{S.G._{yourmeasurement}}{2.65g/cm^3} x100)$$

If your error is greater than ±5%, you MUST REPEAT the part of the experiment that introduced your error until your error margin is acceptable.

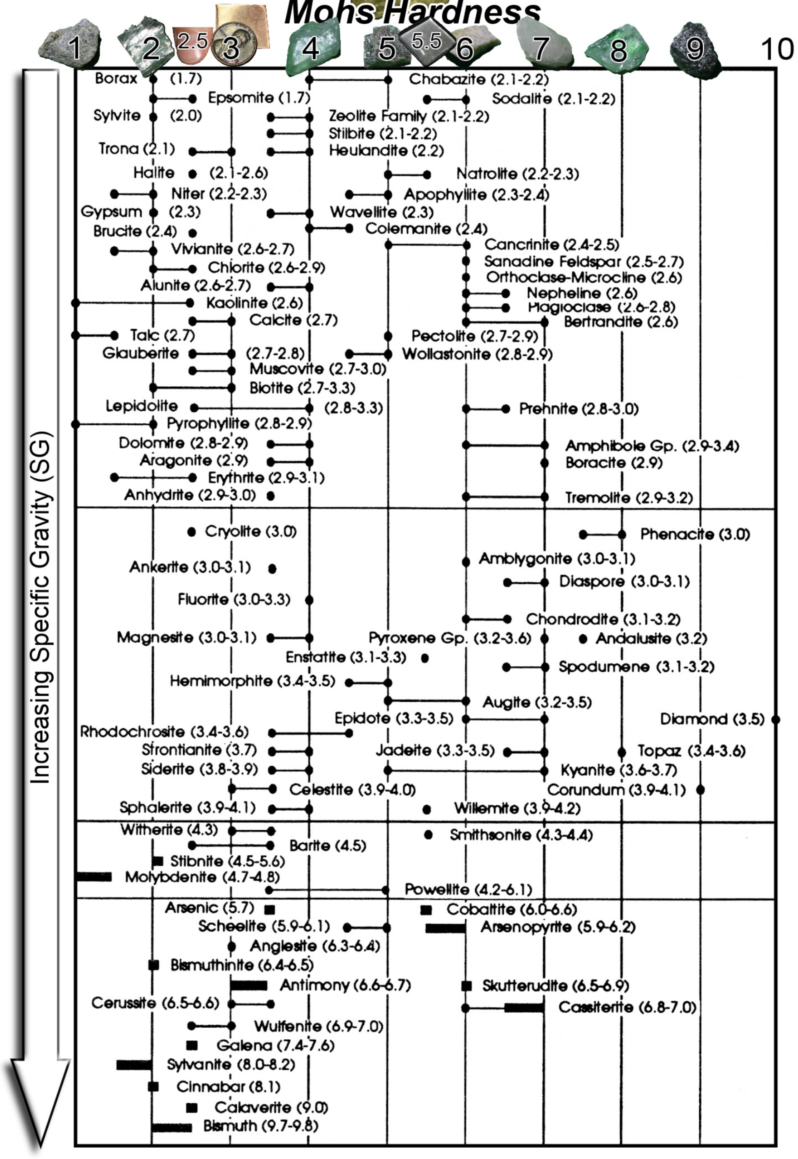
(Intentionally left blank for printing)

White, Light Gray, Colorless, Silvery

Indistinct Cleavage



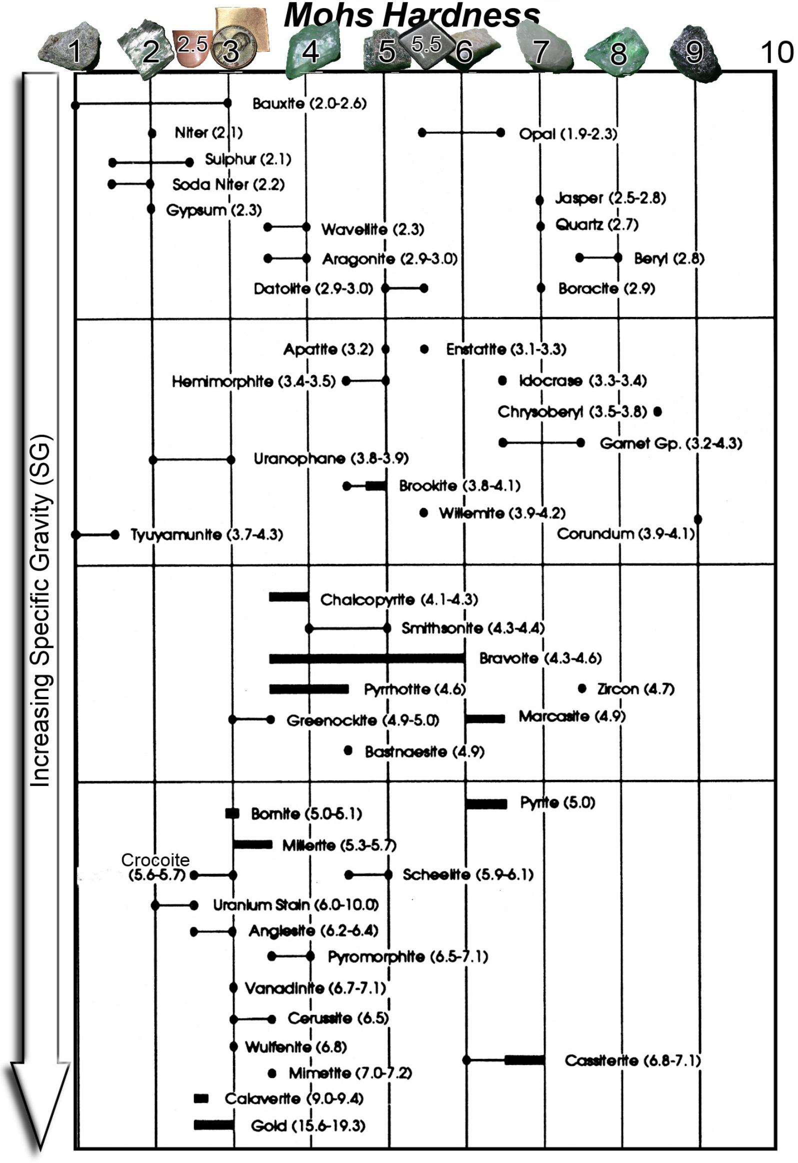
Distinct Cleavage



Yellow, Orange, Cream, Gold, Brass, Bronze

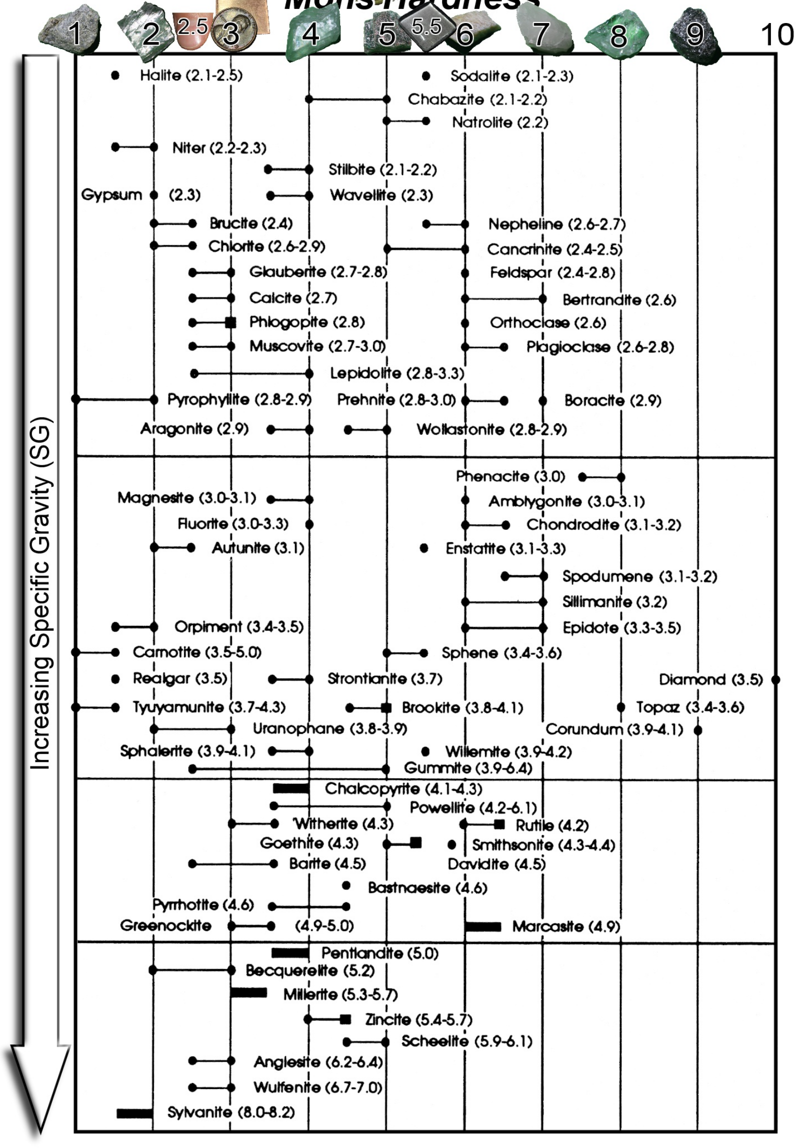
Indistinct Cleavage

Mohs Hardness



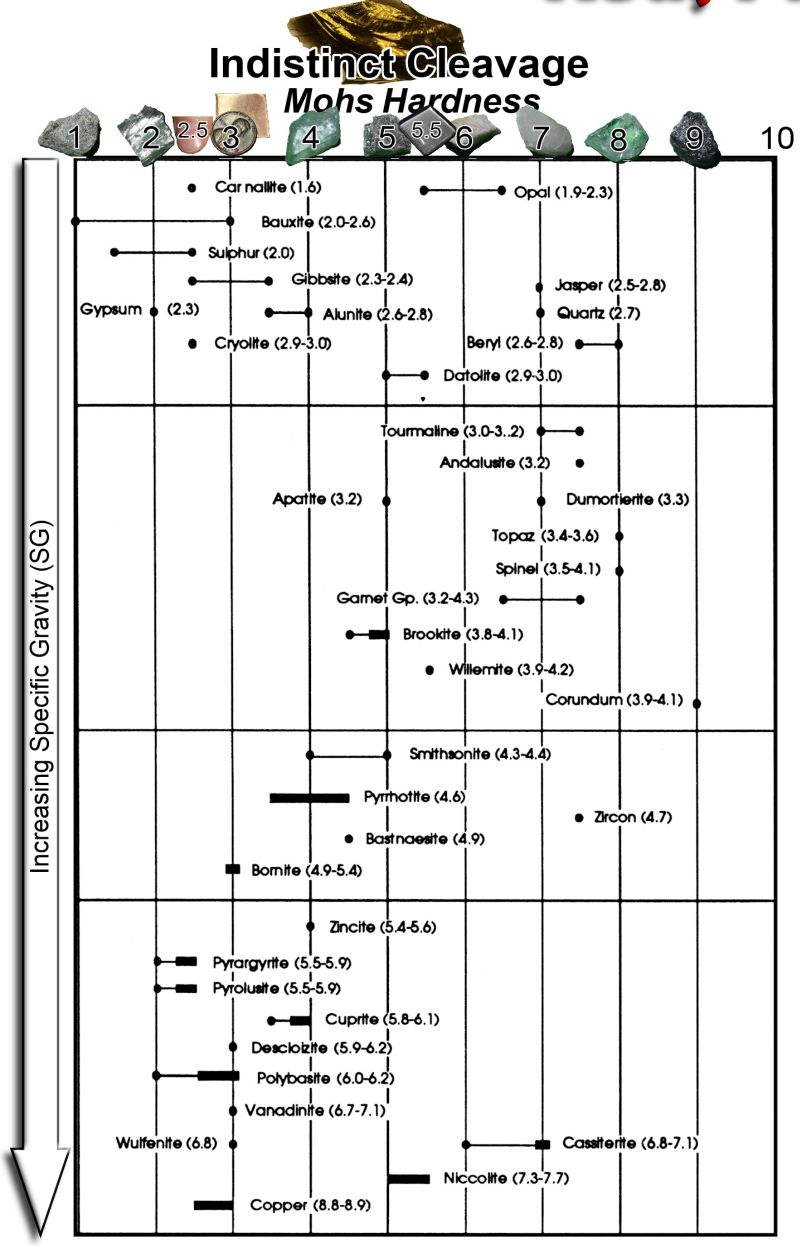
Distinct Cleavage

Mohs Hardness

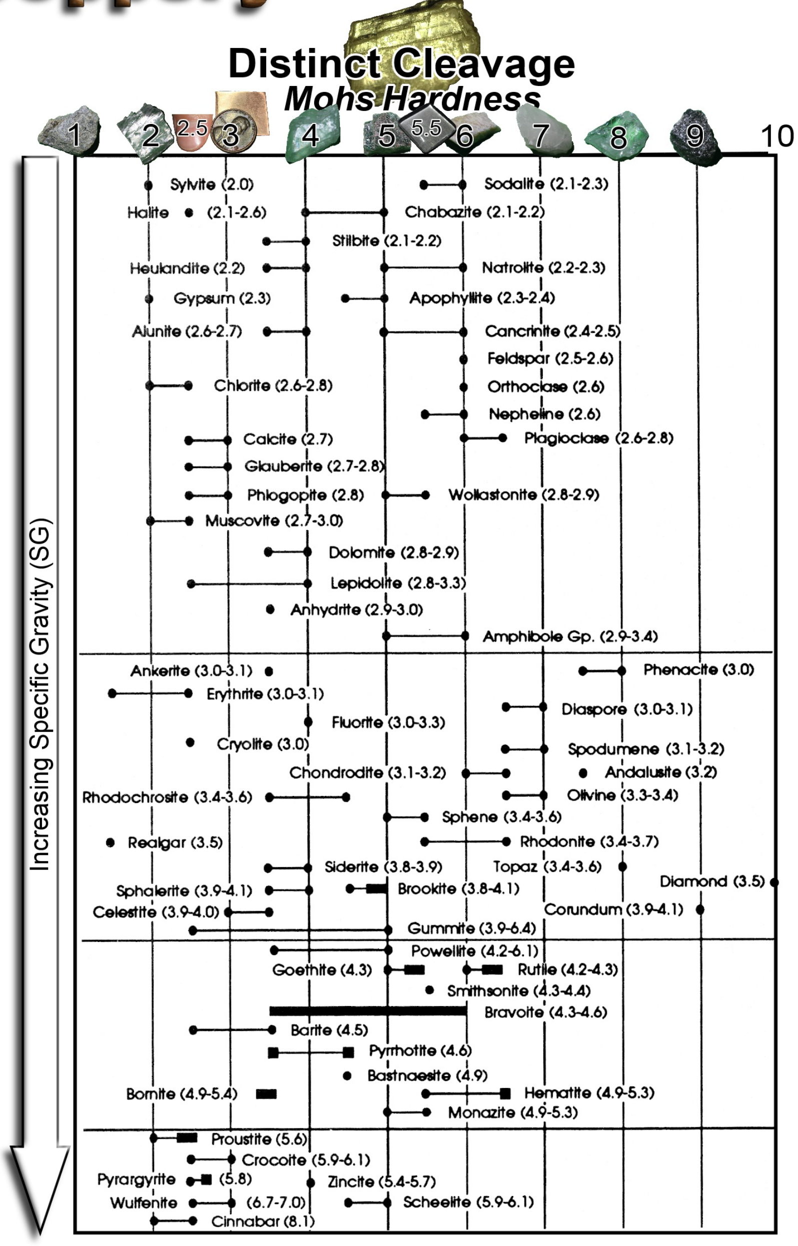


Red, Pink, Coppery

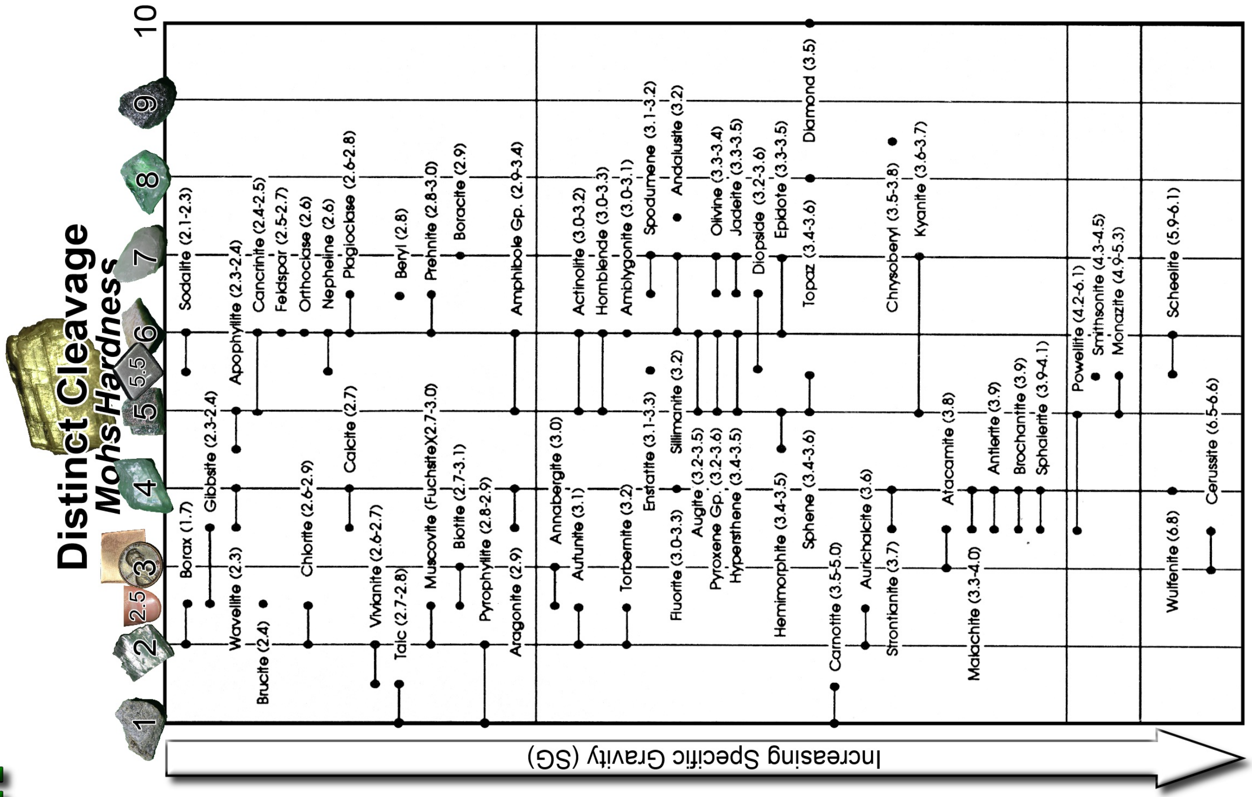
Indistinct Cleavage

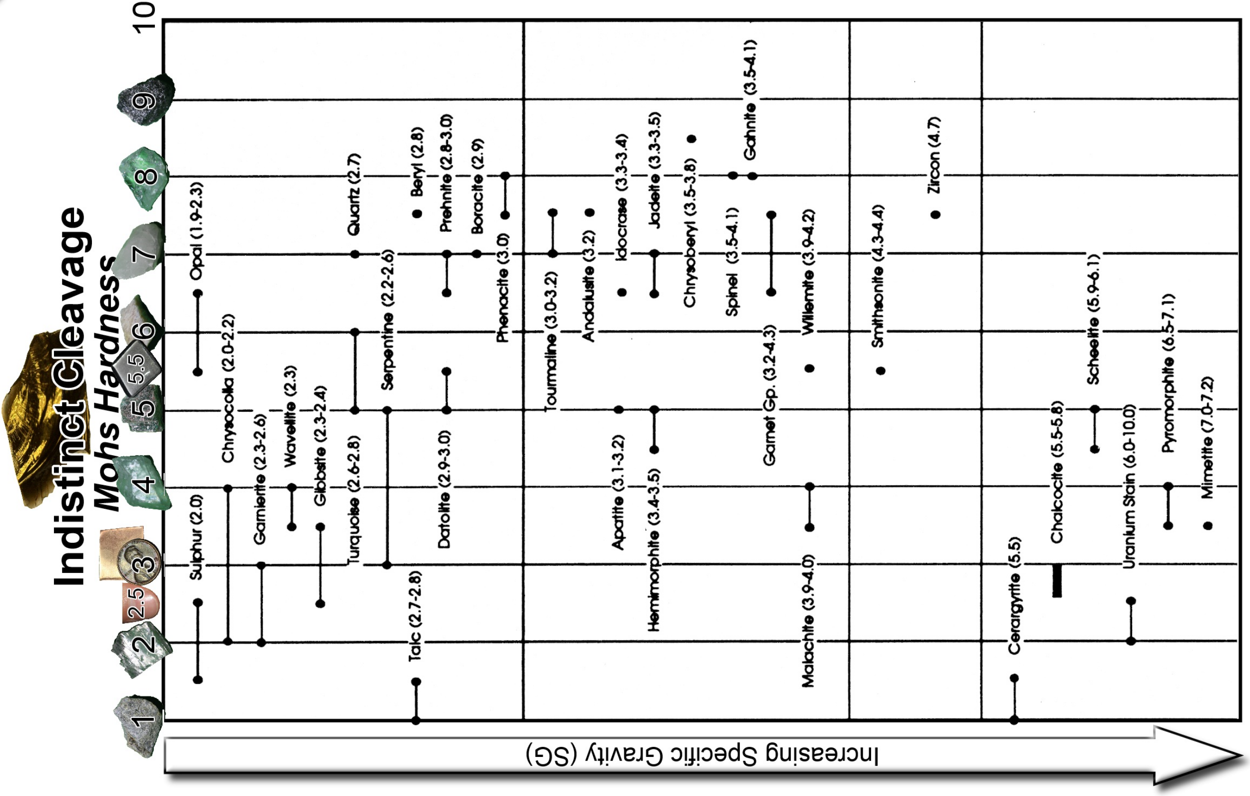


Distinct Cleavage

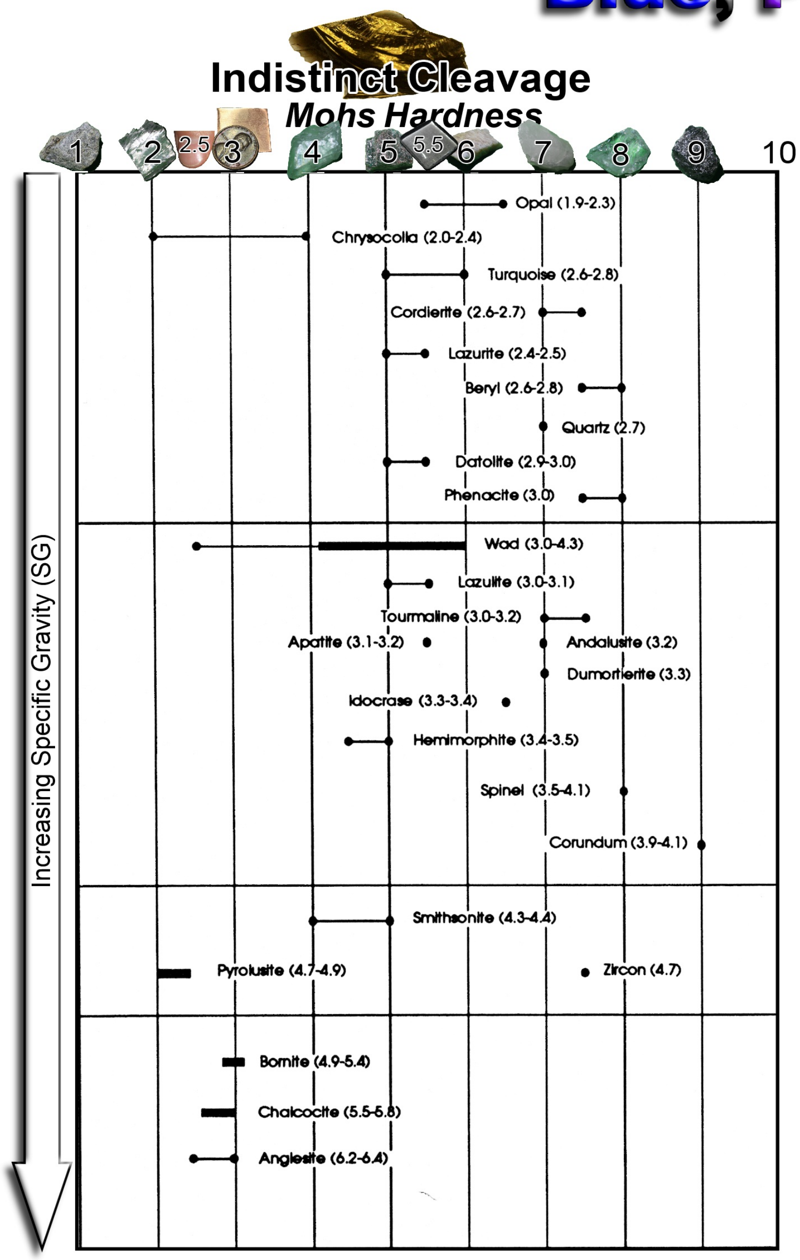


Green

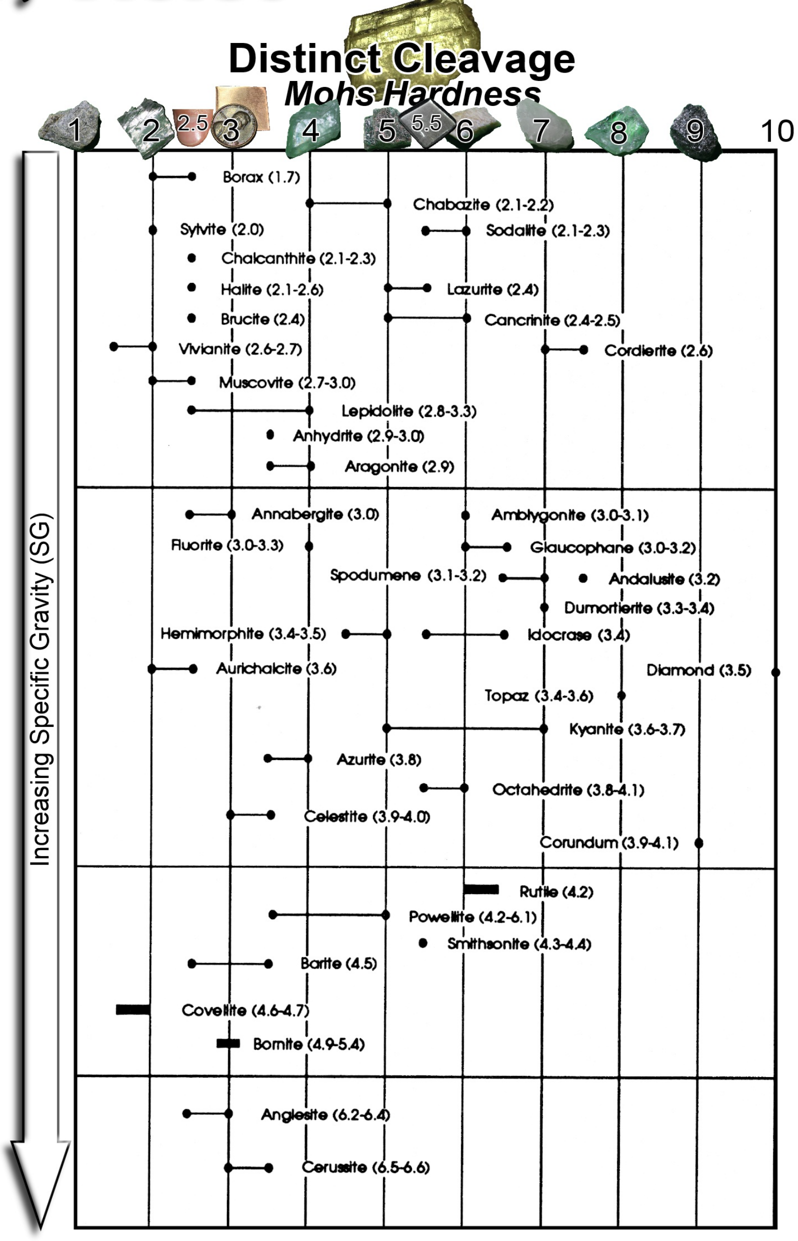

Distinct Cleavage
Mohs Hardness


Indistinct Cleavage
Mohs Hardness

Blue, Purple, Violet

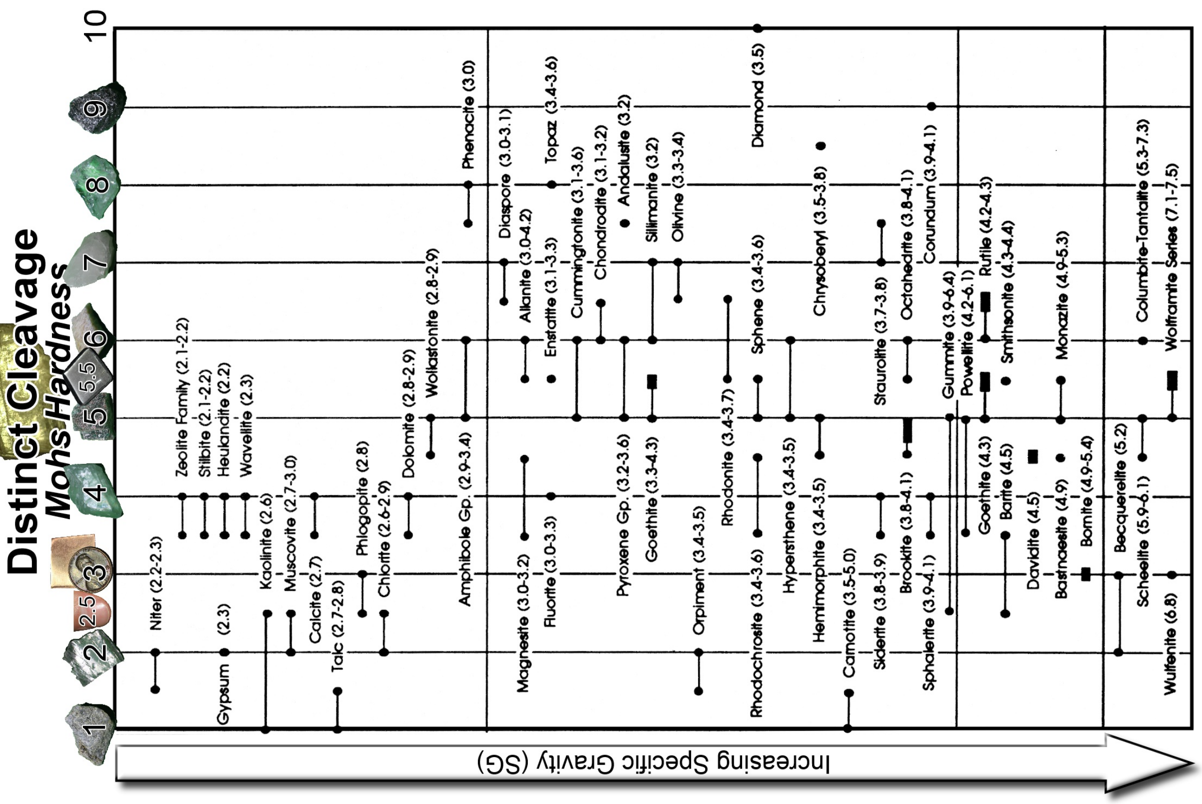

Indistinct Cleavage

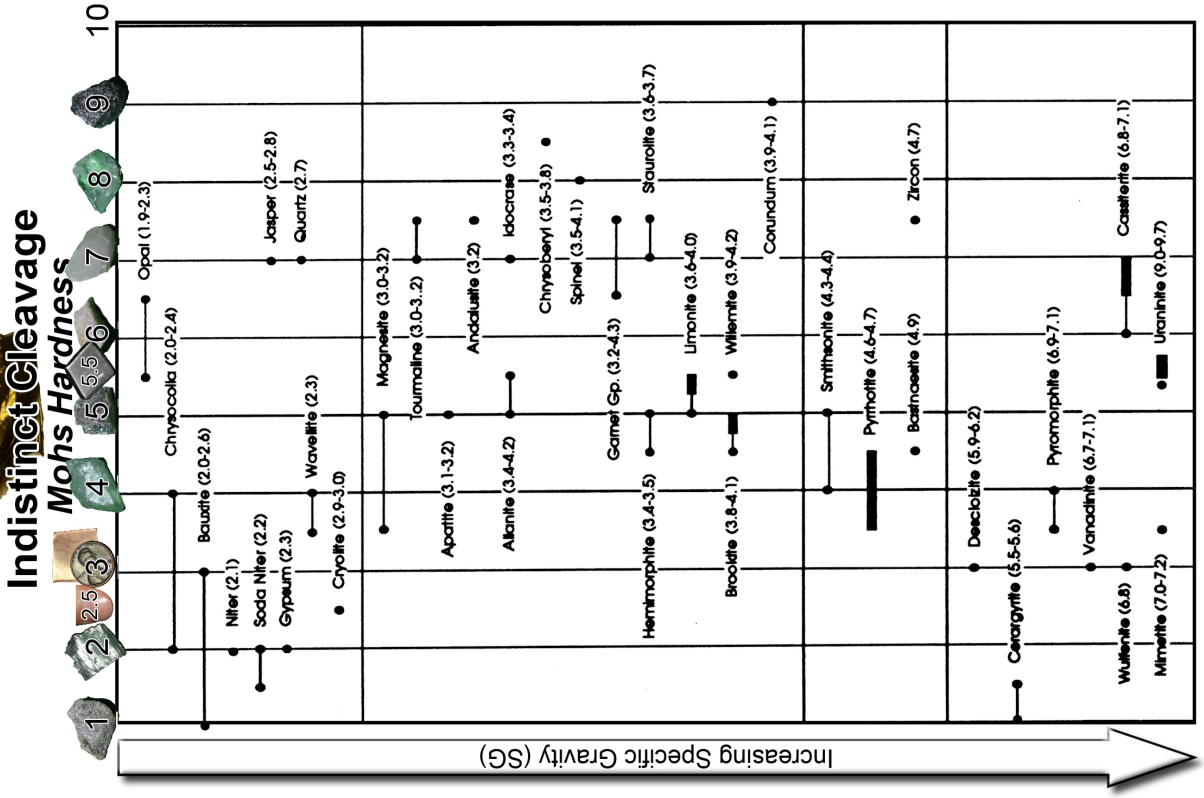
Mohs Hardness


Distinct Cleavage

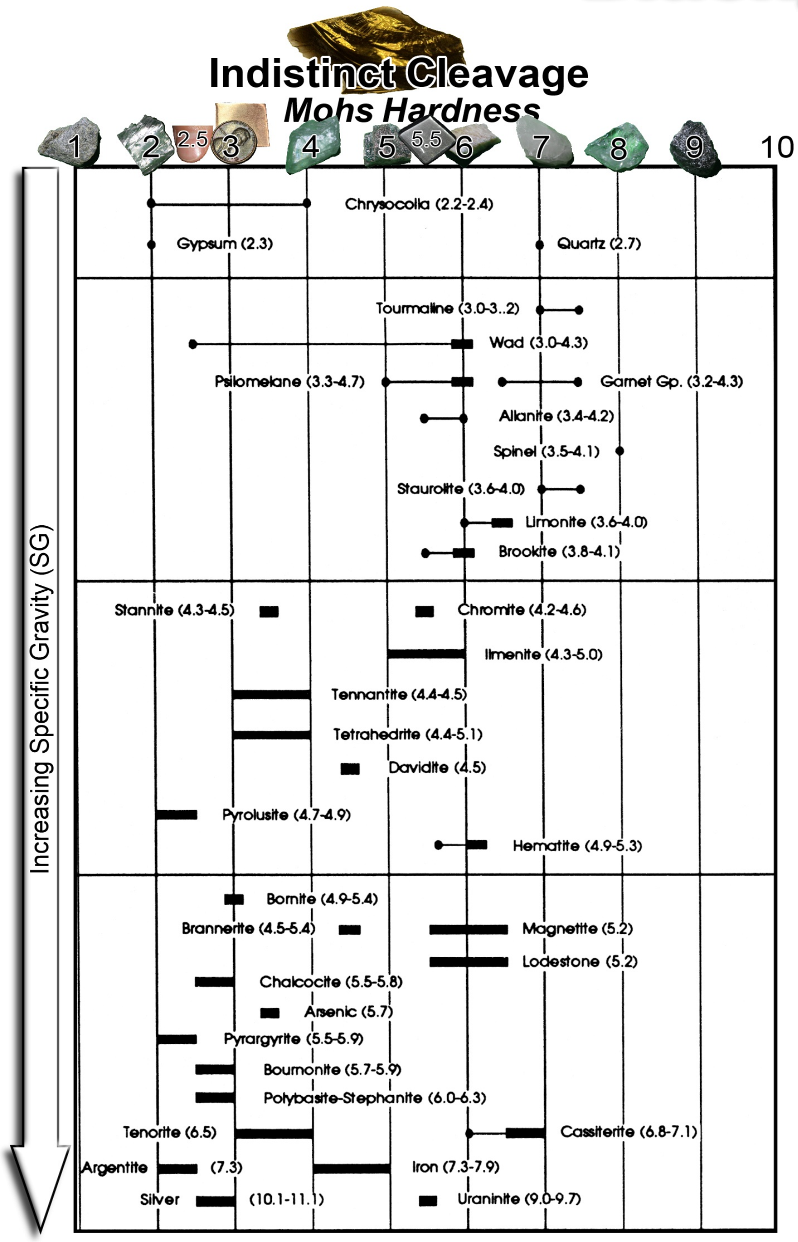
Mohs Hardness

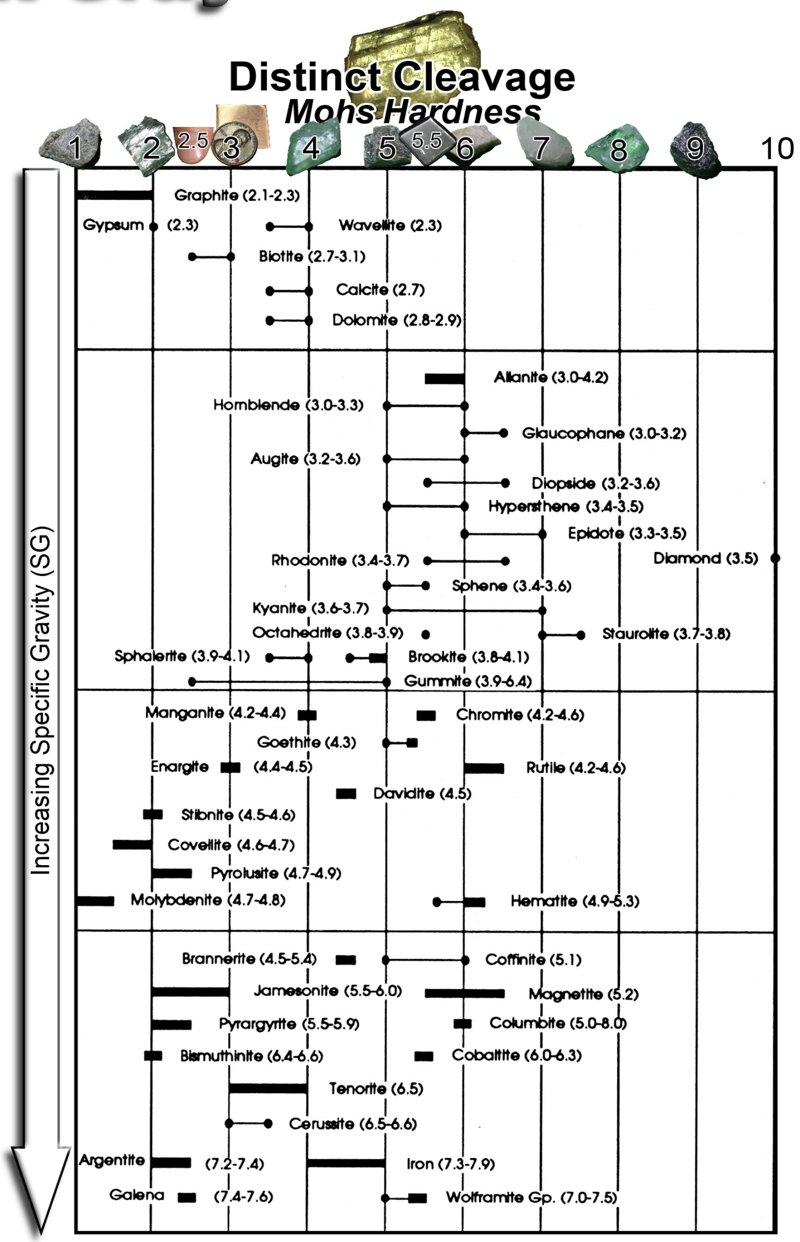
Brown


Distinct Cleavage
Mohs Hardness
1
2
2.5
3
4
5
5.5
6
7
8
9
10
Increasing Specific Gravity (SG)
Niter (2.2-2.3)
Gypsum (2.3)
Zeolite Family (2.1-2.2)
Stilbite (2.1-2.2)
Heulandite (2.2)
Wavellite (2.3)
Kaolinite (2.6)
Muscovite (2.7-3.0)
Calcite (2.7)
Talc (2.7-2.8)
Phlogopite (2.8)
Chlorite (2.6-2.9)
Dolomite (2.8-2.9)
Wollastonite (2.8-2.9)
Amphibole Gp. (2.9-3.4)
Phenacite (3.0)
Magnesite (3.0-3.2)
Fluorite (3.0-3.3)
Diaspore (3.0-3.1)
Allanite (3.0-4.2)
Enstatite (3.1-3.3)
Topaz (3.4-3.6)
Cummingtonite (3.1-3.6)
Chondrodite (3.1-3.2)
Andalusite (3.2)
Pyroxene Gp. (3.2-3.6)
Goethite (3.3-4.3)
Sillimanite (3.2)
Olivine (3.3-3.4)
Orpiment (3.4-3.5)
Rhodonite (3.4-3.7)
Diamond (3.5)
Rhodochrosite (3.4-3.6)
Sphene (3.4-3.6)
Hypersthene (3.4-3.5)
Hemimorphite (3.4-3.5)
Chrysoberyl (3.5-3.8)
Carnotite (3.5-5.0)
Siderite (3.8-3.9)
Staurolite (3.7-3.8)
Brookite (3.8-4.1)
Octahedrite (3.8-4.1)
Corundum (3.9-4.1)
Sphalerite (3.9-4.1)
Gummite (3.9-6.4)
Powellite (4.2-6.1)
Goethite (4.3)
Rutile (4.2-4.3)
Barite (4.5)
Smithsonite (4.3-4.4)
Davidite (4.5)
Bastnaesite (4.9)
Bornite (4.9-5.4)
Monazite (4.9-5.3)
Becquerelite (5.2)
Scheelite (5.9-6.1)
Columbite-Tantalite (5.3-7.3)
Wulfenite (6.8)
Wolframite Series (7.1-7.5)

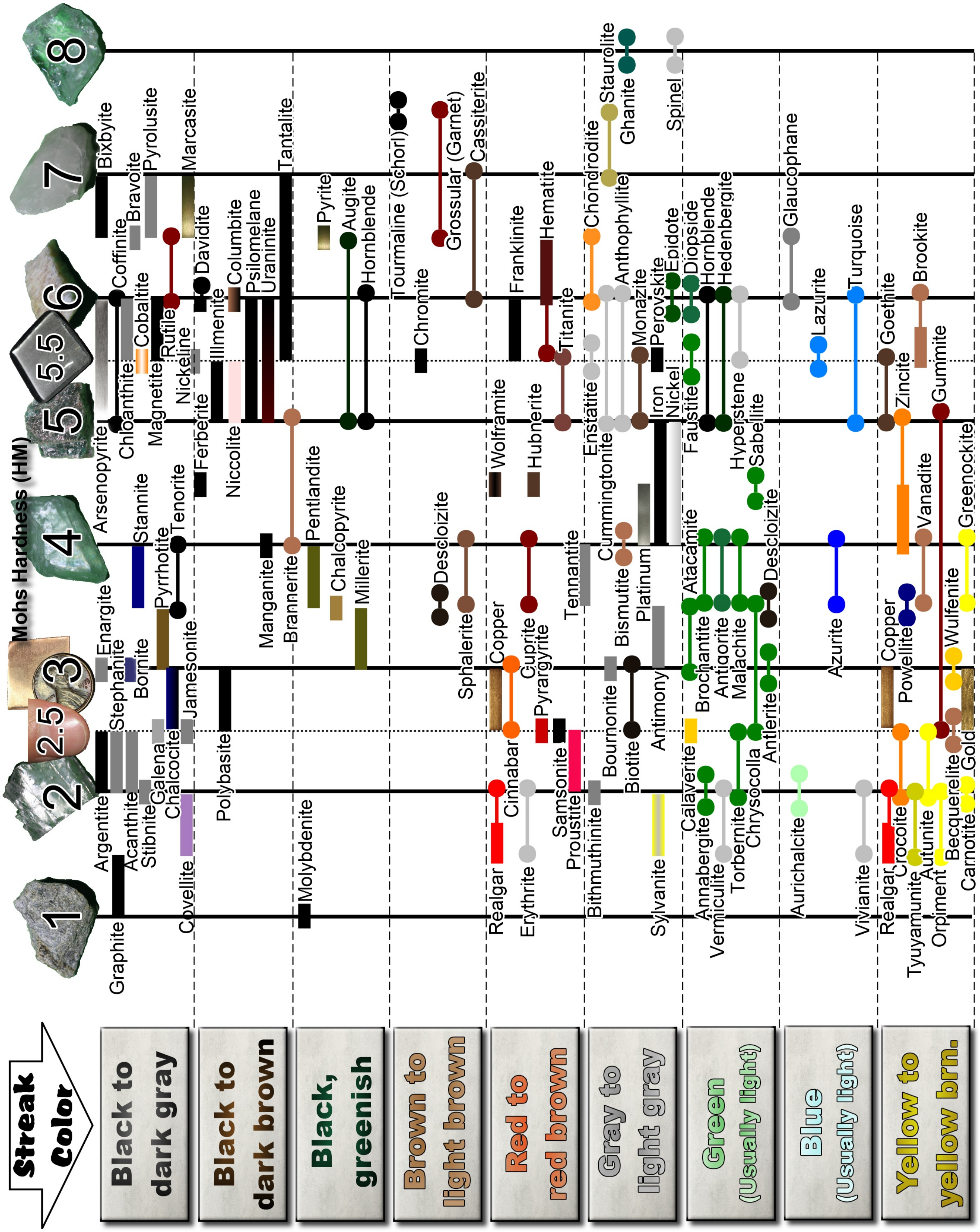

Indistinct Cleavage
Mohs Hardness
1
2
2.5
3
4
5
5.5
6
7
8
9
10
Increasing Specific Gravity (SG)
Opal (1.9-2.3)
Chrysocolla (2.0-2.4)
Bauxite (2.0-2.6)
Niter (2.1)
Soda Niter (2.2)
Gypsum (2.3)
Cryolite (2.9-3.0)
Wavellite (2.3)
Jasper (2.5-2.8)
Quartz (2.7)
Magnesite (3.0-3.2)
Tourmaline (3.0-3.2)
Apatite (3.1-3.2)
Andalusite (3.2)
Allanite (3.4-4.2)
Idocrase (3.3-3.4)
Chrysoberyl (3.5-3.8)
Spinel (3.5-4.1)
Garnet Gp. (3.2-4.3)
Staurolite (3.6-3.7)
Hemimorphite (3.4-3.5)
Limonite (3.6-4.0)
Willemite (3.9-4.2)
Brookite (3.8-4.1)
Corundum (3.9-4.1)
Smithsonite (4.3-4.4)
Pyrrhotite (4.6-4.7)
Bastnaesite (4.9)
Zircon (4.7)
Descloizite (5.9-6.2)
Cerargyrite (5.5-5.6)
Pyromorphite (6.9-7.1)
Vanadinite (6.7-7.1)
Cassiterite (6.8-7.1)
Uraninite (9.0-9.7)
Wulfenite (6.8)
Mimetite (7.0-7.2)

Black, Dark Gray



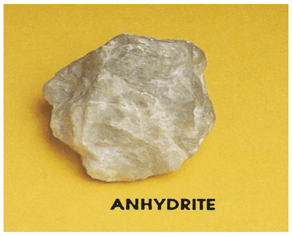


Determinative Table A - Color of streak and hardness of minerals



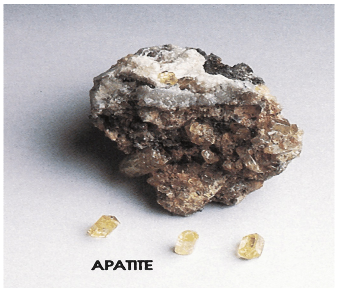
MINERAL DESCRIPTIONS - COMMON MINERALS

ANHYDRITE $CaSO_4$ *MINERAL GROUP:* Sulfate SEE GYPSUM



APATITE $Ca_5(F_3Cl)(PO_4)_3$ *MINERAL GROUP:* Phosphate

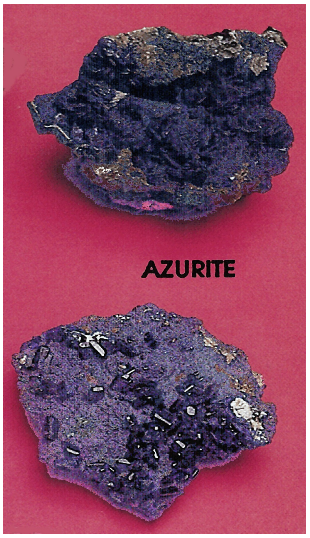
COLOR: Generally green or brown, but may be white, blue, violet or colorless, mottling common. ***CLEAVAGE:*** Imperfect cleavage and conchoidal and uneven fracture. ***HARDNESS:*** 5, brittle. ***S.G.***: 3.1-3.2 g/cm^3 ***LUSTER:*** Vitreous luster, transparent to opaque. ***CRYSTALS:*** Usually hexagonal, prismatic, pyramidal, also massive, granular. ***STREAK:*** White. ***OCCURRENCE:*** Common mineral in sedimentary beds (phosphates), pegmatites, veins, metamorphosed limestones, in magnetite veins, and minute crystals in igneous rocks.



$$SG(\frac{g}{cm^3}) = \frac{W_{air}(g)}{W_{air}(g) - W_{water}(g)}$$

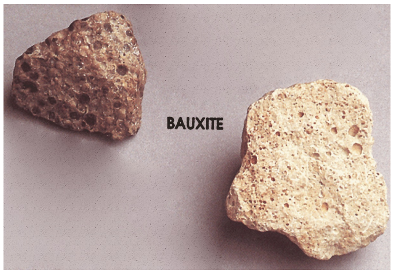
AUGITE (Pyroxene) $Ca(Mg, Fe, Al)(Al,Si)_2O_6$ *MINERAL GROUP:* Inosilicate
COLOR: White to green to black. Pale green = diopside. Dark green to black = augite. ***CLEAVAGE:*** Good prismatic cleavage at ~ 90°(house-top or stair-step like), may have basal parting, uneven fracture and brittle. ***HARDNESS:*** 5 - 6. ***S.G.***: 3.2-3.5 g/cm^3 ***LUSTER:*** Vitreous luster, transparent to translucent, latter true for augite on thin edges. ***CRYSTALS:*** Monoclinic, usually stout prisms, 4- or 8-sided cross section, also granular, massive. ***STREAK:*** Gray. ***Other:*** Diopside nearly colorless and augite black. ***OCCURRENCE:*** Common mineral in contact metamorphic environment with epidote, idocrase, garnet, tremolite. Very common rock-forming mineral in igneous rocks of low quartz content.

AZURITE $Cu_3(CO_3)_2(OH)_2$ *MINERAL GROUP:* Carbonate
COLOR: Azure blue. ***CLEAVAGE:*** Good cleavage in one direction, poor in second direction and conchoidal fracture. ***HARDNESS:*** 3.5 - 4.0, brittle. ***S.G.***: 3.8 g/cm^3 ***LUSTER:*** Vitreous luster, translucent to opaque. ***CRYSTALS:*** Monoclinic, with crystal groups, botryoidal, massive, fibrous, radiating, sometimes earthy. ***STREAK:*** Blue to pale blue. ***Other:*** Effervesces in HCl. ***OCCURRENCE:*** Common secondary copper mineral associated with malachite in oxidized zone environment.

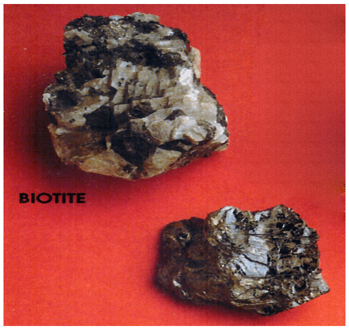


BARITE $BaSO_4$ *Mineral Group:* Sulfate
Color: White or colorless, gray, yellow, blue, red, or brown tints. ***Cleavage:*** Two direction perfect cleavage, right angles, uneven fracture. ***Hardness:*** 2.5 - 3.5, brittle. ***S.G.***: 4.5 g/cm^3 (High for non-metallic mineral) ***Luster:*** Vitreous luster, sometimes pearly on cleavage face. Transparent to opaque. ***Crystals:*** Orthorhombic, tabular, often divergent, barite roses, granular, earthy. ***Streak:*** White. ***Other:*** Insoluble in acids. ***Occurrence:*** A common mineral in veins, beds, residual masses in clay.

BAUXITE $Al_2O_3 * 2H_2O$ *Mineral Group:* Oxide Mixture
Color: Generally white, gray yellow, brown and red. ***Cleavage:*** Imperfect or non-existent. Earth fracture. ***Hardness:*** 1.0 - 3.0, earthy. ***S.G.***: 2.0 - 2.6 g/cm^3 ***Luster:*** Dull & earthy, opaque. ***Crystals:*** None. Massive, earthy. Small rounded nodules in claylike matrix. ***Streak:*** Cream white, yellow, brown or reddish. ***Other:*** Adheres to tongue. Clayey odor, non-plastic with water. ***Occurrence:*** Common mineral, generally in tropical climates from weathering and leaching of aluminum rich rocks. Often associated with laterite soils.



BIOTITE $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$ *Mineral Group:* Phyllosilicate
Color: Black, brownish black, greenish black. ***Cleavage:*** Perfect micaceous (elastic) cleavage, uneven fracture. ***Hardness:*** 2.5 - 3.0 ***S.G.***: 2.7 - 3.1 g/cm^3 ***Luster:*** Vitreous luster, translucent to opaque. ***Crystals:*** Monoclinic (small angle), scales, foliated, tabular, short prismatic, and hexagonal. ***Streak:*** Greenish gray. ***Occurrence:*** Common mineral in igneous and metamorphic rocks. Light colored variety of mica see "muscovite."



BORNITE Cu_5FeS_4 *Mineral Group:* Sulfide
Color: Purplish to blue tarnish on weathered mineral (Peacock color, hence "Peacock ore"). Bronze on fresh surface. ***Cleavage:*** Poor cleavage & uneven fracture. ***Hardness:*** 3.0 ***S.G.***: 4.9 - 5.4 g/cm^3 ***Luster:*** Metallic luster. ***Crystals:*** Isometric, rare crystals, massive. ***Streak:*** Grayish black. ***Other:*** Purplish tarnish when moistened most distinctive feature (Peacock ore!). ***Occurrence:*** Fairly widespread in copper-quartz veins, pegmatites and some igneous rocks. Associated minerals are chalcopyrite and other copper minerals.

CALCITE $CaCO_3$ *MINERAL GROUP:* Carbonate
COLOR: Usually colorless or white, often light tones of gray, yellow, green, blue, red. ***CLEAVAGE:*** Perfect rhombohedral cleavage and conchoidal fracture. ***HARDNESS:*** 2.5 - 3.0. ***S.G.***: 2.7 g/cm^3 ***LUSTER:*** Vitreous to pearly luster. Transparent to opaque. ***CRYSTALS:*** Hexagonal - rhombohedral. Crystals common, tabular, prismatic, acute, dog-tooth like. ***STREAK:*** White. ***Other:*** Effervesces vigorously in dilute acids, even vinegar. May fluoresce under UV light. Transparent mineral will show double refraction of written text when viewed through the crystal. ***OCCURRENCE:*** An abundant mineral in rocks, veins, spring deposits, cave deposits, and shells of sea animals. Makes up limestone rock and travertine terraces of hot springs.

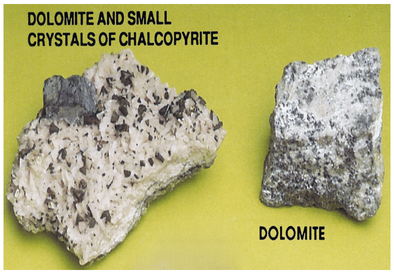
CHALCOPYRITE $CuFeS_2$ *MINERAL GROUP:* Sulphide
COLOR: Brass yellow with common bronze or iridescent tarnish. ***CLEAVAGE:*** Indistinct cleavage and uneven fracture. ***HARDNESS:*** 3.5 - 4.0, brittle. ***S.G.***: 4.1 - 4.3 g/cm^3 ***LUSTER:*** Metallic luster, opaque. ***CRYSTALS:*** Tetragonal. Tetrahedral crystals, usually massive. ***STREAK:*** Greenish black. ***OCCURRENCE:*** Associated with sphalerite, bornite, chalcocite. tetrahedrite. pyrrhotite. pyrite, galena. Occurs in veins, contact metamorphic deposits, igneous rocks and some gneisses and schists.

CHLORITE $(MgFe)_5Al_2Si_3O_{10}(OH)_8$ *MINERAL GROUP:* Phyllosilicate
COLOR: Green. Also yellowish, brown or reddish. ***CLEAVAGE:*** One direction micaceous. Uneven fracture. ***HARDNESS:*** 2.0 - 2.5. Flexible but not elastic. ***S.G.***: 2.6 - 2.9 g/cm^3 ***LUSTER:*** Vitreous to pearly or silky. Mostly opaque, rarely translucent. ***CRYSTALS:*** Monoclinic. Tabular, pseudo hexagonal, scaly, earthy, rarely prismatic. ***STREAK:*** Light green to colorless. ***OCCURRENCE:*** Common and wide spread in microcrystalline form in clays and soils. Macroscopic amounts found in schists, serpentine and other low grade metamorphic rocks. May occur in mafic igneous rocks as alteration product of pyroxene, amphibole and biotite.

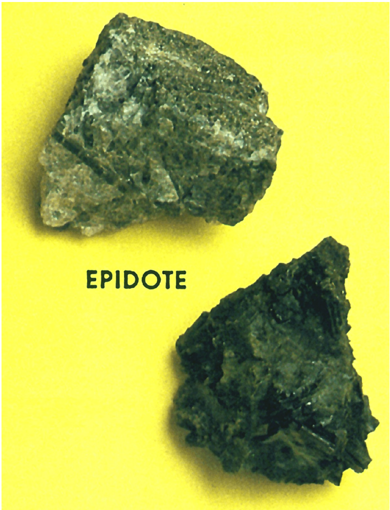
COPPER Cu *Mineral Group:* Native mineral
Color: Typical copper to copper red color. May have black or green tarnish. ***Cleavage:*** No cleavage and hackly fracture. ***Hardness:*** 2.5 - 3.0, malleable. ***S.G.***: 8.8 - 8.9 g/cm^3 ***Luster:*** Metallic luster, opaque. Dull when tarnished. ***Crystals:*** Isometric. Branching groups, scales, plates, wirelike, massive. ***Streak:*** Copper red color. ***Occurrence:*** Uncommon in large quantities. Occurs in oxidized zone of copper deposits, also in openings in igneous rocks, in veins, in pore spaces in sandstones and conglomerates. Associates are malachite, azurite, calcite, native silver.

CORUNDUM Al_2O_3 *Mineral Group:* Oxide
Color: Blue (clear = sapphire), purple (clear = oriental amethyst), red (clear = ruby), yellow (clear = oriental topaz), non-transparent brown to gray, and sometimes nearly white. ***Cleavage:*** Pseudo-cleavage nearly rectangular, uneven to conchoidal fracture. ***Hardness:*** 9.0, brittle. ***S.G.***: 3.9 - 4.1 g/cm^3 ***Luster:*** Adamantine to vitreous. Transparent to translucent, as well as opaque. ***Crystals:*** Hexagonal. ***Streak:*** None; appears white. ***Other:*** Inert to acids. Extreme hardness is the most indicative feature. Note: Weathered or decomposed edges of corundum can be soft and give false hardness measurements. ***Occurrence:*** An accessory mineral in crystalline rocks such as granular limestone or dolomite, some gneiss, and micaceous and chlorite slate. Rarely occurs in igneous rocks. May be present in placer deposits. Important localities are Burma, Sri Lanka, Thailand and Montana, U.S.A.

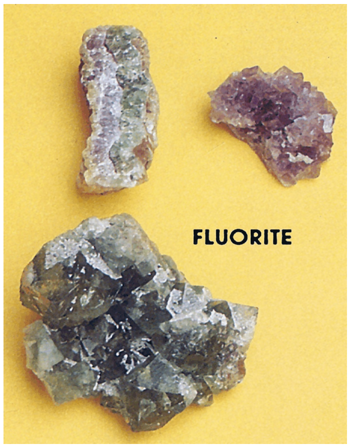
DOLOMITE $CaMg(CO_3)_2$ *Mineral Group:* Carbonate
Color: Generally white, gray or pink. Can be colorless. ***Cleavage:*** Good three-direction cleavage, not right angles. Conchoidal fracture. ***Hardness:*** 3.5 - 4.0, quite brittle. ***S.G.***: 2.8 - 2.9 g/cm^3 ***Luster:*** Vitreous to pearly and dull. Transparent to translucent, as well as opaque. ***Crystals:*** Hexagonal - rhombohedral. Often curved, massive, granular. ***Streak:*** White. ***Other:*** Does not effervesce with cold acids, or will effervesce only very slightly. Powdered mineral effervesces more readily. Effervesces in hot HCl. ***Occurrence:*** Common associate with calcite. May occur in veins and as alteration product of limestone. Sometimes makes massive dolomite deposits of several hundreds if not thousands of feet in thickness (Austrian Alps).



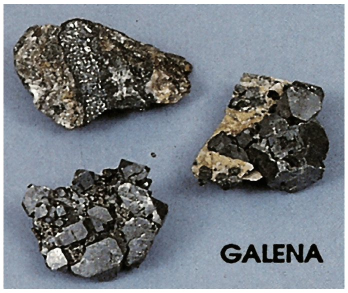
EPIDOTE $Ca_2(Al,Fe)_3(SiO_4)_3OH$ *MINERAL GROUP:* Sorosilicate
COLOR: Pistachio green to blackish green. ***CLEAVAGE:*** Perfect in one direction, uneven fracture. ***HARDNESS:*** 6.0 - 7.0, brittle. ***S.G.***: 3.3 - 3.5 g/cm^3 ***LUSTER:*** Vitreous. Transparent to opaque. ***CRYSTALS:*** Monoclinic. Prismatic, striated, also granular and fibrous. ***STREAK:*** grayish to colorless. ***OCCURRENCE:*** Common associate with feldspar, hornblende, quartz and chlorite.



FLUORITE CaF_2 *MINERAL GROUP:* Halide
COLOR: Colorless, white, yellow, green, blue, purple, violet, pink, red, brown, sometimes with various shades in same sample. ***CLEAVAGE:*** Perfect octahedral cleavage with smooth and flat fracture. ***HARDNESS:*** 4.0, brittle. ***S.G.***: 3.0 - 3.3 g/cm^3 ***LUSTER:*** Vitreous luster. Transparent to translucent. ***CRYSTALS:*** Isometric. Cubic crystals common, twined, massive, fine granular. ***STREAK:*** White. ***Other:*** May be fluorescent. If heated in darkened room continues to glow with removal of heat (phosphorescence). ***OCCURRENCE:*** Common mineral in veins associated with quartz, calcite, galena, barite and others.



GALENA PbS *MINERAL GROUP:* Sulphide
COLOR: Lead gray. Fresh surface silvery and shiny. ***CLEAVAGE:*** Perfect cubic cleavage. ***HARDNESS:*** 2.5, very brittle. ***S.G.***: 7.4 - 7.6 g/cm^3 ***LUSTER:*** Metallic luster. Opaque. ***CRYSTALS:*** Isometric. Cubic, octahedral crystals, massive, granular. ***STREAK:*** Lead gray. ***OCCURRENCE:*** Common mineral in veins, beds. Associate minerals pyrite, sphalerite, quartz, calcite, fluorite, barite and others.



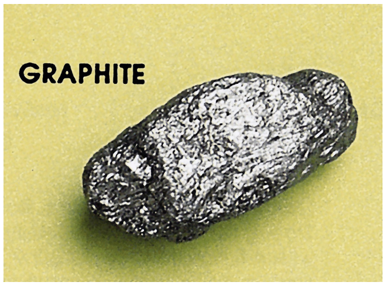
GARNET (Group) $X_3Y_2(SiO_4)_3$ *Mineral Group:* Nesosilicate

X: divalent metals (Ca, Fe, Mg, &/or Mn) Y: trivalent metals (Al, Cr, Fe, &/or Mn)

Color: Variety of colorations depending on chemical composition. Garnet variety names based on typical common color: reddish brown to brown to brownish black = Almandite ($Fe_3Al_2(SiO_4)_3$); various shades of green to brown to black = Andradite ($Ca_3Fe_2(SiO_4)_3$); Colorless to white, pale green, amber, honey yellow = Grossularite ($Ca_3Al_2(SiO_4)_3$); Deep red, ruby red to nearly black = Pyrope ($Mg_3Al_2(SiO_4)_3$); Dark hyacinth red, pink, orange. Sometimes with tints of violet and brownish red = Spessartite ($Mn_3Al_2(SiO_4)_3$); Distinctive emerald green = Uvarovite ($Ca_3Cr_2(SiO_4)_3$) ***Cleavage:*** Indistinct cleavage and uneven fracture. ***Hardness:*** 6.5 - 7.5 ***S.G.***: 3.4 -4.3 g/cm^3 (Almandite 4.3; Andradite 3.7$^+$; Grossularite 3.5; Pyrope 3.6; Spessartite 4.3; Uvarovite 3.8) ***Luster:*** Vitreous to resinous luster, transparent to translucent. Can be opaque. ***Crystals:*** Isometric. Dodecohedrons. trapezohedrons or combination, also massive. ***Streak:*** No streak (white). ***Occurrence:*** Common mineral in metamorphic rocks (Alamandite, Pyrope, Spessartite, Uvarovite [Serpentines]) including marble (Grossular, Andradite), in igneous rocks (Andradite [volcanic], Pyrope [Ultramafic], Spessartite [Granite]), pegmatites (Spessartite) and in sands as a heavy mineral.

GRAPHITE C *Mineral Group:* Native mineral

Color: Black. ***Cleavage:*** Basal perfect cleavage, but often hard to identify because of small crystal size. ***Hardness:*** 1.0 - 2.0, sectile, greasy feel, flexible but not elastic. ***S.G.***: 2.1 - 2.3 g/cm^3 ***Luster:*** Dull metallic luster, opaque. ***Crystals:*** Rhombohedral-Hexagonal. Flat tabular crystals, generally massive, foliated. ***Streak:*** Black. Will leave streak also on paper. ***Other:*** Even though it is carbon, it will not burn!. Easily marks paper. ***Occurrence:*** Fairly common in veins, metamorphic, igneous and sedimentary rocks. Associated with garnet, pyroxene, amphibole, chlorite, micas, and others.



GYPSUM $CaSO_4*2H_2O$ *Mineral Group:* Sulfate

ANHYDRITE $CaSO_4$

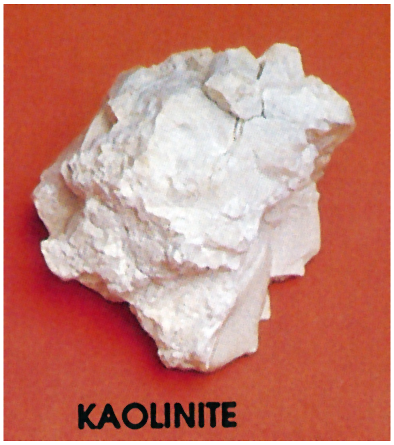
Color: Colorless, white, pale gray, sometimes tints of yellow, reddish or other colors. ***Cleavage:*** Gypsum - One direction perfect cleavage, conchoidal and uneven fracture. Anhydrite - Three directional cleavage at right angles, fracture is uneven to splintery. ***Hardness:*** Gypsum 2.0; Anhydrite 3.5. ***S.G.***: Gypsum 2.3 g/cm^3, Anhydrite 2.9 - 3.0 g/cm^3 ***Luster:*** Vitreous luster, somewhat pearly. Transparent to opaque. ***Crystals:*** Gypsum - Monoclinic, nice tabular crystals (often very large), also fibrous, massive, granular. Anhydrite - Orthorhombic, rare crystals, massive, granular, fibrous. ***Streak:*** White. ***Other:*** Anhydrite is harder than Gypsum and may also fluoresce under UV light. ***Occurrence:*** Both minerals are evaporites and are most often associated with each other, salt, limestone, clays. In addition, anhydrite occurs also in veins with metallic minerals, as well as in openings in basalt.

HALITE NaCl *Mineral Group:* Halide
Color: Generally colorless to white, but tints of yellow, red, sometimes blue. ***Cleavage:*** Perfect cubic cleavage, conchoidal fracture. ***Hardness:*** 2.5. ***S.G.***: 2.1 - 2.6 g/cm^3 ***Luster:*** Vitreous luster, transparent to translucent. ***Crystals:*** Isometric. Cubic crystals, massive, granular. ***Streak:*** White. ***Other:*** Readily soluble in water. Tastes salty. ***Occurrence:*** Occurs in salt flats, salt domes; associates are gypsum, calcite, sylvite (KCl), anhydrite and clay. Evaporite mineral.

HEMATITE Fe_2O_3 *Mineral Group:* Oxide
Color: Silvery steel gray to black, sometimes iridescent. Red when earthy. ***Cleavage:*** No distinct cleavage. but parting. Uneven or splintery fracture. ***Hardness:*** 5.5 - 6.5 (down to 1.0 in earthy red varieties), quite brittle. ***S.G.***: 4.9 - 5.3 g/cm^3 ***Luster:*** Earthy to metallic luster. ***Crystals:*** Hexagonal-rhombohedral. Tabular, columnar, massive, botryoidal and mammillary. ***Streak:*** Good red streak. ***Other:*** Will often stick to a strong magnet (Neodymium Magnet) due to magnetite impurities. Slowly soluble in HCl. ***Occurrence:*** Accessory in igneous rocks, in veins with magnetite, contact metasomatic deposits, red cement in sandstones, other sedimentary rocks.

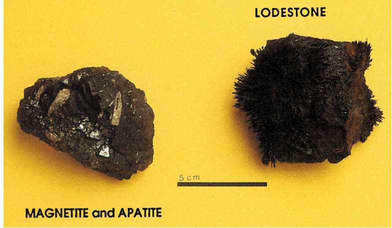
HORNBLENDE (Amphibole) $Ca_2Na(Mg,Fe)_4(Al,Fe,Ti)_3Si_6O_{22}(O,OH)_2$ *Mineral Group:* Inosilicate
Color: Light to dark green to black. ***Cleavage:*** Cleavage at ~120° or 60°, uneven fracture. ***Hardness:*** 5.0 - 6.0, quite brittle. ***S.G.***: 3.0 - 3.3 g/cm^3 ***Luster:*** Vitreous luster, translucent on thin edges. ***Crystals:*** Monoclinic. Perfect to prismatic. Diamond-shaped cross section, also bladed, columnar, fibrous, some massive. ***Streak:*** White to pale green. ***Occurrence:*** Abundant mineral in igneous rocks, schists and gneiss. Common associates calcite, plagioclase. quartz, garnet.

KAOLINITE (China Clay) $Al_2Si_2O_5(OH)_4$ *Mineral Group:* Phyllosilicate
Color: White, commonly stained brown, gray, and other colors. ***Cleavage:*** Rarely seen, but perfect one direction cleavage; uneven fracture. ***Hardness:*** 1.0 -2.5, dusty. ***S.G.***: 2.6 g/cm^3; difficult to assess, traps air bubbles ***Luster:*** Earthy luster, opaque. ***Crystals:*** Monoclinic. Usually earthy masses. Under very high magnification (usually SEM) displays hexagonal looking plates. ***Streak:*** White. ***Other:*** Soft soapy feel between fingers, often leaves powder on hand. Earthy odor. Sticks to tongue. ***Occurrence:*** Common secondary mineral from weathering of silicates, especially feldspar.

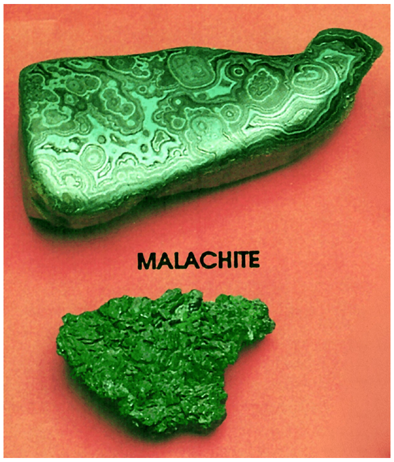


LIMONITE $FeO(OH)*nH_2O$ *Mineral Group:* Oxide
Color: Dull beige or yellow brown or rusty appearance. Brown shades, may have nearly black exterior. ***Cleavage:*** No distinct cleavage. ***Hardness:*** 5.0 - 5.5. ***S.G.***: 3.6 - 4.0 g/cm^3. ***Luster:*** Non-metallic to sub-metallic, opaque. ***Crystals:*** Not crystallized. Stalactic, botryoidal or mammillary forms common. Internal fibrous or sub-fibrous structure; earthy, concretionary and also massive. ***Streak:*** Yellowish brown. ***Other:*** Turns to hematite when heated. ***Occurrence:*** A common mineral. Alteration product of other Iron-bearing minerals.

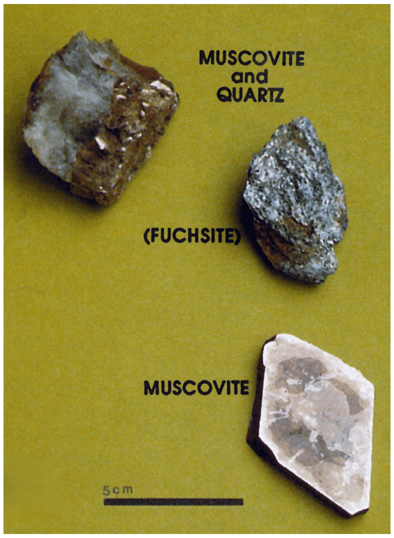
MAGNETITE (LODESTONE) Fe_3O_4 *Mineral Group:* Oxide
Color: Black. ***Cleavage:*** No cleavage, but octahedral parting, uneven fracture. ***Hardness:*** 5.5 - 6.5, quite brittle. ***S.G.***: 5.2 g/cm^3. ***Luster:*** Metallic, opaque. ***Crystals:*** Isometric. Octahedrons common, also granular, massive. ***Streak:*** Black. ***Other:***Attracted by magnet. May also be strongly magnetic (Lodestone). ***Occurrence:*** Common mineral in igneous and metamorphic rocks, black sands. Also in large ore bodies, where it is often associated with Apatite.



MALACHITE $Cu_2CO_3(OH)_2$ *Mineral Group:* Carbonate
Color: Bright green, black surface often visible. ***Cleavage:*** Cleavage one direction perfect, but rarely visible, uneven fracture. ***Hardness:*** 3.5 - 4.0, brittle. ***S.G.***: 3.9 - 4.0 g/cm^3 ***Luster:*** Translucent to opaque and vitreous (crystals), silky (fibrous), dull (earthy). ***Crystals:*** Monoclinic, often botryoidal or in crystal groups, also massive, fibrous, radiating, sometimes earthy. ***Streak:*** White to pale green. ***Other:*** Effervesces in HCl. ***Occurrence:*** Common copper mineral associated with azurite, native copper and other copper bearing minerals.



MUSCOVITE $KAl_3Si_3O_{10}(OH)_2$ *Mineral Group:* Phyllosilicate
Color: Colorless. light tones of yellow, brown, green. Bright green, chrome bearing variety is known as "fuchsite". ***Cleavage:*** Perfect micaceous (elastic) basal cleavage, plates flexible and elastic. ***Hardness:*** 2.5 - 3.0 ***S.G.***: 2.7 - 3.0 g/cm^3 ***Luster:*** Transparent to translucent vitreous luster, also pearly when fine grained. Larger flakes have the appearance of plastic and sparkle readily in sunlight. ***Crystals:*** Monoclinic (small angle), hexagonal, tabular crystals, scaly, foliated masses. ***Streak:*** White. ***Occurrence:*** Common mineral in granite pegmatite and schist. Dark colored variety of mica see "biotite."



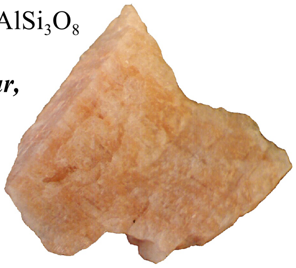
OLIVINE $(Mg,Fe)SiO_4$ *Mineral Group:* Nesosilicate
Fosterite ($MgSiO_4$) - *Fayalite* ($FeSiO_4$)
Color: Green, olive-green, sometimes brownish, grayish-red. ***Cleavage:*** Indistinct cleavage, conchoidal fracture. ***Hardness:*** 6.5 - 7.0, brittle. ***S.G.***: 3.3 - 3.4 g/cm^3 ***Luster:*** Transparent to translucent and vitreous luster. ***Crystals:*** Orthorhombic. Isolated grains in mafic igneous rock, aggregates, crystals rare. ***Streak:*** White. ***Occurrence:*** Found occasionally in mafic and ultramafic igneous rocks. Main mineral of the earth's mantle. Associated with augite, chromite, magnetite, serpentine, garnet and spinel.

ORTHOCLASE-MICROCLINE (Feldspar) $KAlSi_3O_8$

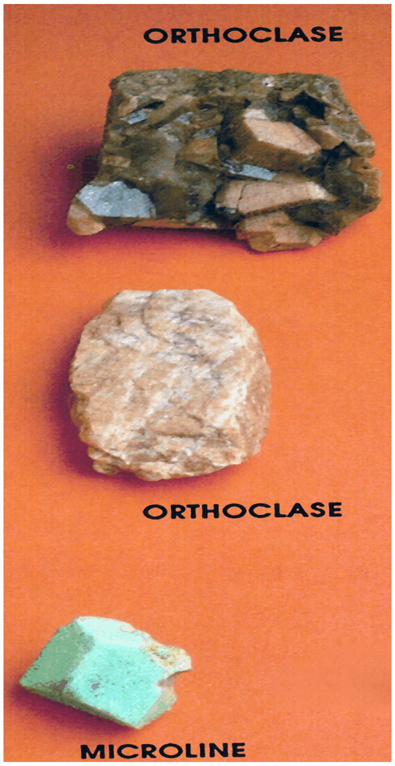
Mineral Group: Tectosilicate

Other generic names: ***Potassium Feldspar, K-Feldspar, K-spar***

Other varieties: ***Amazonstone*** *- green microcline;* ***Sanidine*** *- glassy orthoclase with tabular, square crystals;* ***Adularia*** *- low temperature colorless transparent orthoclase with mainly prismatic crystals;* ***Moonstone*** *- "adularia" with pearly or bluish sheen*



Color: Usually pink to creamish pink. Also colorless, white, light gray, cream, green, red, red tone. ***Cleavage:*** Two good cleavages at right angles. Uneven to conchoidal fracture in third direction. ***Hardness:*** 6.0, brittle. ***S.G.***: 2.6 g/cm^3 ***Luster:*** Translucent to transparent with vitreous luster. Also opaque. ***Crystals:*** Monoclinic (Orthoclase) - Triclinic (Microcline). Crystals usually prismatic, twinned, shapeless and massive. ***Streak:*** White. ***Other:*** Distinct pink mineral color very common(!). ***Occurrence:*** One of the most abundant of rock-forming minerals in igneous rocks, metamorphic rocks, also in veins. Common associates are quartz and muscovite, especially in granite pegmatites.



PLAGIOCLASE (Feldspar) $NaAlSi_3O_8$ - $CaAl_2Si_2O_8$

Mineral Group: Tectosilicate

Isomorphous series: ***Albite - Oligoclase- Andesine - Labradorite - Bytownite - Anorthite***

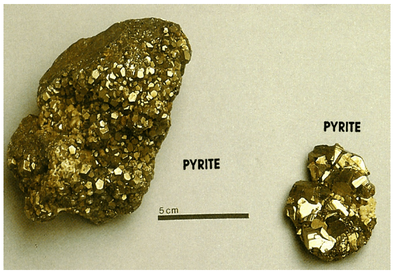
Other varieties: ***Sunstone*** *- "oligoclase" with scales which reflect in reddish and golden tones ;* ***Moonstone*** *- "albite" with pearly - bluish sheen*

Color: Gray, white, also colorless, green, yellowish or reddish. Bluish iridescent color plays in black to dark brown labradorite and andesine. ***Cleavage:*** Two very good cleavages (86° and 94°). Uneven to conchoidal fracture in third direction. ***Hardness:*** 6.0 - 6.5, brittle. ***S.G.***: 2.6 - 2.8 g/cm^3 ***Luster:*** Vitreous luster and transparent to translucent. Also opaque. ***Crystals:*** Triclinic. Tabular crystals, twins, massive, shapeless, striae on cleavages. ***Streak:*** White. ***Occurrence:*** Abundant minerals in most intermediate colored igneous rocks and some metamorphic rocks such as gneisses.

PYRITE FeS_2

Mineral Group: Sulphide

Color: Pale to medium brassy yellow. ***Cleavage:*** Indistinct cleavage. Conchoidal to uneven fracture. ***Hardness:*** 6.0 - 6.5, brittle. ***S.G.***: 5.0 g/cm^3 ***Luster:*** Metallic luster, opaque. ***Crystals:*** Isometric. Cubes, pyritohedrons, octahedrons, striated, massive, granular. ***Streak:*** Black. ***Other:*** Sparks when struck with steel. ***Occurrence:*** Common mineral associated with other sulfide minerals. Generally alters to limonite.



QUARTZ (crystalline varieties) SiO_2 *Mineral Group:* Tectosilicate

Variants: ***Amethyst*** *- deep blue to purple quartz gemstone ;* ***Aventurine*** *- usually green quartz variety with mica, hematite, or other platy mineral inclusions yielding a glistening effect;* ***Cat's eye*** *- an opalescent variety of quartz due to fibrous mineral inclusions;* ***Citrine*** *- yellow amber colored gemstone quartz due to Fe impurities;* ***Ghost quartz*** *- growth stages visible in the mineral;* ***Milky quartz*** *- cloudy white quartz;* ***Rose quartz*** *- rose or pink colored translucent to transparent massive quartz;* ***Rutilated quartz*** *- "rutile" needles throughout the mineral;* ***Smoky Quartz*** *- black to dark grey variety of quartz caused by exposure to natural radioactive sources, such as U;* ***Tiger's eye*** *- silica pseudomorph after "crocidolite";.*

Color: Colorless, rosy, smoky, brown, black, purple. ***Cleavage:*** Indistinct cleavage, conchoidal fracture. ***Hardness:*** 7.0, brittle to tough. ***S.G.***: 2.7 g/cm^3 ***Luster:*** Transparent to translucent, vitreous luster. ***Crystals:*** Hexagonal. Commonly 6-sided crystals, horizontally striated prisms, glassy grains. ***Streak:*** White. ***Occurrence:*** An abundant and ubiquitous mineral in sedimentary rocks, metamorphic and lighter colored igneous rocks.

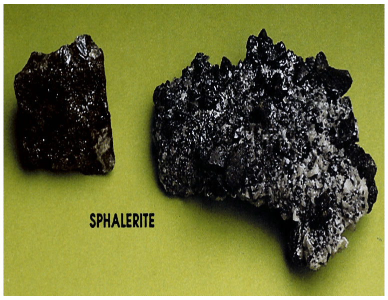
QUARTZ (crypto - crystalline varieties) SiO_2 *Mineral Group:* Tectosilicate

Variants: ***Agate*** *- curved banded colors: moss-like forms, bloodstone or heliotrope (small red spots in green chalcedony);* ***Carnelian*** *- red / flesh colored chalcedony ;* ***Chalcedony*** *- various colors, waxy luster;* ***Chert*** *- dull, opaque, light to dark, splintery fracture;* ***Chrysoprase*** *- deep green to apple green;* ***Flint*** *- opaque, dull, dark, white coating;* ***Jasper*** *- red brown to red yellow, dull, opaque ;* ***Onyx*** *- banded colors;* ***Prase*** *- dull green, translucent;* ***Sard*** *- brown chalcedony.*

Color: White to gray usually, almost all other colors. ***Cleavage:*** Indistinct cleavage, conchoidal fracture. ***Hardness:*** 7.0, brittle to tough. ***S.G.***: 2.5 - 2.8 g/cm^3 ***Luster:*** Vitreous to greasy. Also opaque. ***Crystals:*** Hexagonal. No crystals. Massive, botryoidal, banded, layered. ***Streak:*** White. ***Occurrence:*** Abundant, ubiquitous as cherts, chalcedony in veins and openings. Also as layers / bands in sedimentary rocks.

SPHALERITE ZnS (also contains Fe, Mn, Cd) *Mineral Group:* Sulphide

Color: Yellow, brown, black, red, some white. ***Cleavage:*** Perfect dodecohedral cleavage (six directions). Conchoidal fracture. ***Hardness:*** 3.5 - 4.0, brittle. ***S.G.***: 3.9 - 4.1 g/cm^3 ***Luster:*** Resinous to adamantine. Transparent to opaque. ***Crystals:*** Isometric. Tetrahedrons, dodecohedrons, cubes. Usually rounded crystals, massive, granular, some botryoidal. ***Streak:*** Brown to yellow to white. ***Other:*** Dissolve mineral powder in warm HCl and H_2S (rotten egg smell) is produced. Often fluoresces. ***Occurrence:*** Common and most important zinc mineral. Occurs in veins & replacement sulphide bodies. Associated with galena, pyrite, chalcopyrite and others.

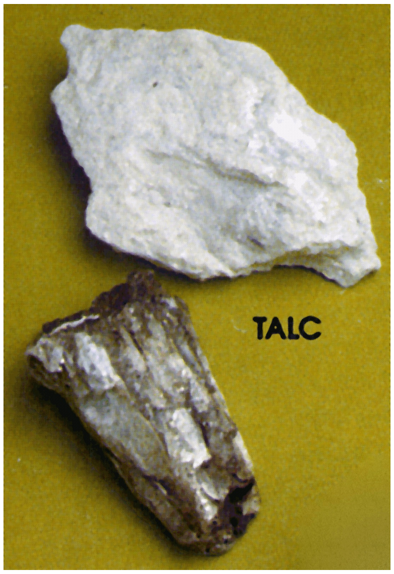


SULPHUR S *Mineral Group:* Native mineral

Color: Bright yellow. ***Cleavage:*** Poor cleavage. Conchoidal to uneven fracture. ***Hardness:*** 1.5 - 2.5, brittle. ***S.G.***: 2.1 g/cm^3 ***Luster:*** Resinous. Transparent to translucent, opaque. ***Crystals:*** Orthorhombic. Pyramidal, tabular, stalactic, massive. ***Streak:*** White. (Yes, it is NOT yellow!) ***Other:*** Melts in flame. Burns readily with sulphur odor and blue flame. ***Occurrence:*** Volcanic setting as incrustations, in sedimentary rocks, mainly limestones. In bituminous or sub-bituminous coal as yellow translucent globules. Associates: calcite, gypsum, anhydrite, aragonite, clay.

SYLVITE KCl *Mineral Group:* Halide
Color: Colorless to white, often tinted yellowish or reddish from impurities. ***Cleavage:*** Perfect cubic cleavage. Conchoidal fracture. ***Hardness:*** 2.0, brittle. ***S.G.***: 2.0 g/cm^3 ***Luster:*** Transparent to translucent and vitreous luster. ***Crystals:*** Isometric. Cubes with octahedrons, massive, compact. ***Streak:*** White. ***Other:*** Slippery feel, dissolves in water, bitter salty taste. ***Occurrence:*** Occurs in salt deposits, rarer than halite (NaCl).

TALC $Mg_3Si_4O_{10}(OH)_2$ *Mineral Group:* Phyllosilicate
Color: White, gray, green, brown. ***Cleavage:*** Micaceous cleavage. Flexible but not elastic layers, uneven or hackly fractures. ***Hardness:*** 1.0 - 1.5, sectile. ***S.G.***: 2.7 - 2.8 g/cm^3 ***Luster:*** Rarely transparent, mostly opaque with pearly to greasy luster ***Crystals:*** Monoclinic. Rare crystals. Mostly foliated or massive. ***Streak:*** White. ***Other:*** Soapy feel. Will NOT stick to tongue. ***Occurrence:*** Secondary mineral in metamorphic rocks mainly. Also in igneous rocks.



TOPAZ $Al_2SiO_4(F,OH)$ *Mineral Group:* Nesosilicate
Color: Mainly colorless. Also white, pale to amber yellow, brown. Rarely reddish, greenish or bluish. ***Cleavage:*** Perfect in one direction (basal cleavage), uneven fracture. ***Hardness:*** 8.0, brittle. ***S.G.***: 3.5 - 3.6 g/cm^3 ***Luster:*** Good vitreous luster, transparent to translucent. ***Crystals:*** Orthorhombic. Pointed prisms, striated columnar, and granular. ***Streak:*** White. ***Occurrence:*** Rare in pegmatites. More common in cavities of silicic volcanic extrusive rocks (rhyolites). Also in some metamorphic rocks and placers. Associated with fluorite, tourmaline and quartz.

TOURMALINE $Na(Mg,Fe,Li,Al,Mn)_3Al_6(BO_3)_3(Si_6O_{18})(OH,F)_4$ *MINERAL GROUP:* Cyclosilicate

COLOR: Black common, brown, also green, blue, red. May have zoned colors. Colored varieties are Schorl (black), Indicolite (blue), Dravite (brown), Brazilian Emerald (green), Rubelite (pink), Watermelon Tourmaline (Zoned: Red to pink inside with green outside rim) ***CLEAVAGE:*** No visible cleavage, uneven to conchoidal fracture. ***HARDNESS:*** 7.0 - 7.5, brittle. ***S.G.***: 3.0 - 3.2 g/cm^3 ***LUSTER:*** Transparent to opaque and vitreous luster. ***CRYSTALS:*** Hexagonal. Slender, vertically striated prisms with triangular cross section, also massive. ***STREAK:*** White. ***OCCURRENCE:*** Common mineral; usually In pegmatites, igneous rocks, and metamorphic rocks. Associates include quartz, feldspars, micas, topaz, beryl, apatite, and fluorite. Excellent gem quality crystals at Paris and Auburn, Maine; Pala, California; also in Minas Gerais, Brazil; Ural Mountains, Russia; and Madagascar.

2 IGNEOUS ROCKS

2.1 VOLCANIC (EXTRUSIVE) IGNEOUS ROCKS

Volcanic rocks solidify from a lava (magma) on the earth's surface and form lava flows. The rock which results from the crystallization of a lava is determined by the original composition and its cooling history. In contrast to a lava flow, a buried or partly buried magma, under high vapor pressure or its solidified equivalent may be explosively ejected into the air. The resultant broken fragments or breccia and fine particles fall through the atmosphere and form ash deposits such as *tuff,* or ash and fragmental material called *tuff breccia.* In certain types of volcanic eruptions, partly solidified magma with included gases and molten magma may blow out almost horizontally from a vent and form glowing avalanches or *ash-flows.* Some of these eruptions which are very violent in character may cover tens of thousands of square miles in a series of eruptions. In the rare case where a magma, or lava or ash flow, arrives on the surface and is very rapidly cooled, a *glass,* or *vitrophere* (if crystals are visible in the glass matrix) may result. If very rapid loss of vapor occurs from a magma and it also cools quickly, a frothy, glassy rock results and *pumice* forms. This may also be blown explosively into the atmosphere and fall to the earth and be incorporated into other volcanic material to form *pumice tuff breccias,* or if the explosively generative particles are sand size or less, a *pumicite* may form.

Table 2.1 - The More Abundant Minerals of Igneous and Sedimentary Rocks

Mineral	**Igneous Rocks**	**Sedimentary Rocks**
Feldspars	50 %	16 %
Quartz	21 %	35 %
Pyroxene, Amphibole, Olivine	17 %	-
Micas	8 %	15 %
Magnetite	3 %	-
Clay Minerals	-	9 %
Dolomite	-	9 %
Chlorite	-	5 %
Calcite	-	4 %
Hematite, Limonite	-	4 %
Others*	1 %	3 %

*Others may include: Titanite, Ilmenite for igneous rocks; and Apatite, Topaz, Zircon for sedimentary rocks.

2.2 PLUTONIC (INTRUSIVE) IGNEOUS ROCKS

More often, the magma does not reach the surface of the earth. In this environment it cools or solidifies below the surface in the host rock it has invaded or partly assimilated. Because of its much lower rate of heat loss in this setting, the crystallization process has more time, nucleation of crystals begin, seed minerals are able to grow larger, and the final solidified rock mass has a crystalline aggregate of minerals readily visible to the eye in a much finer-grained matrix. With longer cooling time, and possibly greater depth of the cooling magma below the surface, the mineral growth may finally be almost equigranular, medium to coarse-grained, and of *phaneritic* texture. These mineral crystals are called *phenocrysts* and the texture of the igneous rock is *porphyritic*. Thus, a rhyolite porphyry is a rock whose composition is very much like granite, but whose visible minerals are few to as much as 25% of the rock volume. The minerals include quartz and feldspar, the latter mainly of the orthoclase variety.

2.3 IDENTIFYING IGNEOUS ROCKS

The general color of the solidified igneous rock is not only a guide to its name, but also suggests the chemical composition, and in turn the minerals of the rock. The light colored or felsic rocks are made up of an abundance of quartz and feldspars, either megascopic (visible) or microscopic in size. Rhyolite and light-colored pumice and granite are in this group. The darker colored, more iron-rich, or mafic (magnesium- ferrum (Latin: Iron) rich) igneous rocks consist of the more calcium-rich feldspars and the magnesium-iron bearing biotite, amphiboles, pyroxenes, and olivine. These include extrusive basalts and the intrusive equivalent gabbro rocks of the crust. An intermediate colored and compositional group lies between the felsic and mafic groups. It includes the diorites and andesites, which are among the very abundant igneous rock types in the world.

The most simple classification of igneous rocks would be to describe them as light colored, medium-colored and dark-colored. In essence we do this by listing them as felsic, intermediate, and mafic, and even ultra-mafic. The classification thus denotes feldspar-silica-rich rocks, through those which are made up of increasing contents of magnesium, calcium, and iron to those which consist essentially of high content of iron-magnesium-calcium with low silica content. The textural characteristic of these rock groups indicates the crystallization history of the rock.

The classification chart of the igneous rocks (figure 2.1) includes the more important igneous rock types. It is based on texture,

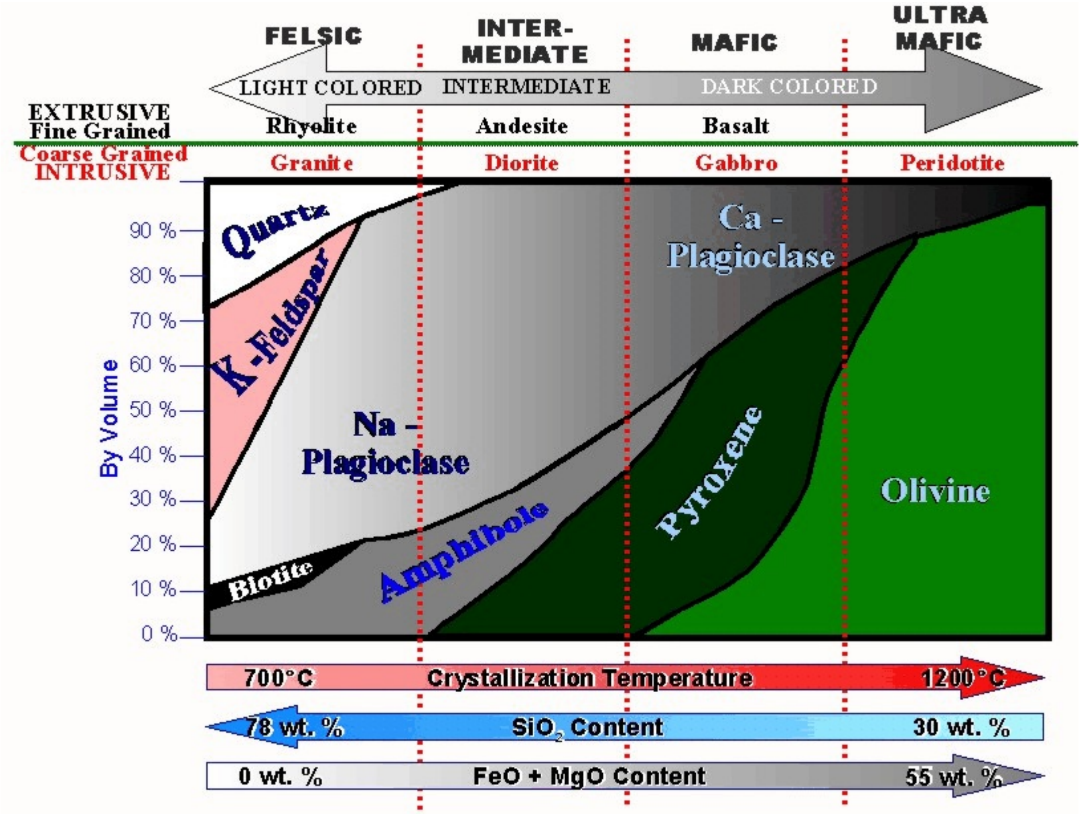


Figure 2.1- Classification chart of igneous rocks

or grain size of the included minerals (coarse grained = phaneritic = intrusive; fine grained = aphanitic = extrusive), color (light = felsic; dark = mafic), and mineral composition. If the visible minerals can be identified in the field, the naming of the rock is a relatively simple matter.

Table 2.2 - Igneous Rock ID Table

Texture	**Light Color**	**Intermediate Color**	**Dark Color**
Fragmental	Pumice, Tuff & Tuff Breccia		
Glassy & Phenocrysts	Obsidian - Vitropheres		
Aphanitic *(Rare Phenocrysts in very fine-grained matrix)*	Rhyolite	Andesite	Basalt *(Maybe smooth vesicular, ropy, amygdaloidal or breccia)*
Porphyritic *Fine-grained matrix*	Rhyolite Porphyry	Andesite Porphyry	Basalt Porphyry
Phaneritic *Somewhat equigranular*	Granite & Variants	Diorite	Gabbro, Peridotite
Pegmatitic	Pegmatites (Very coarse grained)		
	Mineralogy Essential Visible Minerals		
	Feldspar, Quartz some dark minerals (minor)	Feldspar (often with striations) 20% - 40% dark minerals	40% - 70% dark minerals Biotite, Hornblende, Pyroxene, Olivine, Magnetite

A simple classification matrix is given in table 2.2. To classify an igneous rock first identify the visible minerals, note the color of the rock, refer to the general position of this color on the igneous rock ID table, identify the column for the visible mineral composition, then find the row which best matches the texture of the rock. The chart block lists the rock name. As an example of the procedure, if the rock is light colored, has quartz and feldspar and minor biotite in a matrix of finer-grained or aphanitic material, and the phenocrysts comprise about 20 percent of the volume, the rock would be a rhyolite porphyry.

Another helpful aid in estimating percentages of minerals in a sample is the use of a percentage estimation chart as presented in figure 2.2.

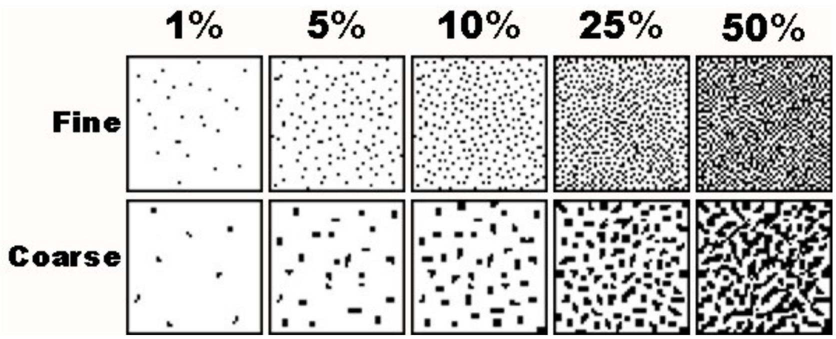


Figure 2.2- Percentage Estimation Chart

LAB EXERCISE 3 - IGNEOUS ROCK IDENTIFICATION

Name:	Course ID:

During this lab you are required to positively identify by name the igneous rocks given to you by your instructor and/or igneous sample sets using the procedure described under IDENTIFYING IGNEOUS ROCKS, especially table 2.2. You will complete the provided blank Igneous Rock ID Exercise Table in conjunction with your testing.

Materials needed:

- Professional Rock / Mineral Identification Kit (See above for ordering information)
- Set of Igneous Rocks included in the kit above
- Magnifying glass or hand lense (Included in kit)
- Table 2.2
- Figure 2.1
- Igneous Rock ID exercise tables
- Percentage Estimation Chart

Procedure:

1. Pick an unknown Igneous Rock sample from your kit (write down sample number or letter, if applicable). Follow the outline given under IDENTIFYING IGNEOUS ROCKS, especially in conjunction with table & figure 2.2. Write down the results in the blank Igneous Rock ID Exercise Table as you go.
2. Use a hand lense or magnifying glass to identify as many of the mineral grains and phenocrysts as possible.
3. Use two colors to complete the table. Mark in blue all the values you have obtained by your own measurements or observations. Write in black everything you have researched, copied or otherwise obtained by looking it up.
4. The fields above the *"IGNEOUS ROCK NAME"* row should be completed using ONLY OWN OBSERVATIONS / MEASUREMENTS.
5. The fields below the *"IGNEOUS ROCK NAME"* row should be completed using RESEARCH or FIGURE 2.1.

IGNEOUS ROCK ID EXERCISE TABLES

Name:____

Complete using 2 colors. Mark your own measurements in ***blue****. Mark researched or copied values in* ***black!***

PASTE IGNEOUS ROCK SAMPLE from KIT HERE: *(clear scotch tape)*								
Color: *light, intermed., or dark*								
Texture: *aphanitic, phaneritic, porphyritic, phenocrysts, etc.*								
Minerals: *list as many as you can identify and their estimated %*								
IGNEOUS ROCK NAME:								
Research	Intrusive / Extrusive:							
	Essential Minerals:							
	Accessory Minerals:							
	Approx. Silica content:							
	Approx. Formation Temp.:							

Make additional copies of this page if needed.

IGNEOUS ROCK ID EXERCISE TABLES **Name:**______________________________

Complete using 2 colors. Mark your own measurements in ***blue****. Mark researched or copied values in* ***black!***

PASTE IGNEOUS ROCK SAMPLE from KIT HERE: *(clear scotch tape)*							
Color: *light, intermed., or dark*							
Texture: *aphanitic, phaneritic, porphyritic, phenocrysts, etc.*							
Minerals: *list as many as you can identify and their estimated %*							
IGNEOUS ROCK NAME:							
Research: Intrusive / Extrusive:							
Essential Minerals:							
Accessory Minerals:							
Approx. Silica content:							
Approx. Formation Temp.:							

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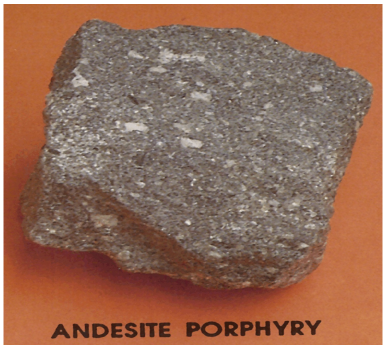
IGNEOUS ROCK DESCRIPTIONS

ANDESITE *Si-content:* ~ 60% *Rock Group:* Intermediate Extrusive Igneous Rock (Intermediate Color)

Texture: Aphanitic, porphyritic (common). ***Description:*** While phenocrysts are not abundant in this intermediate gray porphyritic rock, they are mainly of plagioclase. The mafic mineral content is relatively low and the matrix is dense of darker gray tone. The rock is part of a lava flow. ***Composition:*** The usual andesite contains more mafic minerals, usually hornblende with more or less biotite and/or augite. Calcium content slightly exceeds potassium and sodium content combined.

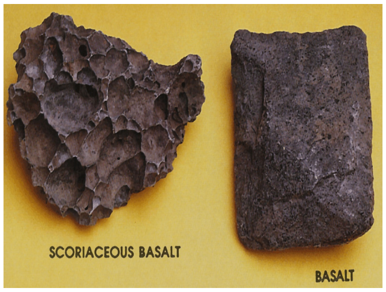
Major minerals: Plagioclase (Anorthite < 59%), Biotite
Minor minerals: Magnetite, Ilmenite, Quartz (<10%), Hornblende, Pyroxene
Occasional minerals: Orthoclase, Anorthoclase, Olivine



BASALT *Si-content:* ~ 50% *Rock Group:* Mafic Extrusive Igneous Rock (Dark Color)

Texture: Aphanitic, occasionally porphyritic. ***Description:*** A few ferromagnesian phenocrysts, mainly augite, in a dense, dark colored matrix. The increased density over the lighter colored igneous rocks is apparent. Vesiculation (gas bubble cavities) common due to accelerated escape of large quantities of gas during the rapid cooling of large lava flows (Scoriaceous Basalt). ***Composition:*** Normally basalt consists of dark gray plagioclase feldspar in a dark-colored matrix. Augite and olivine are commonly present, while hornblende and biotite are scarce. Some magnetite may be visible. Calcium oxide is about 10 percent, content of K and Na is less than 3 percent total. Weathering may produce Clay and Zeolites in vesicles.

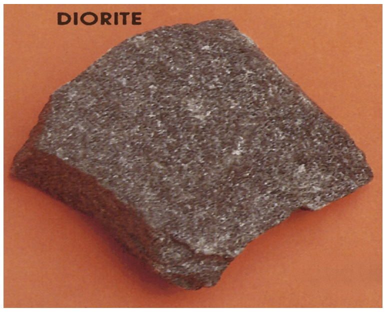
Major minerals: Plagioclase (Anorthite >50%), Pyroxene
Minor minerals: Glass, Olivine, Magnetite, Apatite, rarely quartz
Occasional minerals: Leucite, Nepheline, Sodalite, Mica (Phlogopite)



DIORITE *Si-content:* ~ 57% *Rock Group:* Intermediate Intrusive Igneous Rock (Intermediate Color)

Texture: Phaneritic (smaller grains). ***Description:*** Holocrystalline (all minerals are crystalline and visible to the unaided eye) often resulting in a "Salt & Pepper" appearance. Light to dark mineral content is about 65% / 35%. Composite color is usually dark grey. ***Composition:*** Hornblende is the dark mineral. Content of K_2O + Na_2O to CaO is about 5.5 / 6.7 % respectively.

Major minerals: Plagioclase (Anorthite < 50%), Hornblende
Minor minerals: Quartz (< 10%), Allanite (dark silicate containing Ce, Th, La, & Y), Ilmenite
Occasional minerals: Pyroxene, K-feldspar, Biotite



GABBRO *Si-content:* ~ 48% *Rock Group:* Mafic Intrusive Igneous Rock (Dark Color)

Texture: Phaneritic. Equigranular. ***Description:*** Dark gray to blackish brown color results from approximately 50% light and 50% dark mineral content. ***Composition:*** The lighter-colored minerals are mainly plagioclase feldspar, the dark minerals mainly pyroxene. Calcium oxide is about 11 percent, content of Na_2O + K_2O is about 1/3 that of the calcium in the rock.

Major minerals: Plagioclase (Anorthite >50%), Pyroxene
Minor minerals: Olivine, Magnetite, Apatite, rarely quartz
Occasional minerals: Leucite, Nepheline, Sodalite, Mica (Phlogopite)

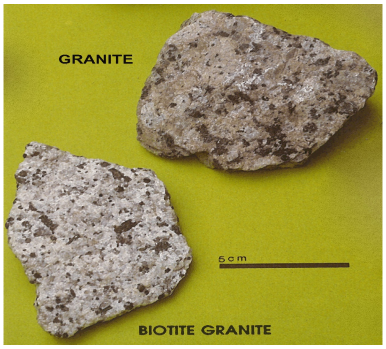
GRANITE *SI-CONTENT:* > 70% *ROCK GROUP:* Felsic Intrusive Igneous Rock (Light Color)

TEXTURE: Phaneritic. Equigranular. ***DESCRIPTION:*** Light to intermediate colors, generally grays to reds with a uniform mix of minerals. ***COMPOSITION:*** Quartz, Orthoclase feldspar, lesser Plagioclase, and even lesser ferromagnesian minerals. A *Biotite Granite* contains biotite. If black, elongate hornblende is visible, the granite is called a *Hornblende Granite*.

MAJOR MINERALS: Quartz, Potassium Feldspar (often pink)

MINOR MINERALS: Plagioclase, Mica, Hornblende

OCCASIONAL MINERALS: Magnetite, Ilmenite.



OBSIDIAN *SI-CONTENT:* variable *ROCK GROUP:* Volcanic Glass, Extrusive Igneous Rock (usually Dark Color)

TEXTURE: Volcanic glass with bright vitreous luster and very distinctive conchoidal fracture. ***DESCRIPTION:*** Formed as the result of sudden cooling or quenching of the original hot magma. Time for solidification was insufficient to permit crystal growth and glass is the final product. Reddish coloration is probably the result of hematitic iron content. Black obsidian may relate to dispersed, very fine-grained magnetite. ***COMPOSITION:*** Water content of obsidian is usually < 1%. Specific gravity ranges from 2.37 for rhyolitic obsidian to 2.77 for basaltic glass. Most natural glasses have a composition approaching the quartz-alkali feldspar cotectic.

MAJOR MINERALS: N/A

MINOR MINERALS: N/A

OCCASIONAL MINERALS: N/A

PEGMATITE *SI-CONTENT:* variable *ROCK GROUP:* usually Felsic Intrusive Igneous Rock (Light Color)

TEXTURE: Phaneritic. Very large crystals (inches to feet). ***DESCRIPTION:*** Usually light colors. Very large grain size, most commonly of granitic composition, but also known for gabbro. Simple pegmatites have a granite composition. The same is true for Layered pegmatites. Zoned pegmatites exhibit a concentric pattern with the core carrying unique assemblages of rare minerals. ***COMPOSITION:*** Large crystals of spodumene (Li bearing pyroxene), Amblygonite (Li bearing phosphate), Columbite-Tantalite (Ta, Nb rare earth oxide), and other rare earth minerals. Major minerals of pegmatites can reach incredible crystal dimensions of several feet.

MAJOR MINERALS: Quartz, Potassium Feldspar, Mica (usually Muscovite)

MINOR MINERALS: Tourmaline, Beryl, Zircon. Apatite, and other rare minerals.

OCCASIONAL MINERALS: N/A

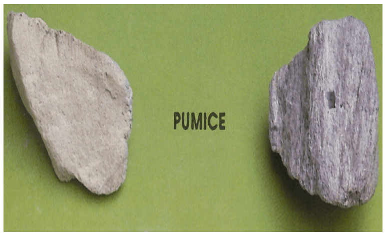
PUMICE *SI-CONTENT:* variable *ROCK GROUP:* usually Felsic Extrusive Igneous Rock (Light Color)

TEXTURE: Volcanic frothy glass. Under hand lens fine fibers surrounded by a multitude of open pores and vesicles visible. ***DESCRIPTION:*** Unique texture results from rapid escape of gas in a surface or near surface environment with extreme vesiculation and rapid cooling of the magma during the degassing period. The high pore space imparts a low specific gravity to the volume of rock which is known to float on water. Light colored, generally white to grayish brown. ***COMPOSITION:*** The oxide composition approaches that of rhyolite, but some is basaltic.

MAJOR MINERALS: N/A

MINOR MINERALS: N/A

OCCASIONAL MINERALS: N/A



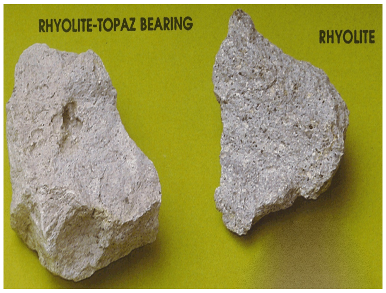
RHYOLITE *SI-CONTENT:* > 72% *ROCK GROUP:* Felsic Extrusive Igneous Rock (Light Color)

TEXTURE: Aphanitic. Sometimes with distinctive, conspicuous banding or layering, often intricately folded as a result of planar development in the cooling of the original lava. Gas may develop pore space within some rhyolites, which may contain minerals (Topaz common) ***DESCRIPTION:*** Dense matrix with minor phenocrysts of feldspar and quartz. Generally light in color in shades of gray, sometimes red. ***COMPOSITION:*** Next to SiO_2, ~13.5% Al_2O_3, $Na_2O + K_2O$ about 8%, 1% CaO.

MAJOR MINERALS: Quartz, Potassium Feldspar (Sanadine)

MINOR MINERALS: Glass, Biotite, Plagioclase (Albite), some Magnetite, Ilmenite

OCCASIONAL MINERALS: Topaz, Amphibole, Diopside.



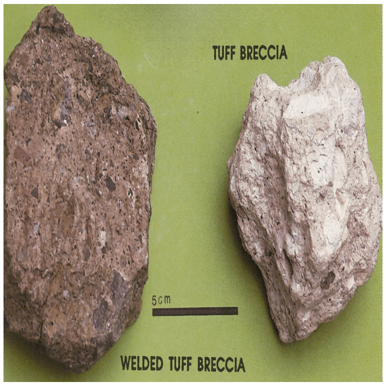
TUFF BRECCIA *SI-CONTENT:* variable *ROCK GROUP:* Volcanic Rock Fragments (variable)

TEXTURE: Angular lithic or rock fragments included in a dense matrix with broken phenocrysts. ***DESCRIPTION:*** Form from explosive ejecta from a main venting area in which solids, semi-molten magma, gas, and water are violently erupted as dense pyroclastic flows with velocities of 100 mph. Almost instantaneous geologic time areas extending for thousands of square miles are covered by these "glowing cloud" masses. Fragment size may range to inches in diameter and may be a function of distance from the explosive center. Coloration is light gray to moderately dark red. ***COMPOSITION:*** *Welded Tuff Breccia*: Solid, dense matrix of rock with volcanic fragments literally welded in place by rapid cooling. *Tuff Breccias:* resemble welded tuff breccias, but lack the dense, more solid matrix. Tuff breccias are quite friable, may powder and erode easily, and have a lower specific gravity.

MAJOR MINERALS: N/A

MINOR MINERALS: N/A

OCCASIONAL MINERALS: N/A



3 SEDIMENTARY ROCKS

Sedimentary rocks are derived from the weathering and erosion of preexistent rocks whether igneous, metamorphic, or sedimentary, or from a combination of these. Such an origin suggests a broad spectrum of composition for the sedimentary rock class. Rocks formed by sedimentary processes develop at or near the surface of the earth. Two major subclasses are recognized: (1) clastic-type sedimentary rocks and (2) chemical precipitates. A less abundant, though economically important organic plant accumulation such as peat, lignite and coal also occurs, as well as fossil animal deposits such as those made up of skeletons of invertebrates. The accumulation of sediments, chemical precipitates, organic deposits and evaporites by deposition is but a first stage of many which result in the final product we call a sedimentary rock. Burial, compaction, dehydration, induration, diagenetic changes and other processes are involved before a sediment can become a rock we can heft and classify.

3.1 CLASTIC SEDIMENTARY ROCKS

The clastic sedimentary rocks are derived from the erosion or weathering away of preexistent rocks. The small and large derived particles are transported by water, wind or ice to the site of deposition. The type of transporting agent to a large extent determines the texture and structure of the rocks formed. Ice is a very poor sorter of rock materials. As it melts and retreats it leaves behind aggregates of fine and coarse particle sizes all heterogeneously arranged. If this sedimentary material is buried, consolidated, and indurated, the rock product formed is called tillite.

Wind is at the other extreme and is a very good sorting agent. Only the finer particles are transported and deposited by this medium and even these are well- sorted by the wind currents. Fine-grained sands, silts and even finer clay particles are part of the sediment load which is deposited. The burial, compaction and induration of these fine-grained sediments produces sandstones, siltstones, and shales. The massive cliffs of Zion National Park, Utah are a striking example of wind deposited sandstones with their conspicuous internal cross-layered structures.

Stream water, one of the main erosional and transporting media, mechanically erode particles of rock, carries them in suspension and as bed load, and redeposit them in the same or a different environment. As an example, it has been estimated that 500,000,000 tons of dissolved and clastic material are carried into the Gulf of Mexico by the mighty Mississippi River each year. A stream is potentially able to carry in suspension and traction an amount of sediment equivalent to the energy available to stream flow. The greater the velocity of the stream, the larger the amount of sediment transported and also the larger the particle size carried and later deposited.

Lake waters and ocean basins are also very important agents in the formation of sedimentary rocks. Within such basins large quantities of fine-grained sediments can be deposited through streams carrying the sediments into the lakes and these waters dispersing the particles across the lake floors. Similarly in the oceans, sediments from the land through stream transport and also from wave erosion and current transport result in extensive clastic deposits.

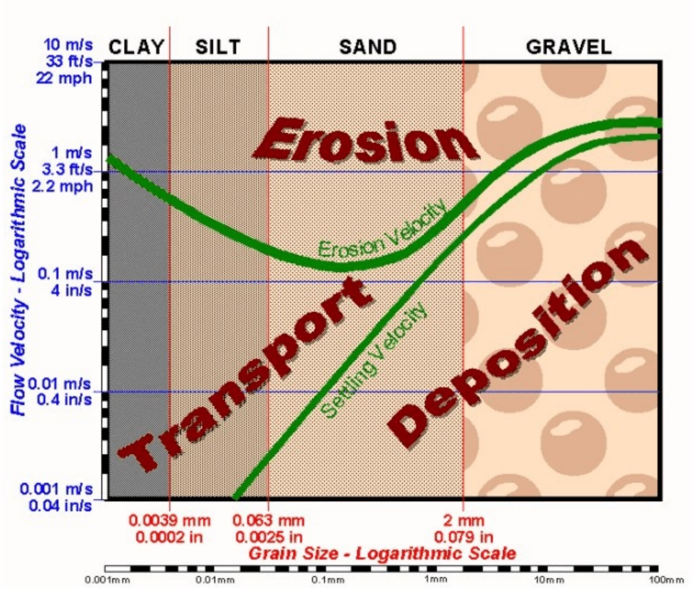


Figure 3.1- Modified Hjulstrom diagram showing sediment transport velocities in relation to erosion & deposition

3.2 CHEMICAL SEDIMENTARY ROCKS

Large quantities of the chemical weathering products of rocks are transported in solution in water. These are not mechanical or visible particles, but dissolved material in the water and invisible to the eye. They are part of the surface waters of the earth. Material in solution in stream waters is estimated at about 30% of the stream load. If this applies to the Mississippi River, about 150.000,000 tons per year of dissolved matter is carried to the Gulf of Mexico each year. The total probably exceeds this amount.

To gain a better grasp of the quantity of this dissolved material in the rivers, it would be the equivalent of 1,500,000 freight cars carrying 100 tons each year or about 4,000 per day, or 166 per hour passing a set point near the mouth of the river and chemically adding this large quantity to the waters of the Gulf. It is obvious that the amount of material in solution transported by the rivers of the world is prodigious. In both lacustrine and marine environments chemical precipitates can form. Witness the extensive marine limestone of the mountains and plains area and the great saline deposits of New Mexico, Kansas, Michigan, New York and elsewhere-the result of both extensive chemical and evaporative processes in ancient seaways.

The minerals calcite and dolomite are chemical precipitates of calcium and magnesium carbonates. These may result from direct chemical precipitation from water or be precipitated by organic processes in a marine environment, such as secretions by corals or clams. In some cases, large calcareous skeletons, such as shells, accumulate to form coquina, a type of sedimentary rock.

Chert which is a locally abundant siliceous rock may result from the accumulation of great quantities of siliceous shells of certain planktonic life forms or be a chemical precipitate from water.

A third, and locally economically important subclass of chemical precipitates are the evaporites or salt deposits. These are the residues from the evaporation of sea or lake waters. They consist mainly of sodium chloride, or salt, gypsum and anhydrite. Much rarer are the trona, sodium bicarbonate deposits, and the borates which include borax, ulexite and other borax-bearing bodies.

Peat and lignite are formed from the compaction and chemical changes on organic accumulations of plant materials. These are plant fragments which have been uniquely preserved from erosion and decay in special sedimentary environments such as swamps, some lagoons, and even some unusual stream areas.

3.3 CLASSIFICATION & IDENTIFICATION OF SEDIMENTARY ROCKS

Clastic sedimentary rocks are classified according to particle size into gravels and breccias of greater than 2 mm in diameter, sand 2 mm down to 1/16 mm, silts 1/16 - 1/256 mm, and as clay or mud for those which are less than 1/ 256 mm in diameter. The particle size also suggests an energy environment for the sedimentary deposits. Sorting and roundness of grains is also helpful in deciphering the transport history and the environment of deposition of grains (see figure 3.2).

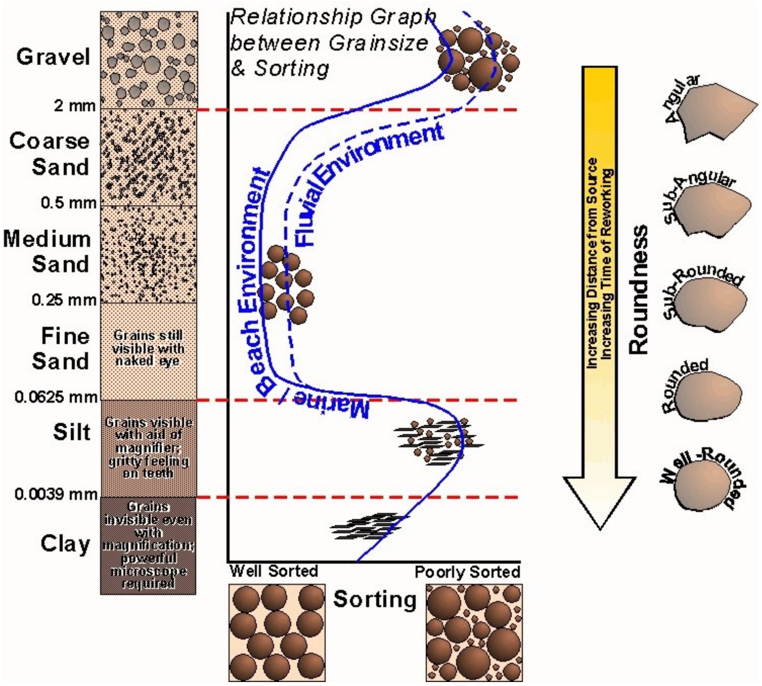


Figure 3.2 - Grainsize, rounding and sorting chart for clastic sediments. (Relationship graph modified after Folk, R.L., 1980, Petrology of Sedimentary Rocks)

In short, the following transport and depositional assumption usually apply:

Grain size:
Small grains - low velocity, quiet depositional environment
Large grains - high velocity, high energy depositional environment

Rounding:
Angular - short transport
Well-rounded - long transport

Sorting:
Poorly sorted - fluctuating transport energies, usually short transport
Well sorted - uniform transport energies, usually longer transport

Organic and chemical sedimentary rocks do not lend themselves to the ready classification of the clastic subclass. In many classifications the type of origin is often used.

In order to distinguish between clastic and chemical sedimentary rocks, the following approximate flow chart (figure 3.3) might be helpful.

Once clastic or chemical / organic sedimentary rocks are distinguished, classification table 3.1 can be used to identify sedimentary rock types. It is based on texture, cement, and composition.

1. Step: Identify Clastic or Chemical / Organic rock (figure 3.3)

2. Step: Identify *"Main Constituents"* in the rock (table 3.1)

3. Step: Identify the *"Texture"* of the rock (figure 3.2 & table 3.1)

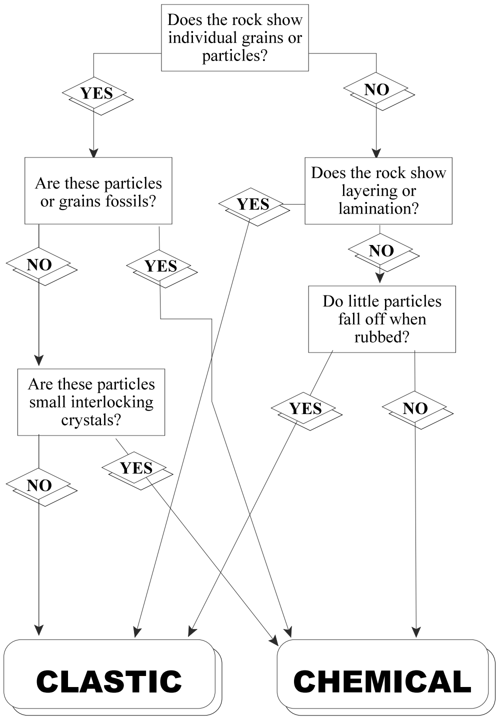
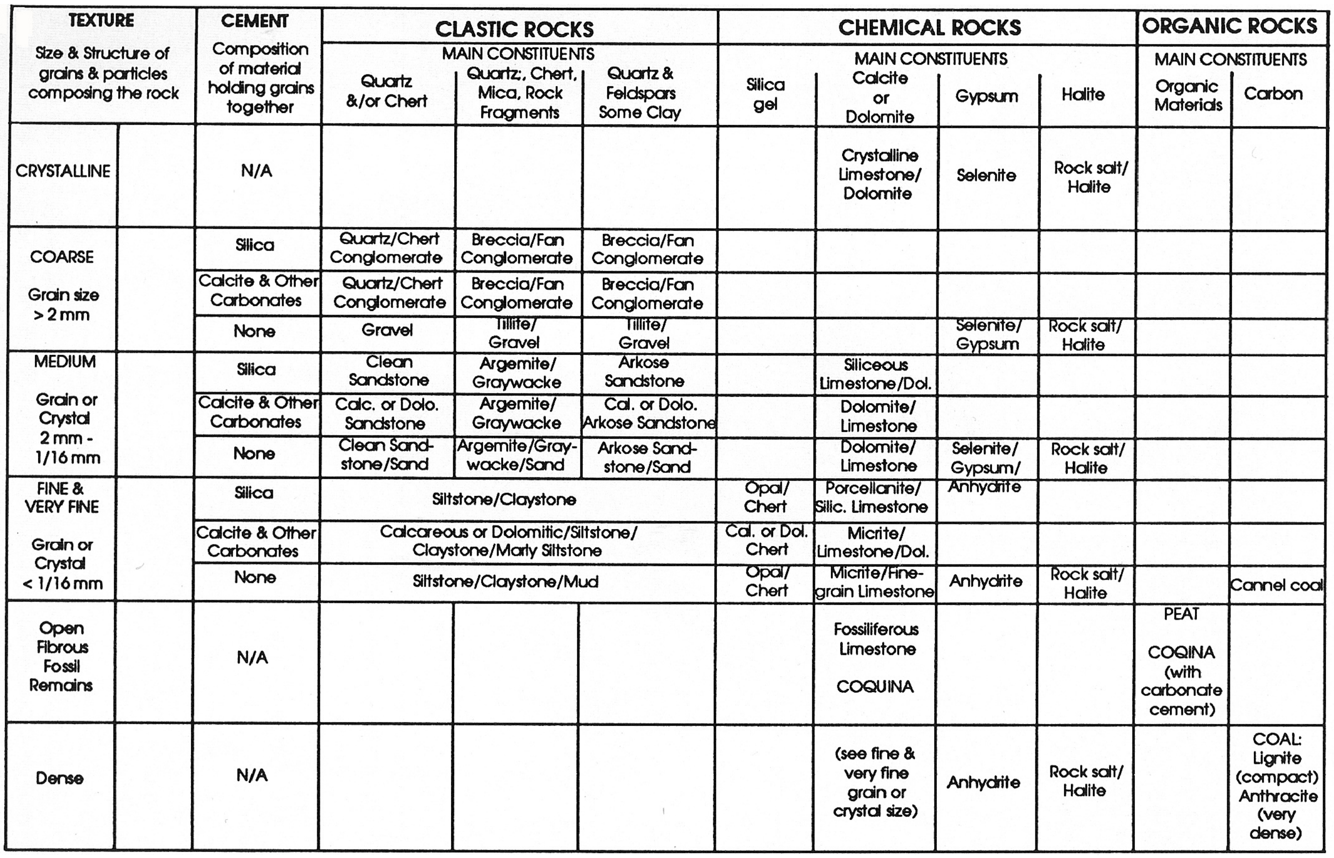


Figure 3.3 - Clastic / Chemical Sedimentary Rock ID flowchart

Table 3.1 - Classification of common sedimentary rocks



TEXTURE Size & Structure of grains & particles composing the rock		CEMENT Composition of material holding grains together	CLASTIC ROCKS			CHEMICAL ROCKS				ORGANIC ROCKS	
			MAIN CONSTITUENTS			MAIN CONSTITUENTS				MAIN CONSTITUENTS	
			Quartz &/or Chert	Quartz;, Chert, Mica, Rock Fragments	Quartz & Feldspars Some Clay	Silica gel	Calcite or Dolomite	Gypsum	Halite	Organic Materials	Carbon
CRYSTALLINE		N/A					Crystalline Limestone/ Dolomite	Selenite	Rock salt/ Halite		
COARSE Grain size > 2 mm		Silica	Quartz/Chert Conglomerate	Breccia/Fan Conglomerate	Breccia/Fan Conglomerate						
		Calcite & Other Carbonates	Quartz/Chert Conglomerate	Breccia/Fan Conglomerate	Breccia/Fan Conglomerate						
		None	Gravel	Tillite/ Gravel	Tillite/ Gravel			Selenite/ Gypsum	Rock salt/ Halite		
MEDIUM Grain or Crystal 2 mm - 1/16 mm		Silica	Clean Sandstone	Argemite/ Graywacke	Arkose Sandstone		Siliceous Limestone/Dol.				
		Calcite & Other Carbonates	Calc. or Dolo. Sandstone	Argemite/ Graywacke	Cal. or Dolo. Arkose Sandstone		Dolomite/ Limestone				
		None	Clean Sand-stone/Sand	Argemite/Gray-wacke/Sand	Arkose Sand-stone/Sand		Dolomite/ Limestone	Selenite/ Gypsum/ Anhydrite	Rock salt/ Halite		
FINE & VERY FINE Grain or Crystal < 1/16 mm		Silica	Siltstone/Claystone			Opal/ Chert	Porcellanite/ Silic. Limestone				
		Calcite & Other Carbonates	Calcareous or Dolomitic/Siltstone/ Claystone/Marly Siltstone			Cal. or Dol. Chert	Micrite/ Limestone/Dol.				
		None	Siltstone/Claystone/Mud			Opal/ Chert	Micrite/Fine-grain Limestone	Anhydrite	Rock salt/ Halite		Cannel coal
Open Fibrous Fossil Remains		N/A					Fossiliferous Limestone COQUINA			PEAT COQINA (with carbonate cement)	
Dense		N/A					(see fine & very fine grain or crystal size)	Anhydrite	Rock salt/ Halite		COAL: Lignite (compact) Anthracite (very dense)

3.4 ENVIRONMENT OF DEPOSITION

In the investigation of the earth's history, sedimentary rocks are the ultimate story tellers. By being observant, one cannot only estimate under what prehistoric conditions the rock was deposited, it is also possible to tell climate characteristics, distance from the source rock, and many other useful features. If one finds a sandstone containing clam shell fossils, it is easy to surmise that we are looking at an ancient beach. A limestone full of corals indicates warm, tropical shallow oceans. Coal seams point toward swamps with massive amounts of dead plant detritus. Sometimes features in the rock unit itself pinpoints the environment. Ripple marks in sandstone point to flowing or agitated water. In fact, even ancient stream directions maybe derived from such keen observations. The following figure 3.4 might be helpful in deciphering the story behind the rocks.

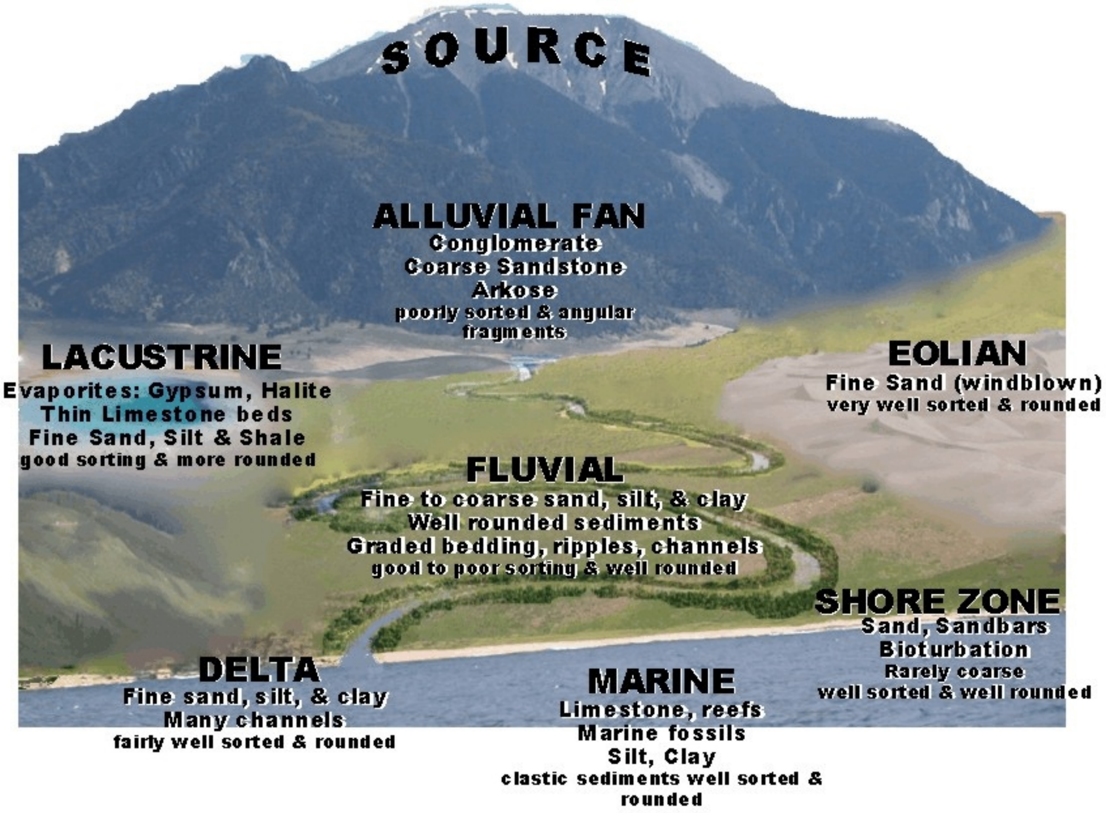


Figure 3.4 - Common depositional environments with simplified sedimentary rock types & features

LAB EXERCISE 4 - SEDIMENTARY ROCK IDENTIFICATION

Name:	Course ID:

During this lab you are required to positively identify by name all sedimentary rocks given to you by your instructor and/or sedimentary sample sets using the procedure described under CLASSIFICATION & IDENTIFICATION OF SEDIMENTARY ROCKS, especially table 3.1. You will complete the provided blank Sedimentary Rock ID Exercise Table in conjunction with your testing.

Materials needed:

- Professional Rock / Mineral Identification Kit (See above for ordering information)
- Set of Sedimentary Rocks included in the kit above
- Hand lense included in kit.
- Table 3.1
- Figure 3.2
- Figure 3.3
- Sedimentary Rock ID exercise table

Procedure:

1. Pick an unknown Sedimentary Rock sample from your kit (write down sample number or letter, if applicable). Follow the outline given under CLASSIFICATION & IDENTIFICATION OF SEDIMENTARY ROCKS, especially in conjunction with the provided table & figures. Write down the results in the blank Sedimentary Rock ID Exercise Table as you go.
2. Use two colors to complete the table. Mark in blue all the values you have obtained by your own measurements or observations. Write in black everything you have researched, copied or otherwise obtained by looking it up.
3. The fields above the *"SEDIMENTARY ROCK NAME"* row should be completed using ONLY OWN OBSERVATIONS / MEASUREMENTS.
4. The fields below the *"SEDIMENTARY ROCK NAME"* row should be completed using RESEARCH.

SEDIMENTARY ROCK ID EXERCISE TABLES

Name:____

Complete using 2 colors. Mark your own measurements in ***blue****. Mark researched or copied values in* ***black!***

PASTE SEDIMENT. ROCK SAMPLE from KIT HERE: *(clear scotch tape)*								
Clastic, Chemical, or Organic:								
Main Constituents: *list as many as you can identify and their estimated %*								
Texture: *next to size, include also roundness, sorting, and reaction with acid*								
SEDIMENTARY ROCK NAME:								
Research	Transport history:							
	Environment of deposition:							

Make additional copies of this page if needed.

SEDIMENTARY ROCK ID EXERCISE TABLES
Name:____

*Complete using 2 colors. Mark your own measurements in **blue**. Mark researched or copied values in **black!***

PASTE SEDIMENT. ROCK SAMPLE from KIT HERE: *(clear scotch tape)*								
Clastic, Chemical, or Organic:								
Main Constituents: *list as many as you can identify and their estimated %*								
Texture: *next to size, include also roundness, sorting, and reaction with acid*								
SEDIMENTARY ROCK NAME:								
Research	Transport history:							
	Environment of deposition:							

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SEDIMENTARY ROCK DESCRIPTIONS

CHERT *ROCK GROUP:* Chemical/Biological Sedimentary Rock

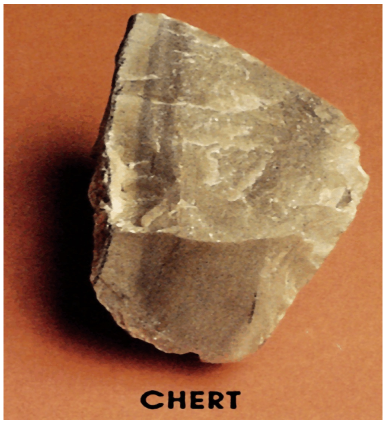
TEXTURE: Brownish gray, slight1y banded, crypto crystalline silica. Hardness of 7. Chonchoidal to splintery fracture.

ENVIRONMENT OF DEPOSITION:.As bands, beds, layers or nodules in other sedimentary units. See Formation History.

FORMATION HISTORY: Theories proposed for the origin of cherts include: 1) chemical sediment precipitate, 2) volcanic activity and silica release to ocean waters and later deposition, 3) normal sediment from activity of silica-secreting organisms and precipitation as a sediment.

RESISTANCE TO EROSION: Usually very high. Would make impressive ledges, but usually too thin.

COMPOSITION: Made entirely of silica (Quartz). Will scratch glass. Often used as arrow head material by aborigines. May also spark when struck together (flint).



COAL *ROCK GROUP:* Chemical/Biological Sedimentary Rock

TEXTURE: Various textures from the fibrous organic matter of the pre-coal stage (peat) to the rich, black coal with vitreous luster and conchoidal fracture.

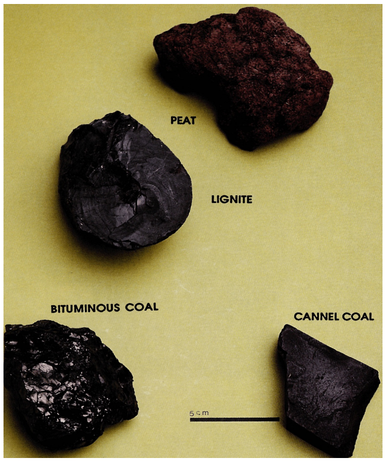
Peat	- fibrous plant material (peat moss). Pre-coal stage.
Lignite	- brown coal. Retains organic materials, lacks porosity of peat.
Bituminous	- Black, glossy or dull, finely granular to homogenous

ENVIRONMENT OF DEPOSITION:.Swamps, tropical swamps, peat bogs.

FORMATION HISTORY: Coal formation begins with peat, which is compacted into lignite and upon deeper burial processes into bituminous coal and eventually the high quality anthracite, also called king of coals.

RESISTANCE TO EROSION: Not very high. Coal is soft, but it is astonishingly resistant to chemical erosion.

COMPOSITION: Made of organic plant materials which are changed into carbon over time. Bituminous coal may include small nodules of yellow sulfur. All coals are known to contain abundant plant fossils.



CONGLOMERATE *ROCK GROUP:* Clastic Sedimentary Rock

TEXTURE: Coarse grained, poorly sorted, rounded particles in matrix of finer grains.

ENVIRONMENT OF DEPOSITION: Close to source. Alluvial fans. Mountain streams of youthful geomorphologic stage. Layers in river sediments during high energy transport events.

TRANSPORT HISTORY: Rounding of grains suggests transport in water.

RESISTANCE TO EROSION: Usually high when cemented. Ledge former common.

COMPOSITION: Larger particles can be any rock type (sedimentary, igneous, metamorphic) of some resilience. Finer material often sand or silt. Arkose common.

DOLOMITE

Rock Group: Chemical/Biological Sedimentary Rock

Texture: Finely crystalline, dull luster. This rock looks like limestone but is a calcium / magnesium carbonate and will not react with acid unless powdered or hot acid is used. It is very often mistaken for limestone and even trained geologists have been fooled, mapping whole dolomite rock units as limestone, because a quick and simple acid test was not applied.

Environment of Deposition:.Dolomite is believed to replace Limestone over time through secondary alteration. Some evidence suggests that primary dolomite may occur from biochemical activity. Dolomite is very common. The most notable occurrence is in the Alps where whole mountain ranges (The Austrian / Italian Dolomites) are comprised of the carbonate.

Formation History: Result of the dolomitization of limestone. The process may occur during or soon after sedimentation or later after rock is completely solidified. May also result from hydrothermal (hot water) alteration near plutonic igneous rocks.

Resistance to Erosion: Usually high. Ledge former.

Composition: Made of dolomite - $(Ca,Mg)CO_3$. Reaction with acid is almost imperceptible. Will effervesce when dolomite is powdered or hot acid is applied.

GYPSUM

Rock Group: Chemical/Biological Sedimentary Rock

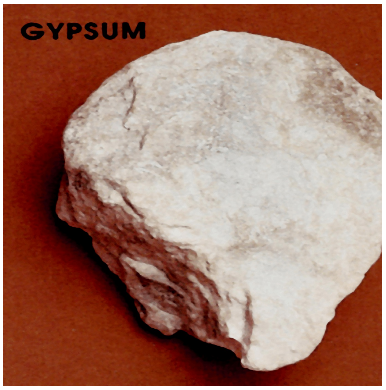
Texture: Usually white to gray, finely crystalline. May show fine to coarse-layering, sometimes intricately folded. Some texture and properties as the mineral gypsum.

Environment of Deposition:.Typical evaporite deposit indicating hot & dry paleo-conditions. Forms sedimentary beds of wide areal extent. Well-layered, often thin to massive-bedded with thicknesses of up to 100 feet, but generally much less.

Formation History: Water from mountain run-off may collect in salt flats, pans, or shallow flood areas in hot climates where it quickly evaporates. If the concentration of calcium and sulfate ions in water is high enough, gypsum will precipitate.

Resistance to Erosion: Very soft. Erodes easily.

Composition: Made of the mineral gypsum. Very soft, can be scratched by fingernail (H:2). Finds extensive use in the building trade, being a major component of plaster and sheet rock.



LIMESTONE

Rock Group: Chemical/Biological Sedimentary Rock

Texture: Dense to grainy to crystalline to fossil bearing.

Crystalline Limestone - medium to coarse-grained, tannish cream, uniform
Coquina - clastic limestone made entirely of mainly shells.
Fossiliferous Limestone - contains abundant fossils &/or fossil fragments
Lithographic Limestone - compact, very fine & even-grained, tannish cream
Oolitic Limestone - comprised of small, somewhat spherical particles
Travertine - hot spring deposit, often banded

Environment of Deposition: Often marine deposits within the Limestone facies (e.g. coral reefs), but can also form in fresh water (e.g. stromatolitic), or in hot springs (travertine) or evaporite deposit.

Formation History: Commonly secreted by biological organisms (shells, clams) & microorganisms. Chemical formation occurs around mineral springs, in evaporite settings or for oolitic limestone.

Resistance to Erosion: Usually high in dry climates, where it can form ledges. Erodes easily in wet areas or environments exposed to acid. Cave formation very common.

Composition: Made predominantly of calcite or aragonite. Often intermixed with some dolomite. Limestones will effervesce with acid.

MUDSTONE, CLAYSTONE, SHALE

Rock Group: Clastic Sedimentary Rock

Texture: Grains are invisible to the naked eye or magnifying glass and are smaller than 1/256 mm.

Shale - shows laminations
Mudstone or Claystone - massive

Environment of Deposition: Very low energy environment, such as quiet flood plains, lake bottoms or deep oceans.

Transport History: Usually transported in water. Deep marine sediments (red clays) are windblown from continents into the oceans.

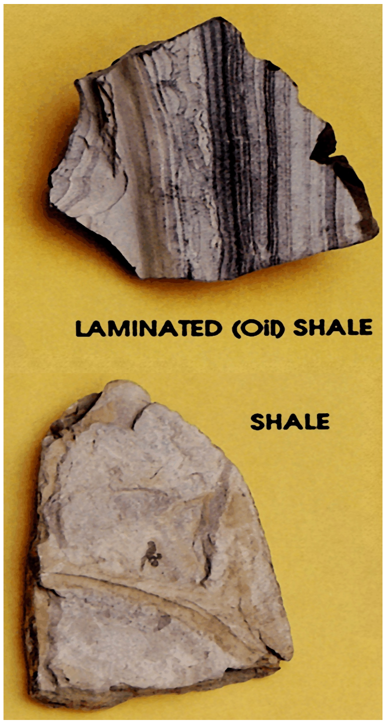
Resistance to Erosion: Very low. Forms extensive valleys or slopes.

Composition: Impossible to determine without instrumentation. The average mudstone contains about 30 % quartz and slightly more clay minerals. The other third is made up of other minerals including carbonates, feldspars, iron oxides and organic matter. Generalizations about mudstone composition can be made by simple tests or observations:

Black shale - high carbon content, frequently in the form of kerogen (hydrocarbons), thus often called "oil" shale. Much research has been done to effect an economic recovery of oil from these rocks, of which the higher content shales carry as much as 25-100 gallons / ton.

"Popcorn" weathering - a popcorn like appearance of the weathered clay or mudstone indicates the presence of the mineral bentonite, a swelling clay. Bentonite forms from the decomposition of volcanic ash.

Marl - Claystone or shale that contains calcite, hence it will effervesce with acid.



SANDSTONE

Rock Group: Clastic Sedimentary Rock

Texture: Grains are sand size, ranging from 1/16 mm for very fine sand to 1 mm for coarse sand.

Environment of Deposition: Varied. Ancient beaches, sand dunes, river channels and sandbars. Bedding, layering, or varving may occur.

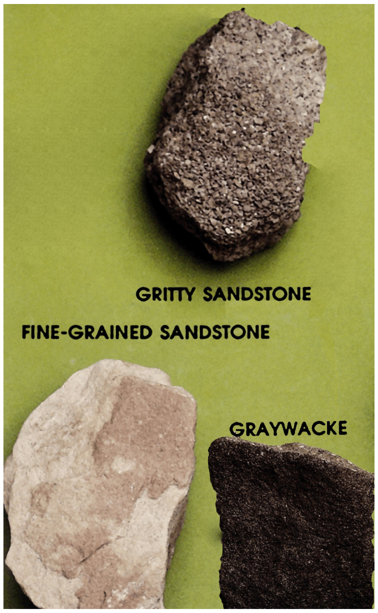
Transport History: Usually transported in water. Very well sorted sandstone often indicative of aeolian (wind) environment.

Resistance to Erosion: Usually high when cemented. May form ledge or hogbacks.

Composition: Varied. Common sandstone variations are named as:

Arenite - clean sandstone, predominantly quartz, with < 10% clay in matrix
Arkose - sandstone rich in K-spar
Litharenite - contains mainly fragments of preexisting rock.
Wacke - sandstone with 10% - 50% clay content

More than 60% of mineral grains in sandstone are usually quartz. Presence of accessory minerals augite, chromite, ilmenite, or topaz grains are indicative of igneous source rock. Grains of actinolite, andalusite, diopside, epidote, garnet, kyanite, rutile, sillimanite, staurolite or tremolite point to a metamorphic source. Greenish glauconite (mica) grains in sandstone are interpreted as having originated as marine fecal pellets.



SILTSTONE *Rock Group:* Clastic Sedimentary Rock

Texture: Grains are very small and range in size from 1/32 mm to 1/256 mm, about the size of very fine sandpaper, often outside the visible range. Siltstone will feel gritty on teeth, while shale or mudstone will be smooth (finer grains).

Environment of Deposition: Low energy environments such as lake beds, river deltas, flood plains, continental shelves or submarine basins. Fine scale bedding permits the use of "laminated" to be added to the rock name. Siltstones are part of the red-bed series of the Colorado Plateau.

Transport History: Transported in water.

Resistance to Erosion: Usually low, forms valleys or slopes. Occasional protruding siltstone ledges may occur when well cemented.

Composition: Difficult to determine visually because of small particle size. Instrumentation required. Intermixing with clay or mudstone customary. Quartz is a probable common component.

4 METAMORPHIC ROCKS

Have you observed what happens to various substances when heat is applied or when other components are mixed with the original substance and heat is applied? The material may change in form. It may become more fluid and tend to flow, or it may combine with the added components and form a new solid substance. In nature rocks behave in a somewhat similar fashion. Given a certain rock type, the addition of heat and/or pressure of increasing intensity over a period of time plus the presence or addition of fluids to this environment causes the rock to adjust to these new conditions. A new equilibrium is established through the formation of more stable minerals. How much change in form occurs is dependent on the magnitude of the stress and temperature and the reaction of the fluid components, and the duration of the reaction time. Simple rocks such as shale, a sedimentary rock mainly composed of clay minerals and some quartz, maybe radically changed. The end product is a metamorphic rock, often completely different in appearance. It may become a phyllite, a rock much hardened and with a visible sheen of micaceous minerals developed within it. Under stress the original shale may be converted to a slate. Where once the shale broke along bedding planes, now the rock parts along cleavage planes, often completely different from the still visible bedding planes of the shale. Under the microscope one can observe the orientation of minute mineral grain parallel to this new breaking of cleavage surface. With even greater heat and stress the original shale may be changed to a schist, a metamorphic rock with clearly visible foliation planes and platy minerals aligned parallel to the schistose structure. Under extreme heat and pressure all of the components of the rock may be reorganized, even flowage may occur, and dark and light minerals tend to segregate together to form a banded-rock called a gneiss.

As in the case of the origin of the deeply burled igneous rocks, we have no way of observing these changes as they occur. We must base our conclusions on field observations and the inferred conditions of temperature and pressure. Fortunately, abundant and well-controlled laboratory experiments have been performed which permit well-documented conclusions as to the effects of temperature, pressure and fluids on various rock materials and the end products produced. The development of the ultrahigh pressure tetrahedral press by Tracy Hall and his associates have resulted in productive research at pressure more than 1,000,000 PSI and at temperatures up to 1500 degrees Centigrade.

Two stress environments for metamorphic rocks are recognized: 1) static or load metamorphism under elevated temperatures, and 2) dynamic stress environment with increased temperature. A third environment of metamorphism is that of increased temperature. The latter may act on the rock in both stress environments and locally only as heat near a cooling magmatic body. Figure 4.1 displays a temperature and pressure diagram with related metamorphic classes, rock types and type minerals.

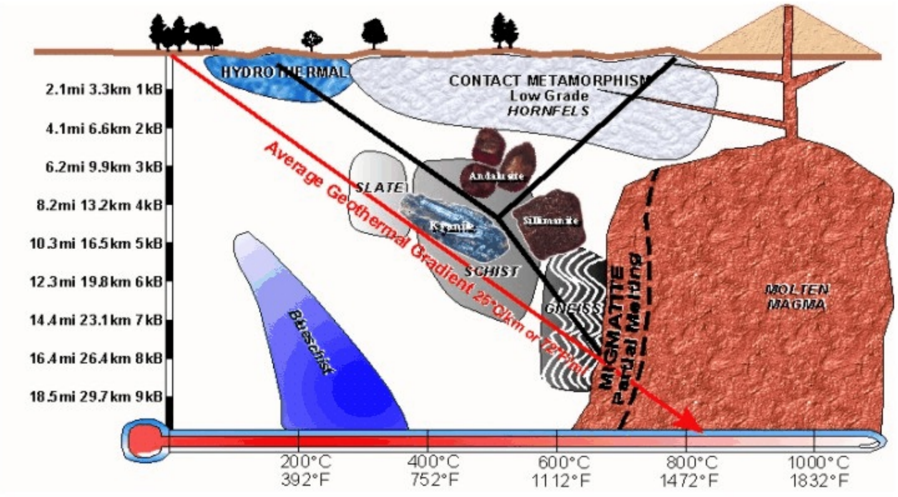


Figure 4.1 - Temperature / Pressure Diagram for metamorphic environments and most common rock types

With these factors operating in nature, certain visible changes are wrought by metamorphism. The constituents of the rock may be completely reorganized to form a new more stable mineral assemblage. Grain size of the minerals is generally increased with a resultant coarser texture. The internal structure of the rock may change, and commonly a parallel arrangement of the constituent minerals may take place. In many cases the overall composition of the rock may remain the same, while in others constituents are lost or others added. The terms non-additive and additive metamorphism have been given to these processes.

Because the metamorphic processes take place at high pressure and high temperature, many of the minerals which form are also common to igneous rocks. Table 4.1 includes those minerals common in metamorphic rocks. Figure 4.2 indicates a simplified mineralogy according to grades of metamorphism or their temperature - pressure relationship of formation. While additional factors influence the mineralogy, such as the presence or absence of water as well as of certain protolithic minerals, a general trend can be observed. Mineral assemblages in metamorphic rocks therefore serve as a geo-thermometer and/or geo-barometer indicative of the forces and conditions present in the formation of certain metamorphic rocks.

Table 4.1 - Common Minerals in Metamorphic Rocks with most likely Rock Hosts

Actinolite	S - M	Biotite	S - G	Calcite	M
Chlorite	Sl - Phy - S	Dolomite	M	Feldspar varieties	G - S - CM
Garnet	S - CM	Hematite	S - CM	Hornblende	G - S
Kyanite	S	Magnetite	CM - S - G	Muscovite	Sl - Phy - S
Olivine	M - Eclogite	Pyrite	widespread	Quartz	S - G- Q
Staurolite	S	Talc	S	Tremolite	S - M

G = Gneiss, S = Schist, Q = Quartzite, Sl = Slate, Phy = Phyllite, CM = Contact Metamorphic, M = Marble

4.1 TEXTURE OF METAMORPHIC ROCKS

Recognition and naming of a metamorphic rock requires identification of the major minerals and the textures and structures present. The list of minerals includes most of those common to this rock class. The processes of metamorphism generally produce increase in mineral size, whether by recombination of elements and new mineral development, or by simple crystal growth of preferred minerals. Distinct differences in textures of igneous, sedimentary and metamorphic rocks exist. For most metamorphic rocks crystals are readily visible, and while somewhat interlocked form a mosaic often with rough to well-developed layering characteristics. Some minerals tend to develop good crystal form and are called *idioblastic* with bounding crystal faces. *Xenoblastic* crystals are those without crystal form. A *porphyroblast* is a crystal much larger than the matrix and may contain other mineral inclusions. It is of late stage development in contrast to phenocrysts of igneous rocks which are formed early in the crystallization process. Porphyroblasts may lie athwart the general internal structures of the rock or may show structures bending around them, as if deformed by the developing mineral.

4.2 STRUCTURES OF METAMORPHIC ROCK

Three types of structures are recognized in the metamorphic rock class: 1) planar-parallel planes or flat surfaces of minerals parallel or roughly so; 2) a series of linear or line-like features, such as elongate minerals parallel in their long direction which may or may not lie within the planar structure; 3) massive linear or planar features not visible. One or more of these may be used in the naming of the metamorphic rock.

4.3 CLASSIFICATION AND NAMING OF METAMORPHIC ROCKS

Utilizing texture, structure, and mineral composition we can classify or name the metamorphic rock. In some cases the name may be derived solely from the structural characteristics, such as schist. In others it may be based on the mineral composition, as for quartzite or marble. Additional qualifying terms may give a more specific name to the rock. For a rock with schistose structure and clearly visible biotite, garnet and quartz present, the name would be “garnet biotite quartz schist” based on the relative abundance of each of the mineral phases present, the least abundant first. The panacea of a name which would describe origin, original rock type and intensity of metamorphism and resultant mineralogy, texture and structure has not been derived. We must depend on visible minerals, textures and structures which may or may not denote the rock history.

The chart of Table 4.2 is general in its make up but includes the main criteria for naming of this important rock class. It is self explanatory and is based on typical structures, textures, and minerals.

Table 4.2 - Classification of Metamorphic Rocks

STRUCTURE			TEXTURE	MINERALS	ROCK NAME
	MASSIVE TO FAINTLY LAYERED		Very fine grain	Identifiable under microscope	Hornfels
			Sugary texture, interlocking grains (Faint to distinct layering)	Mainly quartz	Quartzite
			Fine to coarse grains, with or without dark-streaking. Sometimes breciated.	Calcite Dolomite	Marble
		GRANOBLASTIC	Variable grain size	Silicates of calcium, iron, magnesium in or with limestone or dolomite, and near igneous contact, includes garnets, epidote, pyroxene, amphibole and others.	Tactite
			Medium to coarse-grained rock, faintly foliated	Plagioclase, amphiboles, possible garnet, quartz, epidote	Amphibolite
				Feldspar, pyroxene, garnet, kyanite and other silicates	Granulite
	FOLIATED		Very fine-grained, well foliated. Remnant sedimentary structures visble.	Mineral grains very small, microscopic	Slate
			Faint foliation to schistose and well-developed layering	Mica and quartz when recognizable	Phyllite
				Chlorites, plagioclase, epidote	Chlorite schist
				Muscovite, quartz, biotite	Mineral qualifier, as mica schist, biotite, muscovite, sericite schist,or sillimanite mica schist, kyanite, etc.
				Amphibole, plagioclase	Amphibole schist
			Gneissic-banded (dark-light bands)	Feldspar, amphibole, quartz, biotite	Gneiss
			Coarsely-banded mixture or metamorphic & igneous rocks	Feldspar, amphibole, quartz, biotite interlayered and interfingered	Migmatite

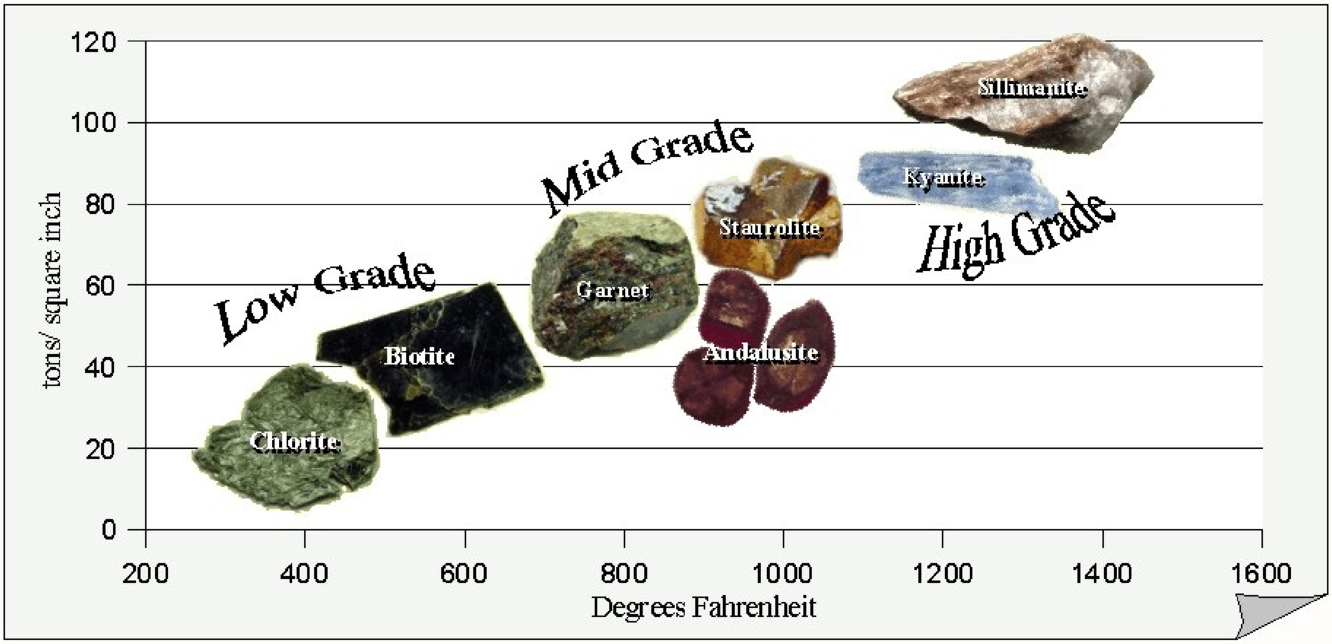


Figure 4.2 - Simplified mineralogy for metamorphic rocks according to temperature & pressure and their indicative grade of metamorphism

LAB EXERCISE 5 - METAMORPHIC ROCK IDENTIFICATION

Name:	Course ID:

During this lab you are required to positively identify by name all metamorphic rocks given to you by your instructor and/or metamorphic sample sets using the procedure described under CLASSIFICATION AND NAMING OF METAMORPHIC ROCKS, using table 4.2. You will complete the provided blank Metamorphic Rock ID Exercise Table in conjunction with your testing.

Materials needed:

- Professional Rock / Mineral Identification Kit (See above for ordering information)
- Set of Metamorphic Rocks included in the kit above
- Handlense included in kit.
- Table 4.2
- Metamorphic Rock ID exercise table

Procedure:

1. Pick an unknown Metamorphic Rock sample from your kit (write down sample number or letter, if applicable). Follow the outline given under CLASSIFICATION AND NAMING OF METAMORPHIC ROCKS, especially in conjunction with table 4.2. Write down the results in the blank Metamorphic Rock ID Exercise Table as you go.
2. Use two colors to complete the table. Mark in blue all the values you have obtained by your own measurements or observations. Write in black everything you have researched, copied or otherwise obtained by looking it up.
3. The fields above the *"METAMORPHIC ROCK NAME"* row should be completed using ONLY OWN OBSERVATIONS / MEASUREMENTS.
4. The fields below the *"METAMORPHIC ROCK NAME"* row should be completed using RESEARCH.

METAMORPHIC ROCK ID EXERCISE TABLES **Name:**____

*Complete using 2 colors. Mark your own measurements in **blue**. Mark researched or copied values in **black!***

	PASTE METAM. ROCK SAMPLE from KIT HERE: *(clear scotch tape)*							
	Foliation: *foliated or non-foliated*							
	Texture: *as presented in the table*							
	Minerals: *list as many as you can identify and their estimated %*							
	METAMORPHIC ROCK NAME:							
Research	Most likely temp.:							
	Most likely depth / pressure:							
	Most likely protolith (source rock):							

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METAMORPHIC ROCK ID EXERCISE TABLES **Name:**____________________________________

Complete using 2 colors. Mark your own measurements in ***blue****. Mark researched or copied values in* ***black!***

	PASTE METAM. ROCK SAMPLE from KIT HERE: *(clear scotch tape)*							
	Foliation: *foliated or non-foliated*							
	Texture: *as presented in the table*							
	Minerals: *list as many as you can identify and their estimated %*							
	META-MORPHIC ROCK NAME:							
Research	Most likely temp.:							
	Most likely depth / pressure:							
	Most likely protolith (source rock):							

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METAMORPHIC ROCKS

GNEISS

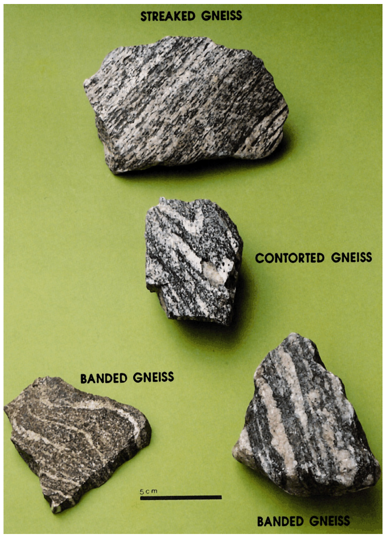
Rock Group: Foliated Metamorphic Rock
Grade of Metamorphism: High; Regional Metamorphism

Texture: The term gneiss applies to a group of rocks with banded or coarsely foliated structure. These are coarse grained, often irregularly banded. Some varieties occur near intrusive masses intricately interlayered in bedded metamorphic rocks and are known as migmatites. They are believed to have formed from the emanations from the partial melting and recrystallization of the original rock under high temperature conditions.

Banded Gneiss - Mainly composed of grainy biotite flakes.
Contorted Gneiss - Sharply folded well-developed dark & light bands.
Streaked Gneiss - distinct foliation, but streaky. Some layers end rather abruptly.

Mineralogy:. Consist mainly of quartz and feldspar with some biotite.

Protolith:. Paragneisses - Metamorphic sequence shale -> slate ->schist -> gneiss.
Orthogneisses - Metamorphism of primary igneous rocks.



HORNFELS

Rock Group: Non-Foliated Metamorphic Rock
Grade of Metamorphism: Usually Low; Contact Metamorphism

Texture: Dark colored rock, mostly brownish black. May show original bedding or other structures of the protolith (usually shale). However, Hornfels is NOT foliated since it breaks readily across these laminations and not only along them. Usually fine to very fine grained (aphanitic).

Mineralogy:. Quartz, Feldspars and Biotite mica (often responsible for the dark color). The presence of Andalusite may form spots.

Protolith:. Any; shale, sandstone, limestone, even basalt.

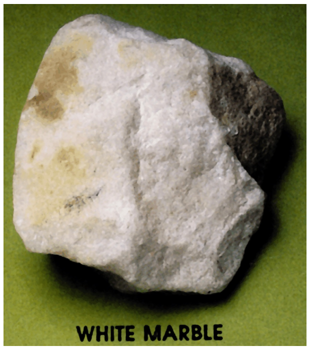
MARBLE

Rock Group: Non-Foliated Metamorphic Rock
Grade of Metamorphism: Variable; Contact & some Regional Metamorphism

Texture: Light colored rock, often white. Has increased grain size and much lighter color than the original rock. Grains are almost equal in size. Bedding planes have been essentially obliterated and the rock considerably changed in appearance.

Mineralogy:. Predominately Calcite or Dolomite. Some biotite may form from impurities in the protolith.

Protolith:. Limestone / Dolomite.



QUARTZITE

Rock Group: Non-Foliated Metamorphic Rock
Grade of Metamorphism: Variable; Contact & Regional Metamorphism

Texture: Various colors. Pink, white, dark, even green. Relic bedding or layering may still be visible. These are NOT foliations indicated by their very parallel & linear arrangement. The mineral grains fracture when the rock is broken.

Mineralogy:. Quartz. Impurities of clay in the protolith will form muscovite.

Protolith:. Sandstone.

SCHIST

Rock Group: Foliated Metamorphic Rock

Grade of Metamorphism: Intermediate; Regional Metamorphism

Texture: Crystalline, somewhat crenulated. and showing distinct foliate structure.

Biotite Schist	- Mainly composed of grainy biotite flakes.
Garnet Schist	-contains fine muscovite and brownish garnet metacrysts.
Muscovite Schist	- Mainly composed of grainy muscovite. Silvery appearance.
Staurolite Schist	- shows visible mineral crosses of staurolite within mica matrix.

Mineralogy: Grain size for this rock is far larger than that of the slate. Platy and other minerals are clearly visible to the eye.

Protolith: Slate.

SERPENTINITE

Rock Group: Foliated Metamorphic Rock

Grade of Metamorphism: Low; Contact or Regional Metamorphism

Texture: Frequently green or green gray, almost wax-like in appearance with a slippery feel. Very soft, may be easily scratched or carved with a knife (soapstone).

Mineralogy: Commonly composed of hydrated magnesium silicate with an approximate composition of $3MgO*2SiO_2*2H_2O$. Other minerals such as Chlorite, Talc and Graphite may also be present. Sometimes contains fibrous veins of chrysotile (asbestos) or similar heat resistant minerals.

Protolith: Mafic or ultramafic igneous rocks, such as Basalt, Gabbro or Peridotite. Forms often at divergent plate boundaries.

SLATE

Rock Group: Foliated Metamorphic Rock

Grade of Metamorphism: Low; Regional or Contact Metamorphism

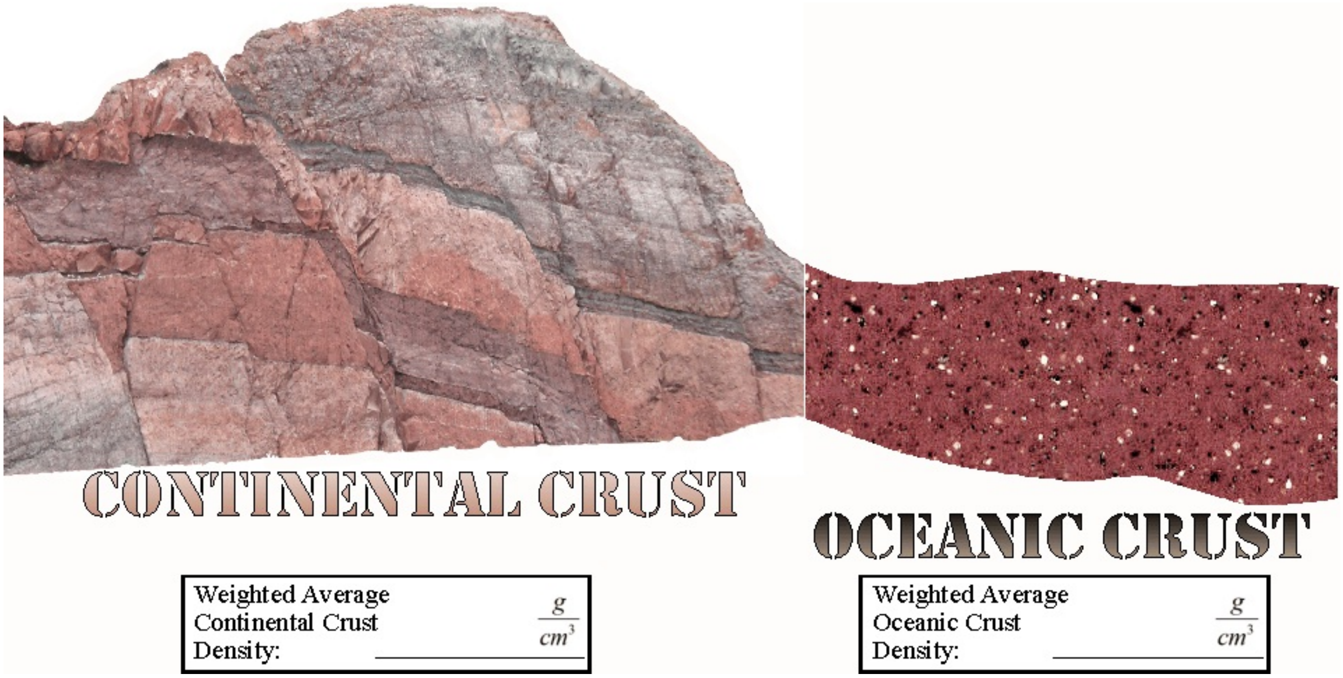
Texture: Homogeneous appearance, very fine-grained texture and composition. May show difference in color banding. Schistosity or cleavage. is independent of bedding. The rock can be cleaved to relatively thin plates parallel to the finely developed schistosity. Numerous types of slates have been described, but the use of color terms such as gray slate or red slate dominates.

Mineralogy:. Has microscopic alignment of platy minerals such as mica and chlorite which are oriented in the plane of cleavage as a result of stress. Compositional terms such as graphitic and calcareous are also used if these minerals are present.

Protolith:. Original shale or fine siltstone.

LAB EXERCISE 6 - CRUSTAL DENSITIES

Name:	Course ID:



Weighted Average Continental Crust Density: ______________ $\frac{g}{cm^3}$

Weighted Average Oceanic Crust Density: ______________ $\frac{g}{cm^3}$

During this Lab exercise you will determine the average crustal densities of both the continental and the oceanic crust and report your findings by completing the figures. You will use your own density measurements of various rock types and the statistical computations of weighted averages to derive at your answers .

Materials Needed

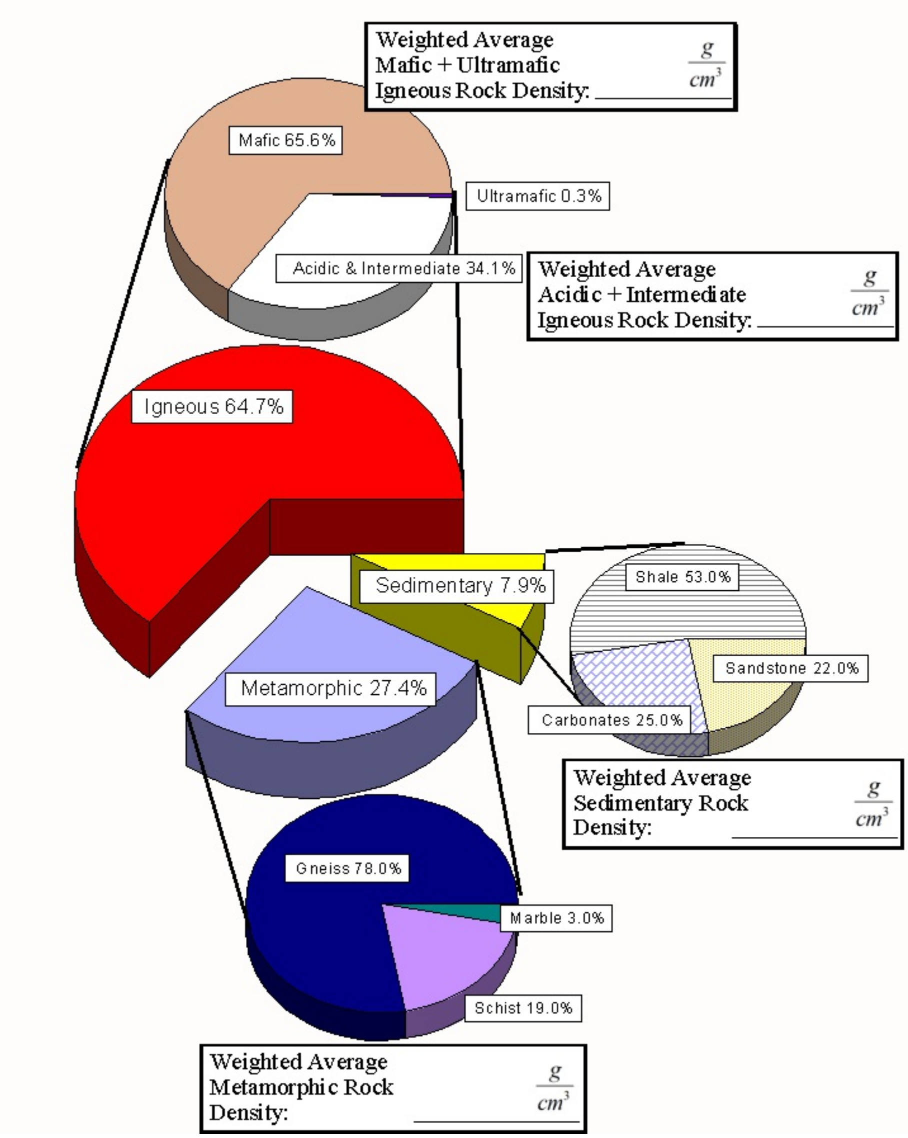
- Density tool from your Rock Mineral Kit
- Samples of crustal rocks from your Rock Mineral kit
- Some background in computing weighted averages

Procedure

Measure and record the densities of...

(a) Igneous Rocks: all mafics & ultramafics in your kit
(b) Igneous Rocks: all acidics & intermediates in your kit.
(c) Sedimentary Rocks: all sandstones, shales / claystones, and carbonates in your kit
(d) Metamorphic Rocks: All Gneisses, schists and marbles in your kit

List your measurements:



Complete the figure to the left by computing weighted averages for each category as indicated.

How to get started?
For the weighted average of acidic + intermediate igneous rocks, compute a straight forward average density of ALL your measured rock samples of the indicated type.

For the weighted average of mafic + ultramafic igneous rocks, compute a straight forward average of ALL your ultramafics first. Separately calculate a straight forward average of ALL your mafic measurements as indicated in the table below:

Ultramafic	**Mafic**
Peridotite (Olivine) g/cm^3	Basalt g/cm^3 Gabbro g/cm^3
Avg: g/cm^3	Avg: g/cm^3

In order to calculated the true average of mafic and ultramafic igneous rocks together we must use weighted averages instead of straight forward averages. Let's assume that the average of all mafic rock samples is 2.98g/cm^3 and averages for the ultramafic rocks are determined to be 3.25g/cm^3. Since mafics are present with 65.6% in the earth's crust, and ultramafics have an abundance of only 0.3%, the weighted average of the system is computed as follows:

$$avg_{weighted} = \frac{\sum(\rho \times \%)}{\sum(\%)} = \frac{(3.25\,{}^{g}\!/_{cm3} \times 0.3\%) + (2.98\,{}^{g}\!/_{cm3} \times 65.6\%)}{(0.3\% + 65.6\%)} = 2.98\,{}^{g}\!/_{cm3}$$ where the Greek letter ρ(rho) denotes density.

Continue calculating the averages and weighted averages for subcategories. At the end you should have established four weighted averages: METAMORPHIC ROCK DENSITY, SEDIMENTARY ROCK DENSITY, ACID + INTERMEDIATE IGNEOUS ROCK DENSITY, and MAFIC + ULTRAMAFIC IGNEOUS ROCK DENSITY.

Since the Oceanic Crust is composed of mafic/ultramafic material, the average density of that crust would be your computed weighted average for mafic + ultramafic igneous rocks.

The other rocks comprise the continental crust, therefore its weighted average must be calculated from the remaining igneous, as well as sedimentary and metamorphic rocks.

How do your values compare to the accepted values printed in your textbook?

5 EARTHQUAKES

Earthquakes occur when stresses or forces applied to solid rock increase to a point beyond the deformation capability. As indicated by figure 5.1, rocks may distort to a certain point. Elastic Deformation is recoverable, meaning the rock will eventually assume the original, non deformed state when stresses are removed. This is usually not instantaneous and may take considerable amounts of time. When rock strain reaches the Elastic Limit, deformation becomes Plastic, which is non-recoverable. The rock will stay in the assumed strained state. Continual application of stress will eventually lead to Rupture Strain. The rock will break and rebound elastically (Elastic Rebound)into a less stressful state, causing movement along the line of breakage. Such lines are called Faults and may move repeatedly over time as long as stresses continue.

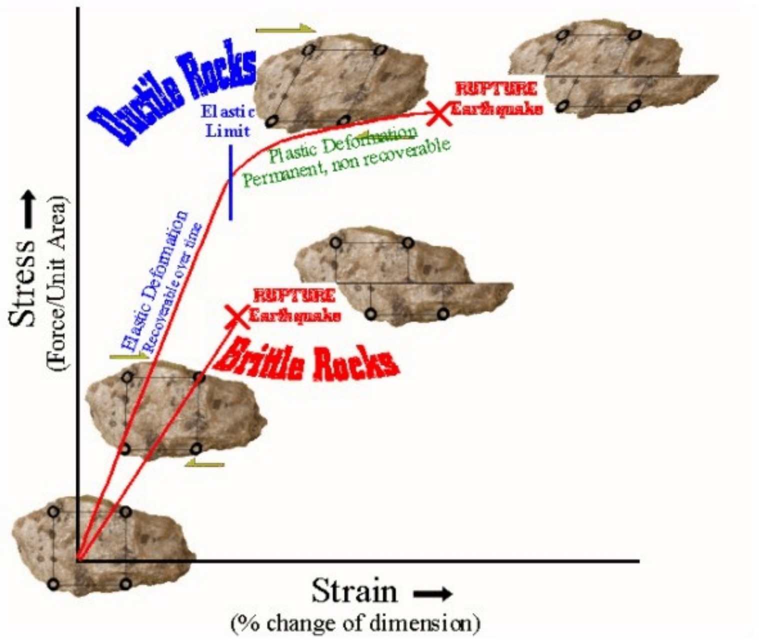
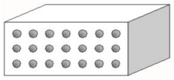
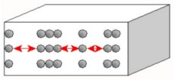
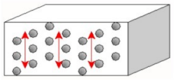
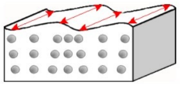
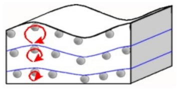


Figure 5.1 - Simplified Stress - Strain Diagram

Faults may assume vertical, horizontal or oblique movement and maybe hundreds of miles in length (e.g., San Andreas Fault, California). The build-up of enough strain for rupture or fault slippage to occur may take considerable time. Some faults may move every few years, while others, such as the Wasatch fault in Utah, may have recurrence intervals of several 10,000 years. During rupture and the associated elastic rebound, a large amount of energy is released in form of Seismic Waves, which travel on the surface and through the interior lithologies of the earth. Special instruments called Seismometers can detect the smallest ground accelerations associated with these seismic waves and record them in form of Seismograms (see figure 5.2). By studying seismic wave forms recorded on seismograms, geologists are able to not only determine the location (Epicenter), depth (Focus or Hypocenter), and strength (Magnitude) of an earthquake, but can examine the interior structure of the earth as well. During an earthquake, three different types of general waves with differing properties and characteristics are released. The attributes of earthquake waves are summarized in table 5.1.

Table 5.1 - Property summary for seismic P-, S-, and surface earthquake waves

	Wave Type	Description	Velocity
	**P-wave** (Primary) Compressional Wave Longitudinal Wave	Propagates through "push - pull" motion. Travels through ALL phases (solid, liquid, gas). Fastest seismic wave. Low energy.	Crust: 5 - 7 km/s Granite: ~ 6 km/s
	**S - wave** (Secondary) Shear Wave Transverse Wave	Move in an "S" or sinusoidal pattern (up-down or side-side). Does NOT travel through liquids. Intermediate energy.	Crust: 3 - 4 km/s Granite: ~ 3.6 km/s
	**L - wave** (Love wave) Surface wave Destructive	High energy surface wave with side to side motion. Velocity is frequency dependent (Lo F = Hi v). Slightly faster than R-waves.	Crust: 2.0 - 4.4 km/s
	**R - wave** (Rayleigh wave) Surface wave Destructive	High energy surface wave with a rolling, water wave motion (circular). Ground Roll.	Crust: 2.0 - 4.2 km/s

5.1 Determining the Epicenter of an Earthquake

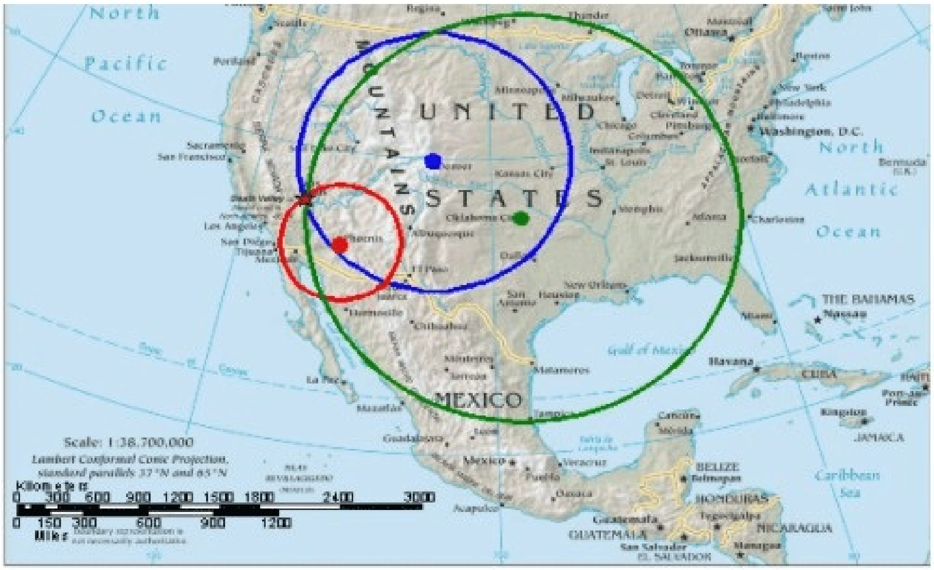
The nondestructive P and S seismic waves are often used to analyze earthquakes. While both are generated simultaneously at the earthquake focal point, both travel with different velocities through the earth. The P- wave is always the fastest and the first to arrive at the various seismic stations around the world, while the S- wave is lagging behind. This time lag is proportional to the distance: The greater the distance of a seismic station from the earthquake epicenter, the greater the time difference between the arrival of the P-wave and S-wave. Since seismograms not only record earthquake intensities but also time, the distance to an earthquake epicenter can be estimated from S-P time-lag interval or the S-P interval for short.

STEP 1: Determine the S-P interval by identifying the P-wave and the S-wave from a seismogram and reading off the time difference between their arrivals from the seismogram record. Figure 5.6 is a helpful example. The P-wave is usually the first set of intense lines on the graph, while the S-wave arrival is marked by the second high intensity set. Always use the beginning or first arrival of each set for your S-P interval estimation as indicated in the figure.

STEP 2: Converting the S-P time interval into distances is accomplished by using the provided lag time graphs, figure 5.3 and 5.4. For close earthquake epicenters within distances of 2,000 km showing S-P intervals of less than 200 seconds use graph 5.3. For distant earthquakes with greater S-P lag-times graph 5.4 will suffice. Find your S-P interval time on the y-axis and draw a straight horizontal line to the S-P graph (marked as a red line). At the intercept draw a vertical line to the x-axis and read the epicenter distance in kilometers.

STEP 3: In order to actually find the exact epicenter location, a process of geometric triangulation is necessary. You will need three seismograms of the same earthquake recorded at three different geographic locations, a map with distance scale showing these locations, a ruler, and a drawing compass. First, use step 1 and 2 above to find the epicenter distance for all 3 locations. Next, use the ruler to extend your map scale if necessary and then draw circles with the drawing compass around each of the seismic station at the radius of the estimated distance for each respective seismic station (see example in figure 5.2 below). You should end up with 3 neatly drawn circles. If done correctly, all three circles will intersect in exactly one point. This is the location of the earthquake epicenter.

Figure 5.2 - Triangulation example locating Earthquake Epicenter. Seismograms for the same earthquake were recorded at 3 different seismic stations. Data and interpreted distances for respective stations are as follows: Phoenix, AZ: SP interval 45s - Distance 430 km; Denver, CO: SP interval 100s - Distance 975 km; Oklahoma City, OK: SP interval 155s - Distance: 1590 km. Epicenter location marked by ☆



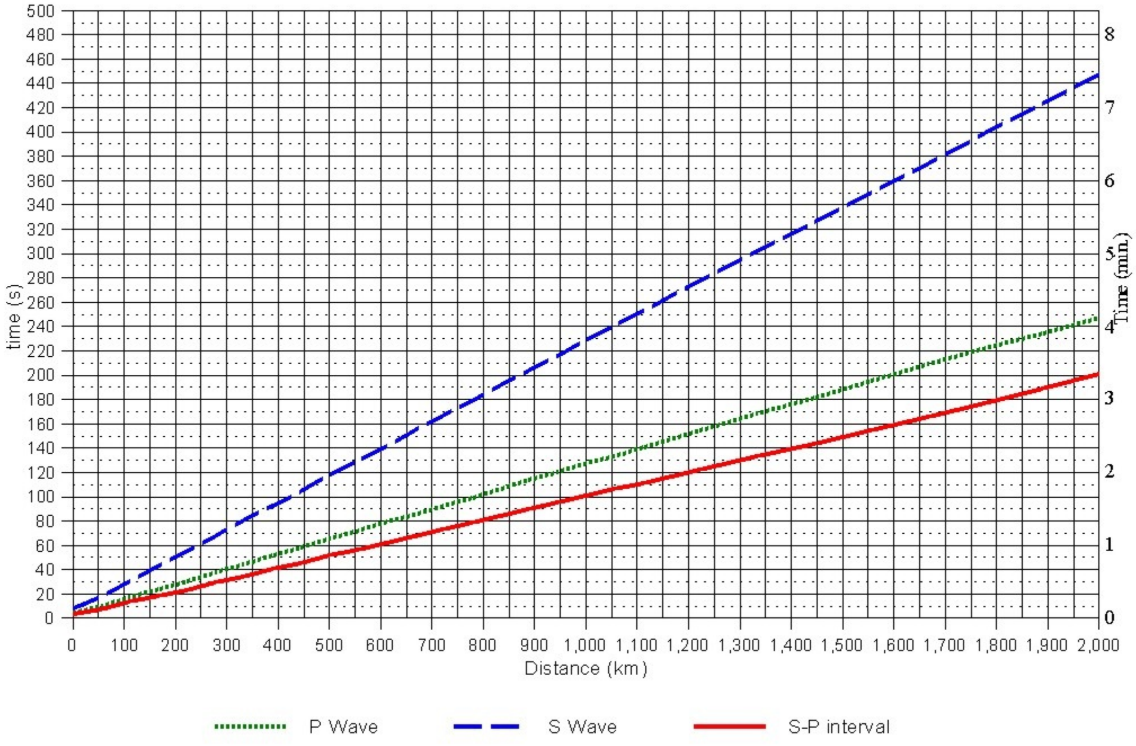


Figure 5.3 - SP interval / epicenter distance graph for close earthquakes

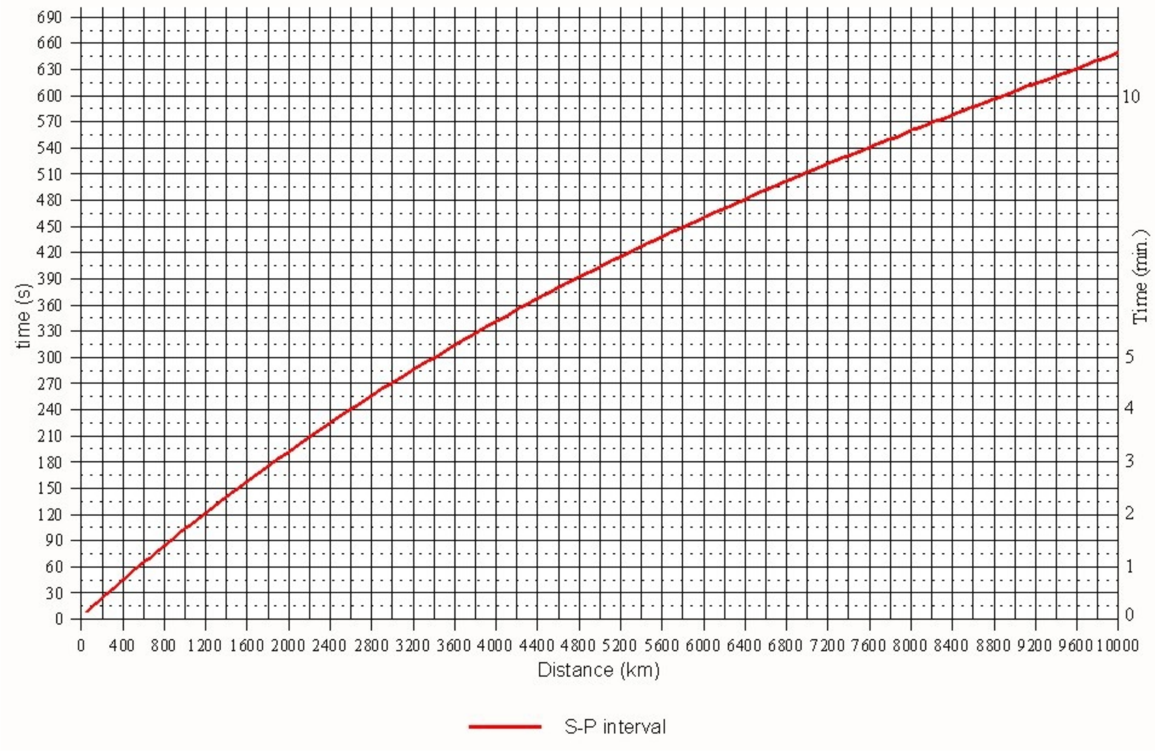


Figure 5.4 - SP interval / epicenter distance graph for distant earthquakes

5.2 Determining the Magnitude of an Earthquake

Several different magnitude scales were developed over the years to identify the strength and therefore the destructive power of earthquakes. The scale most commonly used when reporting earthquakes to the public is the Richter Magnitude, also called the Local Magnitude (M_L). Charles F. Richter (1900-1985) developed the scale for use with California related earthquakes. The Richter Magnitude of an Earthquake can be determined from seismogram readouts. Since the released earthquake energy is expressed in the seismic waves, especially their amplitude, the S-wave amplitude as recorded on a seismogram can be used to find M_L. Be aware, however, that earthquake energy dissipates with distance. Hence the closer the seismograms were recorded to the epicenter, the larger the S-wave amplitude. This makes wave amplitudes not only energy but also distance dependent. The Richter equation for local magnitude contains such a distance correction factor and is expressed as:

$$M_L = \log_{10} S(mm) + (Dist.CorrectionFactor)$$

Where *S(mm)* = largest S-wave amplitude from seismogram baseline in mm
Dist.CorrectionFactor = $3\log_{10}[8SP(s)]-2.92$
SP(s) = SP lag time seconds

While a mathematical approach is possible, the Richter scale equation is of limited use for far distant earthquakes. Students often find the graphical solution using a nomogram (figure 5.5) much easier and quicker. A nomogram is a graphical device using three calibrated scales. By knowing two of the values on two of the scales, the third value can be read from the remaining scale by marking the known values on their respective scales, connecting the points with a straightedge and reading the intersection of the drawn line with the third scale, thus finding the third unknown.

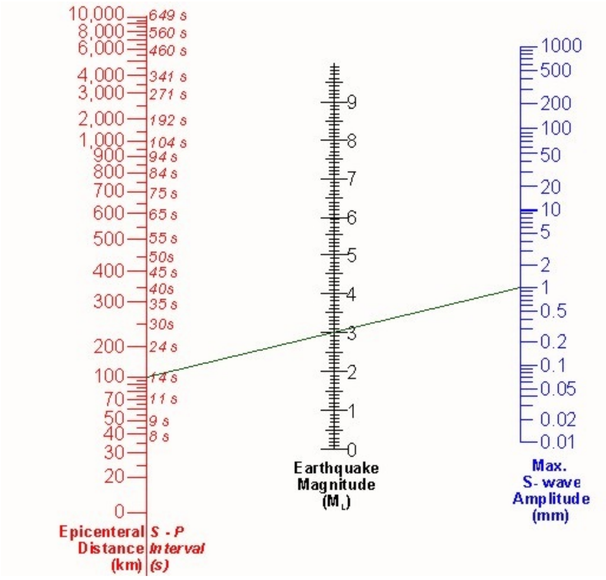


Figure 5.5 - Earthquake Nomogram for Local Magnitude estimation using SP-lag time/ epicenter distance and maximum S wave amplitude

For the magnitude nomogram shown in figure 5.5, the scale on the left is a double scale showing the epicenter distance and SP lagtime. The right-hand scale is the maximum S-wave amplitude in millimeters measured from the seismogram baseline. The middle scale is the local earthquake magnitude. The nomogram example shows a standard earthquake at a distance of 100km with a S-wave displacement of 1mm. The resulting magnitude is 3.0 on the center scale. Other earthquakes can be referenced to such standardized earthquake simulations, producing the said nomogram. A magnitude 4 earthquake at the same distance would thus show 10 mm of S-wave amplitude, a magnitude 5 quake would yield an amplitude of 100 mm, a magnitude 6 generate a 1000 mm amplitude and so forth. The indicated 1, 10, 100 and 1000 mm S-wave amplitudes can be written as 10^0, 10^1, 10^2 and 10^3 respectively showing an “exponential” trend. Thereby a change of one unit in magnitude increases the maximum S-wave amplitude by a factor of 10.

STEP 1: If not previously complete, determine the SP interval and corresponding epicenter distance as explained in 5.1 above. Record this value and mark it on the nomogram left hand (red) scale.

STEP 2: Identify the S-wave on the seismogram and look for the greatest S-wave amplitude spike measured from the central baseline. If the upward displacement has the highest peak, use it. However, if the downward spike is greater, measure it. The seismogram amplitude is already plotted in millimeters. Read the maximum value, record it and mark it on the right hand (blue) scale of the nomogram.

STEP 3: Take a straight edge and neatly connect your two marks. Your line will cross the central scale of the nomogram. Read the earthquake magnitude where your line crosses the central scale.

STEP 4: Repeat this procedure for other seismograms of the same earthquake. If done correctly, ALL lines of the various seismic data plots will intersect in one SINGLE point at the center Magnitude Scale. This point of intersection is your estimated Richter Magnitude.

LAB EXERCISE 7 - EARTHQUAKES

Name:	Course ID:

During this Lab exercise you will become a seismologist determining the location (Epicenter) and strength (Richter Magnitude) of an earthquake. In order to do this exercise, you need to be familiar on how to interpret a seismogram as shown on the right in figure 5.6. By analyzing seismograms of the same earthquake event from three different geographic locations, you will be able to complete the stated objective.

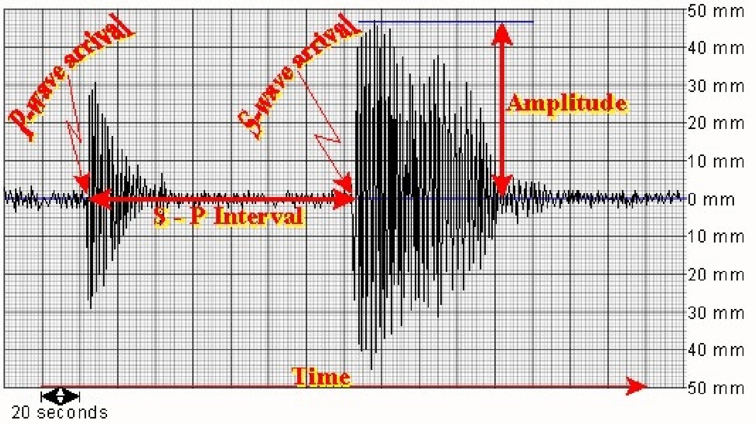


Figure 5.6 - Sample seismogram with explanation

<u>Materials Needed</u>

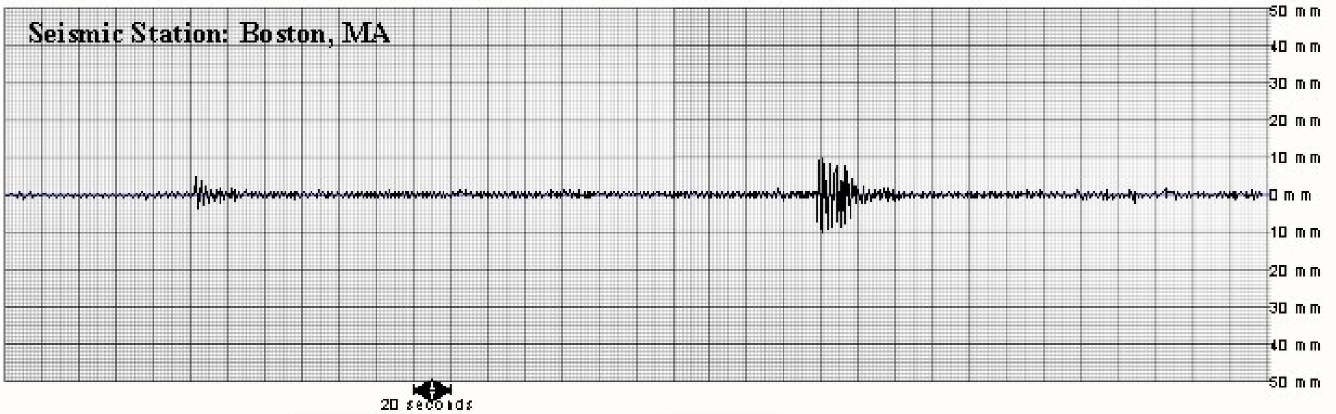
- access to the internet
- drawing compass
- ruler / straightedge
- three seismograms (fig. 5.7)
- Locator map (fig. 5.8)
- SP lag time / epicenter distance graph (fig. 5.4)
- blank earthquake nomogram (as shown in fig. 5.5)

EARTQUAKE LAB

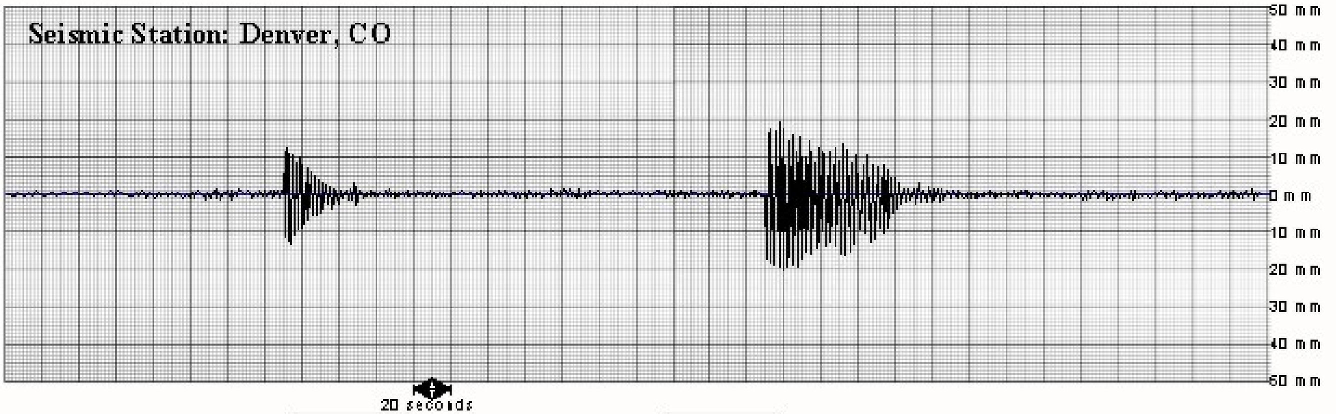
Establish the Earthquake Epicenter and Magnitude for a distant earthquake given in the three seismograms presented in Figure 5.7. Use a drawing compass to pinpoint the earthquake epicenter on the provided location map (Figure 5.8). Also, use the provided nomogram to identify the earthquake magnitude for ALL 3 seismograms. Next to showing the graphical solution on the map and nomogram, give a written response concerning the location and magnitude in the spaces below:

Epicenter Location: *(In the space to the left give a detailed description of the geographic location of the epicenter)*	

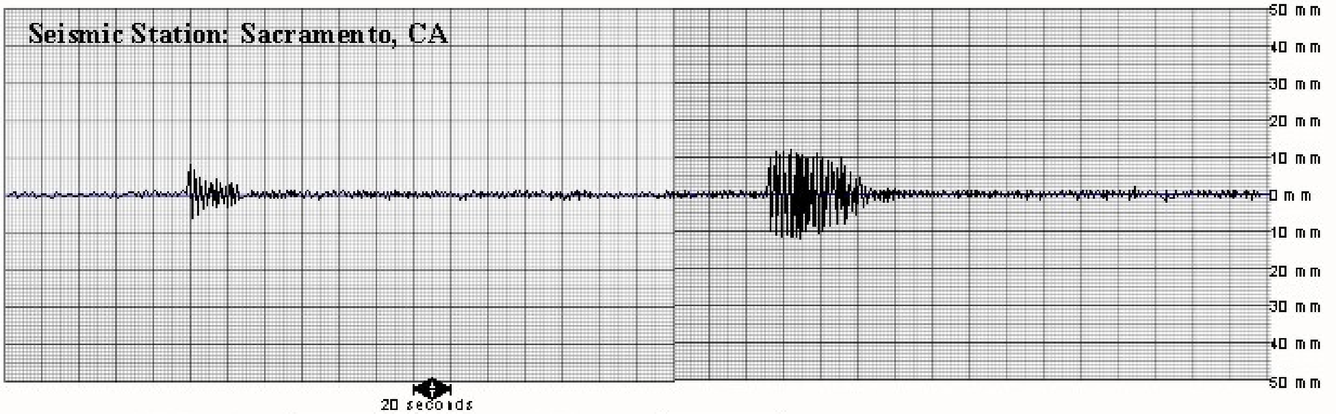
Earthquake Magnitude: *(In the space to the left write down the earthquake magnitude with an accuracy of one decimal)*	



SP Lagtime: ☐ **Epicenter Distance:** ☐



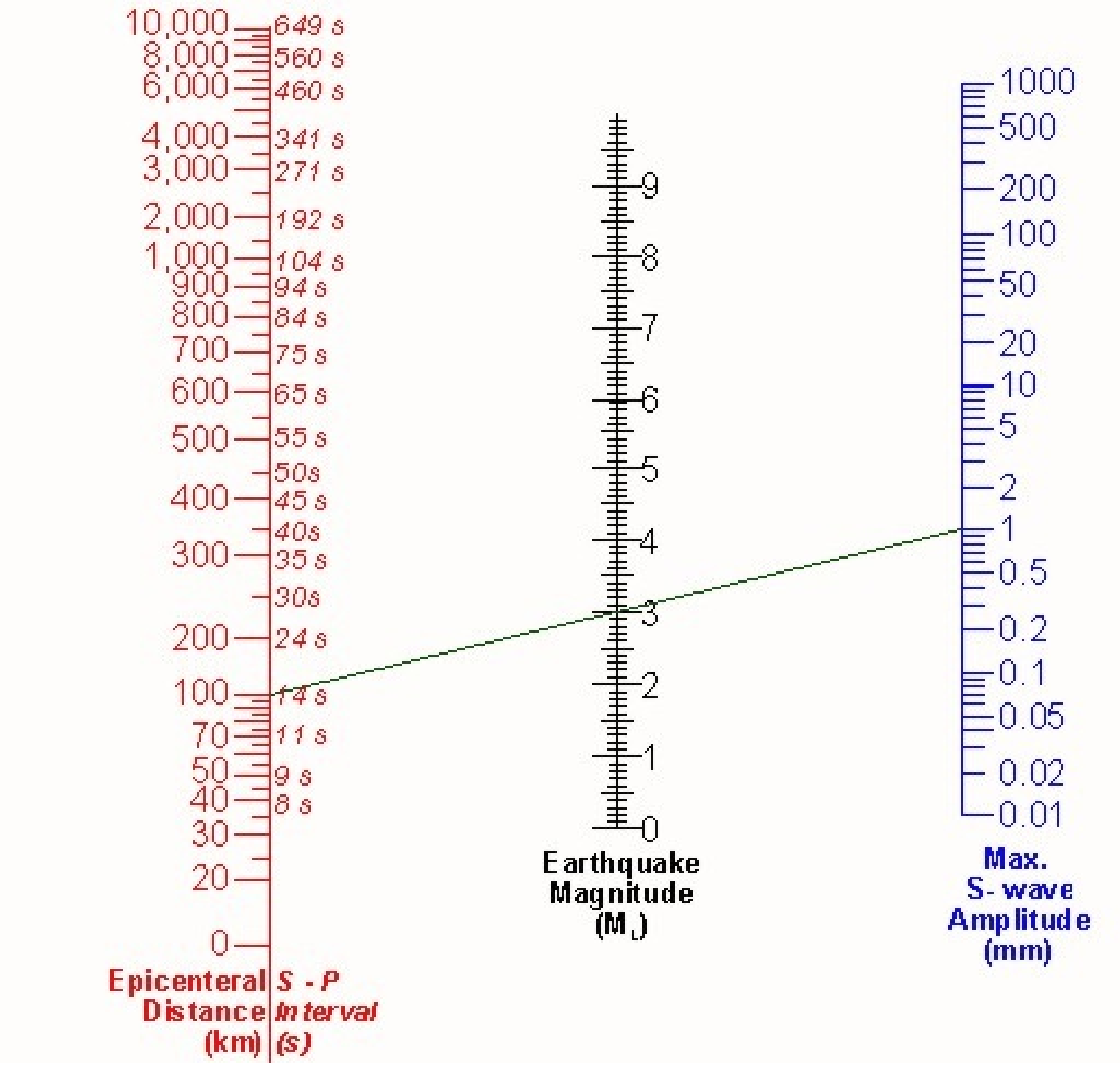
SP Lagtime: ☐ **Epicenter Distance:** ☐



SP Lagtime: ☐ **Epicenter Distance:** ☐

Figure 5.7 - Three station seismograms for CO, CA, and MA

Figure 5.8 - Earthquake epicenter locator map - North America


10,000
8,000
6,000
4,000
3,000
2,000
1,000
900
800
700
600
500
400
300
200
100
70
50
40
30
20
0
649 s
560 s
460 s
341 s
271 s
192 s
104 s
94 s
84 s
75 s
65 s
55 s
50s
45 s
40s
35 s
30s
24 s
14 s
11 s
9 s
8 s
Epicenteral Distance (km)
S - P Interval (s)
9
8
7
6
5
4
3
2
1
0
Earthquake Magnitude (M_L)
1000
500
200
100
50
20
10
5
2
1
0.5
0.2
0.1
0.05
0.02
0.01
Max. S-wave Amplitude (mm)

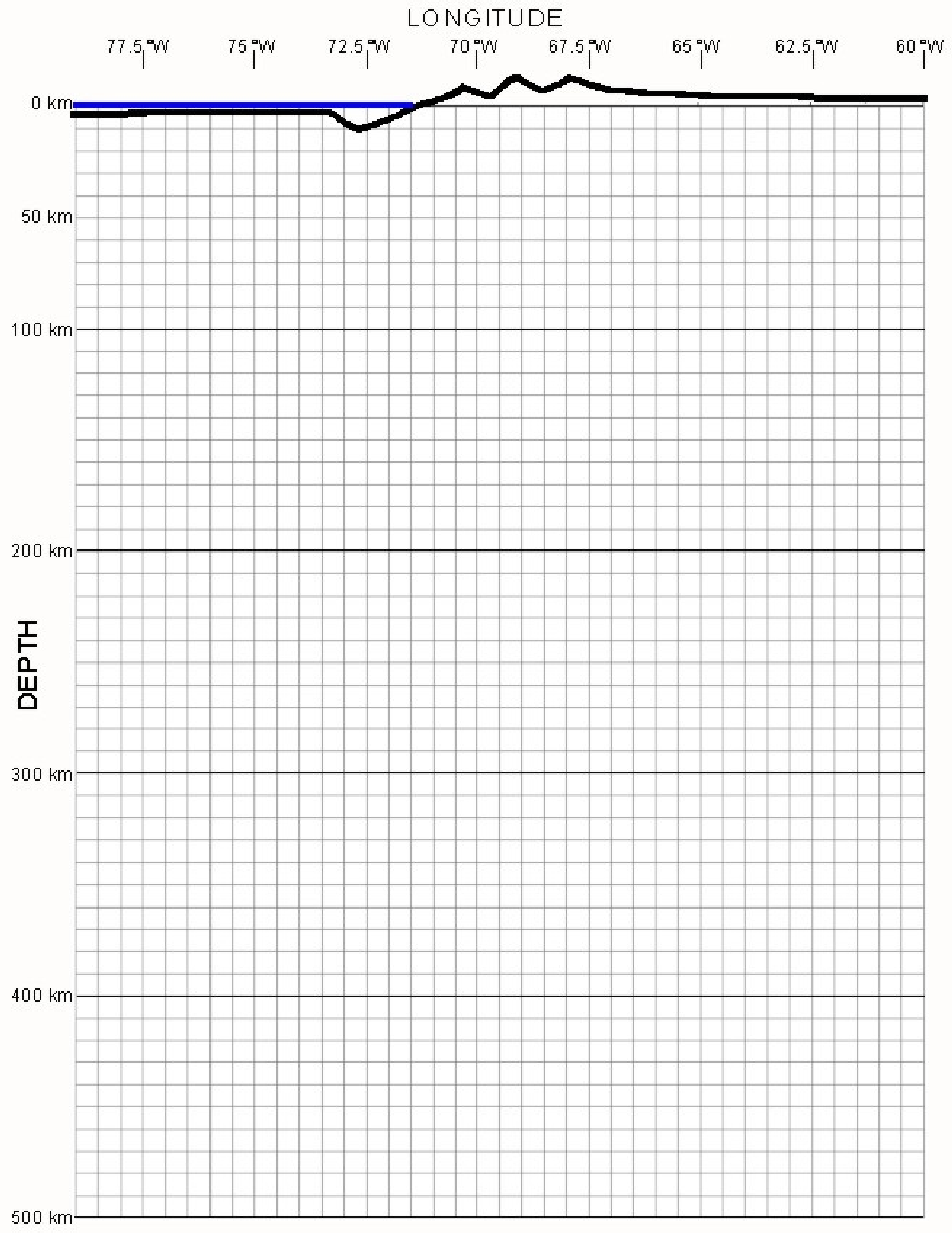
LAB EXERCISE 8 - EARTHQUAKE DEPTH

Name:	Course ID:

Geology - What does the depth of an earthquakes tell us?
The list below summarizes the locations & depth of a few earthquakes around 30°S latitude in South America. Use the table below and the attached depth profile to plot the locations and focal depth of earthquakes.

Year	Month	Day	Latitude	Longitude	Magnitude	Depth (km)
2000	4	23	-28.31	-62.99	7	500
2000	4	23	-28.38	-62.94	6.1	494
2001	1	1	-32	-71.54	5.1	82
2001	3	31	-29.4	-68.33	5.5	104
2001	4	9	-32.67	-73.11	6.7	11
2001	5	15	-28.06	-66.55	5.6	176
2002	2	21	-31.69	-67.36	5.4	120
2002	4	1	-29.67	-71.38	6.4	71
2002	4	14	-31.97	-71.56	5	66
2002	7	18	-29.34	-72.56	5.1	23
2003	8	23	-27.56	-63.26	5.2	481
2004	1	10	-30.88	-71.66	5.7	55
2004	4	3	-29.99	-71.99	5.5	34
2004	10	23	-29.23	-67.19	5	132
2005	1	24	-29.4	-71.71	5.2	42
2005	7	4	-27.01	-63.27	5.1	474
2006	4	30	-27.2	-71.24	5	6
2006	4	30	-27.1	-71.27	5.3	8
2006	4	30	-27.28	-71.24	5.7	19
2006	7	3	-27.97	-66.51	5.1	166
2006	7	8	-28.56	-67.39	5.5	140
2006	7	16	-28.72	-72.54	6.2	10
2007	3	29	-31.57	-72.07	5.3	4
2007	3	29	-31.59	-71.84	5.6	25
2007	5	27	-27.51	-67.41	5.2	150
2007	7	11	-32.67	-70.28	5.1	93
2007	10	27	-31.68	-69.03	5.1	116
2007	12	20	-32.69	-71.81	5	29
2008	1	28	-30.83	-71.88	5.1	30
2008	6	26	-28.72	-71.43	5	50

After completing this exercise explain in the space below how earthquake depth is related to plate tectonics:


LONGITUDE
77.5 °W
75 °W
72.5 °W
70 °W
67.5 °W
65 °W
62.5 °W
60 °W
0 km
50 km
100 km
200 km
300 km
400 km
500 km
DEPTH

6 GEOCHRONOLOGY

LAB EXERCISE 9 - HALF-LIFE EXERCISE

Name:	Course ID:

Objective: What is HALFLIFE of a radioactive element?

I. Get into groups!

II. Materials: a coin or 100 M&Ms, paper, graph paper (lot's of patience)

III. Your group needs to flip the coin 100 times or use 100 M&Ms! Count all heads (MM) and tails you are getting from the 100 flips! Write down under Time 1. Assign:
Heads (MM) = Parent Material
Tails = Daughter Products
KEEP COUNT IN THE FOLLOWING TABLE!

Time	Parent Material	Daughter Products	Cumulative Daughter Products
0	**100**	**0**	**0**
1			
2			
3			
4			
5			
6			
7			

IV. Flip the coin or MM's again but only for the number of Parent Material under Time 1. Again count heads (Parent) and tails (Daughter)!
KEEP COUNT IN THE TABLE! Write results under TIME 2!

V. Flip the coin again or MM's but only for the number of Parent in TIME 2 . Again count heads and tails!
KEEP COUNT IN THE TABLE! Call this TIME 3!

VI. Continue flipping the coins or MM's as many times as you have parents from the previous run. Keep count of heads (Parent) and tails (Daughter)!
CONTINUE TO KEEP COUNT IN THE TABLE! Proceed with TIME 4 and then 5, 6, and so forth!

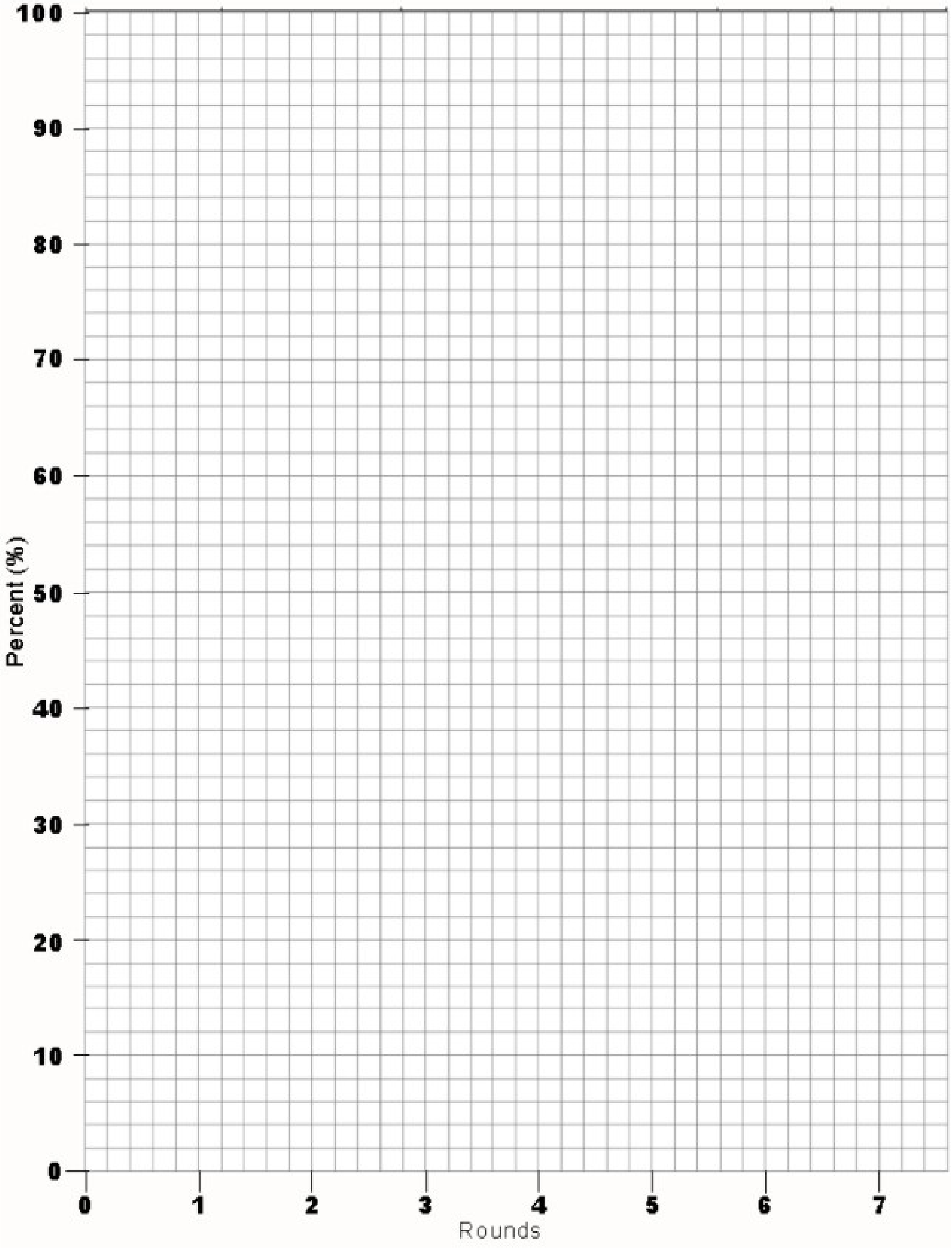
VII. Graph the results for both parent and daughter products (ON GRAPH PAPER).
X-Axis is "Time" column (time 0, time 1, time 2, etc.)
Y-Axis is "Parent Material" column (starting with 100) and "Cumulative Daughter Products" column (starting with 0)

1. What is the general shape of your graphs? Describe!

2. Compare your graph with the graphs of three other groups in the class! Is there a difference? Why or Why not? Explain!

3. If each time on the x-axis represented 1000 years, could you calculate the age of a material that contained 25% parent material and 75% daughter products? Explain how you would do that!

4. This exercise was designed to help you in the understanding of "radioactive halflife". How would you define the principle of "radioactive halflife!" in one short paragraph?


100
90
80
70
60
50
40
30
20
10
0
Percent (%)
0
1
2
3
4
5
6
7
Rounds

(Intentionally left blank for printing)

THE NUMBER OF PROTONS IN AN ATOM DEFINES THE CHEMICAL ELEMENT

An atom with exactly 82 protons is a lead (Pb) atom. If we could selectively remove 3 protons from each lead atom to bring the total proton number down to 79, we would literally turn lead into gold, since gold (Au) has 79 protons. Unfortunately this is impossible. However, gold is gold because it has 79 protons in its atoms, lead is defined by 82 protons in its atomic nucleus and iron (Fe) contains 26 protons in each of its atoms. While the number of protons does NOT vary for each given element, the number of neutrons and electrons may change without changing the element.

ISOTOPES ARE SAME ELEMENTS WITH DIFFERENT NUMBERS OF NEUTRONS

An **isotope** is a specific element with different neutron counts in its nucleus. Hydrogen (H) for example usually does not have neutrons. Nevertheless, certain Hydrogen atoms with 1 or 2 neutrons do exist, being called deuterium and tritium respectively. Both deuterium and tritium are isotopes of hydrogen. Hydrogen, deuterium and tritium would be chemically indistinguishable. While isotopes have therefore no influence in the reacting or combining of elements, their atomic masses differ, thus making the element heavier or lighter than usual. Most isotopes of common elements are also radioactive.

Isotopes are usually named by their unique atomic mass. The average atomic masses are routinely printed in the periodic table of elements. Isotopes deviate from these averages. For example, carbon (C) has an average atomic mass of 12. The heavier carbon isotope C-14 is labeled as such. While isotopes are less interesting in the identification of minerals, they play an important role in the radiometric dating (age determination) of geologic materials.

To distinguish the various isotopes of radioactive elements, they are usually written by the chemical symbol with the atomic mass in the upper lefthand corner (and sometimes with the atomic number in the lower lefthand corner) such as $^{mass\#}_{atomic\#}X$

RADIOACTIVE DECAY & HALF-LIFE

Radioactive isotopes are unstable and decay into other elements until a stable configuration is reached. During the decay process, protons in the nucleus of the atom are literally removed or added, thus changing the element itself. The starting element is referred to as the **parent element** while the decay products are called **daughter elements**. This change from parent to daughter releases large amounts of energy in the form of radiation. Two predominant types of radioactive disintegration are α-decay and β-decay. During **α-decay**, a heavy particle, the α-particle, consisting of two protons and two neutrons (or a helium nucleus), is liberated, thus reducing the atomic mass of the parent element by four and the atomic number by two. When **β-decay** occurs, a single neutron in the parent element changes suddenly into a proton while releasing a very fast electron that leaves the atomic nucleus like a speeding bullet. In this instance the atomic mass from parent to daughter stays unchanged, the atomic number, however, increases by one. Table 6.1 summarizes both decay processes.

Table 6.1 - Forms of Radioactive Decay with Examples

Decay Type	Generic Formula	Example	
α - decay	$^{mass\#}_{atomic\#}X \rightarrow {}^{4}_{2}He + {}^{mass\#-4}_{atomic\#-2}Y$	Decay of U-238	$^{238}_{92}U \rightarrow {}^{4}_{2}He + {}^{234}_{90}Th$
β - decay	$^{mass\#}_{atomic\#}X \rightarrow {}^{0}_{0}e + {}^{mass\#\pm 0}_{atomic\#+1}Y$	Decay of Am-243	$^{243}_{95}Am \rightarrow {}^{0}_{0}e + {}^{243}_{96}Cm$

The time it takes for a certain amount of parent to decay into various daughter products follows the statistical parameter of "halves" and is called the **half-life** of a radioactive element. It is defined as the time it takes for half of the parent to decay into daughter products. Half-life times are unique for each element, almost like a finger print. Some radioactive particles, like the infamous radon gas (Rn-222), have a half-life of only 3.825 days, while dangerous plutonium (Pu-239), a byproduct of nuclear fission, has a half-life of 24,000 years. The half-life decay time is unaffected by ANY change in the physical or chemical environment, such it is stable and constant under ALL conditions.

RADIOMETRIC DATING & ABSOLUTE TIME

Since half-life time is unique for each radioactive isotope, one should be able to calculate how long ago a geologic entity formed, if the amount of parent and associate daughter products in the material can be accurately measured. This technique is applicable when minerals or rocks formed from a virgin state, where the radioactive parent isotope at the point of formation was solely concentrated. The decay process will slowly change the parent to daughter products, such ticking off geologic time. By taking a snapshot of the decay in the present time and mathematically working the process backward, the absolute time of formation can be derived. The following steps are employed:

1. Measure the amount of parent and associated daughter isotopes in a geologic sample
2. Recalculate the measurements to moles or equivalent since one mole of parent would result in one mole of parent if 100% decayed.
3. Estimate the amount of the parent isotope and the point of origin (time 0) by adding the present parent and daughter mole masses together. This will give you P_O or concentration of parent in the beginning.
4. Calculate the amount of parent isotopes that are left from the original state. This is simply done by the following equation:

$$P_{\%} = \frac{P}{P_o} \times 100 = \frac{P}{(P + D)} \times 100$$

where P is the present Parent mole concentration, D is the present Daughter mole concentration, P_O is the original Parent mole concentration.

5. There are two ways to solve now for the absolute time of origin of the geologic material:
    a. **Graphical Solution**: Use the generic decay graph you constructed in Lab Exercise 9 and find the percent parent calculated in step 4 above on the y-axis. From this point, move horizontally over toward the parent decay graph. At the point of intersection with the graph, move vertically downward to the x-axis labeled "Rounds" (As you have ascertained by now, the rounds in the graph are equal to half-life of any radioactive isotope). Read the number of half-lives ("Rounds") to the nearest decimal. The last step is to multiply this number of half-lives with the actual half-life time either read from a radioactive isotope decay table or given to you. The resulting time is the age of the geologic material given in years. Remember, the ratio of parent to daughter remaining in the system today is directly related to the number of half-lives that have transpired since the geologic material formed. For example, a single half-life has passed if 50% of the parent remains, while two half-lives have transpired if 25% of the parent is present.
    b. **Mathematical Solution**: Using a scientific calculator, the absolute age can be calculated with the following equation:

$$t = \frac{t_{hl}}{0.693} \ln \frac{P}{P_o}$$

where t is the geologic time; t_{hl} is the half-life time of the isotope used; ln is the natural logarithm to the base e; P are the present moles of parent; and P_o is the original moles of parent (remember, $P_o = P + D$).

It is to be noted that the answer on your calculator should be a negative number, indicating "years ago!"

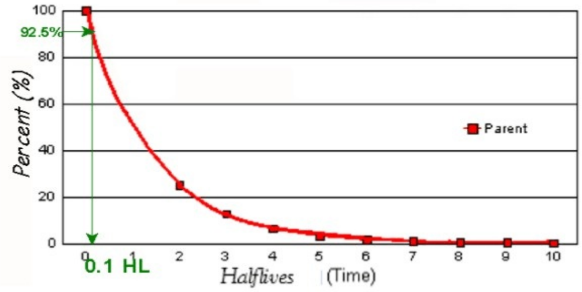
Sample Problem: *You measure in a rock 37 moles U-235 & 3moles Pb-207. The half-life of the U-235 to Pb-207 is 703.8 million years. How old is the rock?*

Percent Parent Calculation: $P_{\%} = \frac{37 moles}{(37 moles + 3 moles)} \times 100 = \frac{37 moles}{40 moles} \times 100 = 92.5\%$

Graphical Solution:
Use decay graph to find number of half-lives as shown in the sample graph. In this case 0.1 half-lives.

Multiply number of half-lives with U-235 to Pb-207 half-life time of 703.8 million years.

Answer:
0.1 HL x 703.8 my = <u>70.38 million years ago</u>



Mathematical Solution:

$$t = \frac{t_{hl}}{0.693}\ln\frac{P}{P_o} = \frac{703.8my}{0.693}\ln\frac{37moles}{40moles} = 1{,}015.58my\ln 0.925 = 1{,}015.58my(-0.07796) = -79.17my$$

Hint: Obviously the mathematical solution is more accurate and will yield better results.

USEFUL RADIOACTIVE ISOTOPES FOR RADIOMETRIC DATING

Radiometric dating has its limitations. It is very useful for geologic material that has formed through virgin processes, such as extruded lava, igneous dikes, hot spring or other mineral deposits. It is highly unsuitable for sedimentary rocks since here we are dealing often with reworked strata. There are certain exceptions, but these tend to be rare. However, a volcanic ash layer in a sedimentary stratigraphic sequence is often a goldmine for geochronology, even if the absolute time is limited to this particular extrusive igneous unit only. Table 6.2 summarizes the most commonly used radioactive isotopes for absolute dating, dating range and their application

Table 6.2 - Useful Radioactive Isotopes for Absolute Geochronology

Parent ⇒ Daughter Isotope Isotope	Half-Life Time	Useful dating range	Applicable Geologic Materials
$^{40}K \Rightarrow {}^{40}Ar$	1.25 x 10^9 years	100,000 - 4.5x10^9 years	Potassium bearing minerals in igneous or metamorphic rocks, e.g., K-feldspar, Muscovite, Hornblende
$^{238}U \Rightarrow {}^{206}Pb$	4.468 x 10^9 years	10x10^6 - 4.6x10^9 years	Zircon bearing igneous or metamorphic rocks
$^{235}U \Rightarrow {}^{207}Pb$	703.8 x 10^6 years		
$^{87}Rb \Rightarrow {}^{87}Sr$	48.8 x 10^9 years	10x10^6 - 4.5x10^9 years	Potassium bearing minerals commonly felsic igneous rocks
$^{14}C \Rightarrow {}^{14}N$	5,730 years	100 - 30,000 years	Organic, carbon bearing materials, such as wood or charcoal. Mostly for archeological applications.

Practice Questions:

Question	**Parent Moles (P)**	**Daughter Moles (D)**	**Method**	**Age?**
A	**7.5**	**1.0**	**$^{40}K \Rightarrow {}^{40}Ar$**	
B	**11.5**	**3.8**	**$^{235}U \Rightarrow {}^{207}Pb$**	
C	**8.4**	**2.5**	**$^{14}C \Rightarrow {}^{14}N$**	

Answers: A: 200 mya, B: 290mya, C: 2,154 ya

7 GEOLOGIC TIME

Geologic time can also be estimated by considering a sequence of events or chronology. Which event came first, which second, and which after that can be determined from certain clues. Take a look at figure 7.1 showing tracks in the snow by different animals. By careful observation we can determine which animal crossed the snowfield first, which second and so on, depending which paw-print is covered up by some later paw prints.

In a similar fashion, layering of rock strata can be used to determine the sequence of events in geologic times by careful observation. The science in geology endowed with the study of such chronologies is called stratigraphy. Certain laws and conditions are the underlying premises for successfully deciphering the earth's past.

In general, the following stratigraphic laws apply when looking at rock layers in a sedimentary sequence:

Figure 7.1 - Illustrating sequence of events by observing animal tracks in the snow.

1. **Law of Superposition** - the first layer is the oldest layer and is on the bottom. Layers get increasingly younger going upward, with the youngest strata on top
2. **Law of Original Horizontality** - sediments are usually deposited in horizontal layers. Any curving or tilting must have come AFTER the layers were laid down.
3. **Law of Original Lateral Continuity** - Erosion may cut valleys, but the strata continues on the other side. Sometimes the gap can be substantial, but layers can be traced over large geographic areas.
4. **Law of Cross-Cutting Relations** - Geologic features such as igneous dikes or sills can cut across strata. Features that cut across other features must be younger than the rock they cut.
5. **Law of Inclusions** - Sometimes sedimentary layers or igneous bodies contain inclusions of other strata or rocks. The rule: Inclusions are older than their host.

The following exercises will train you to decipher the geologic past by working with stratigraphic sections or diagrams and applying the rules and laws mentioned above. A mastery of geochronological calculations from radioactive isotope studies is very helpful for placing the events observed into an appropriate time frame.

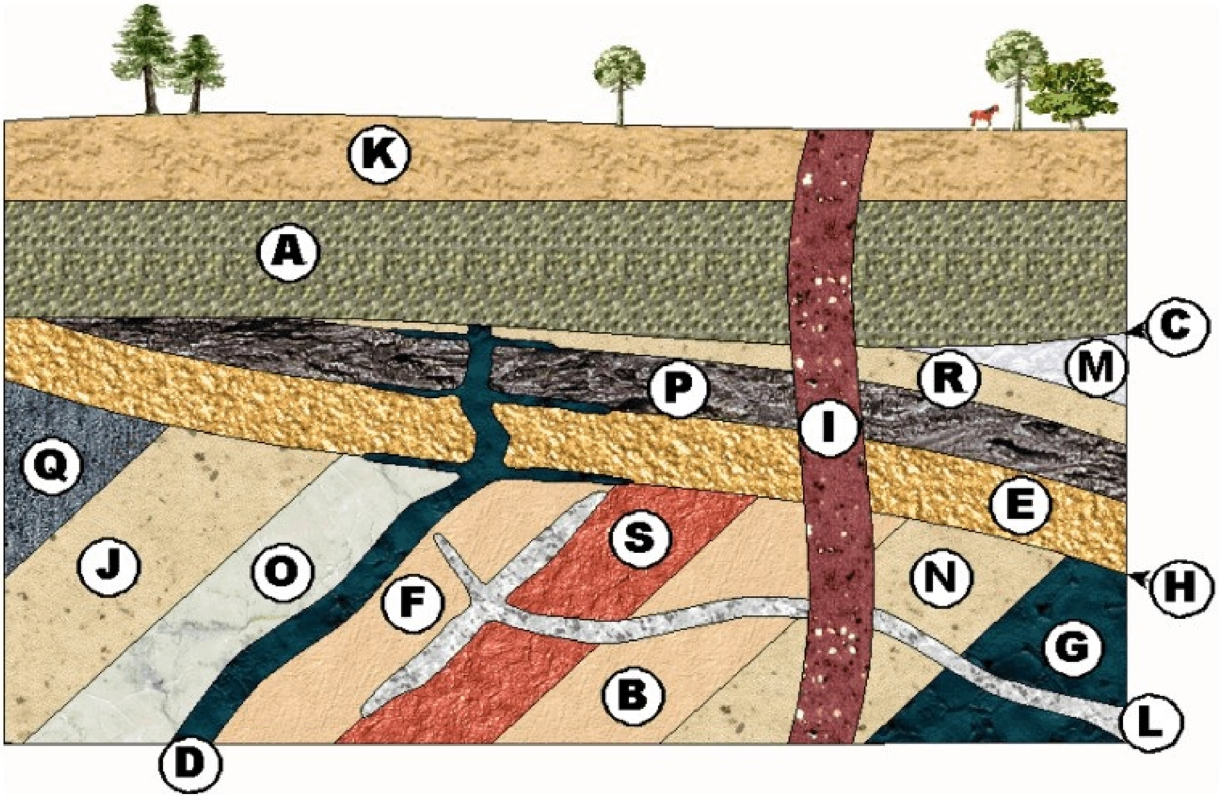
LAB EXERCISE 10 - STRATIGRAPHY & TIME

Name:	Course ID:

Age of Rock Layers

Use the rules of stratigraphic relationships you have learned to solve the geologic history of the stratigraphic section pictured below. Apply also your knowledge of geologic age calculations to narrow the time questions in your geologic history.

Explanation: Letters C and H mark unconformities. Do not forget to include them in your analysis. Letter D depicts a mafic igneous intrusion containing 5.20 moles ^{40}K and 0.45 moles ^{40}Ar. The intermediate igneous intrusion L was analyzed with 12.2 moles ^{238}U and 0.65 moles ^{206}Pb. The granitic pegmatite intrusion I contains K-feldspar with 13.81 moles ^{87}Rb and 0.01 moles ^{87}Sr. Do the appropriate age calculations for all igneous intrusions using table 6.2 as a guide. All other layers depicted are sedimentary in nature with exception of G which is an ancient basaltic lava flow.



Write a history of these rock layers in table form going from the oldest layer (G) to the youngest! Include all events that can be ascertained from the section, such as times of erosion, tilting, folding, etc. Narrow the events to the appropriate geologic time (e.g., Permian, Jurassic, Tertiary, etc.). Use your age calculations as your guide. Remember in your write up: THE OLDEST EVENT IS ON THE BOTTOM!!!!

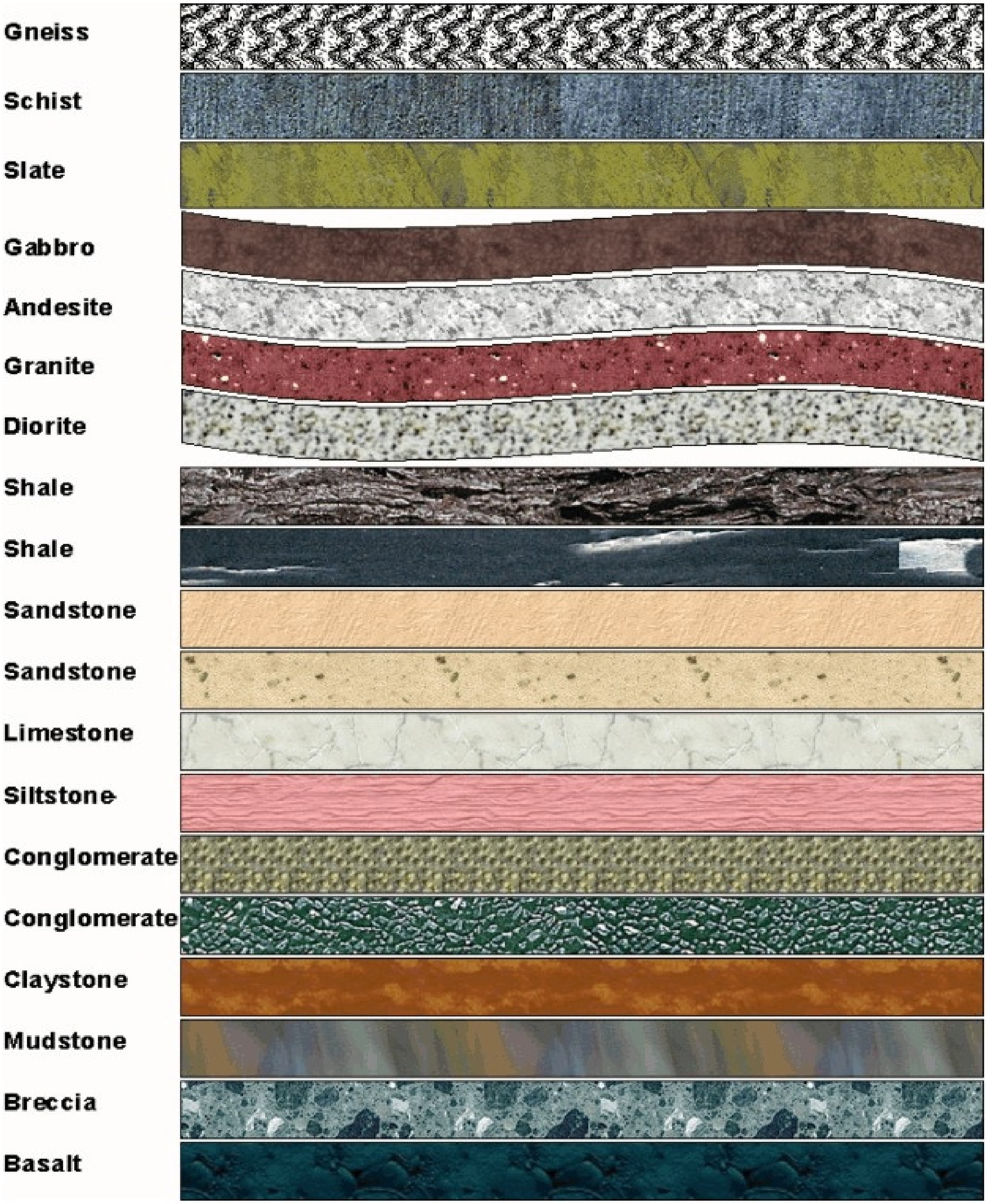
Name:	Course ID:

SEQUENCE OF EVENTS TABULATED WRITE UP (Remember, OLDEST ON BOTTOM)!

LAB EXERCISE 11 - CREATE YOUR OWN STRATIGRAPHIC SECTION

Name:	Course ID:

You will need scissors and glue for this Lab Activity. Print out the depicted geologic units below and cut them out. Then start gluing them together in your own stratigraphic sequence, layer upon layer. The Rules: Younger layers can overlap older layers. Your final section should include at a minimum: 10 rock layers, 1 tilt, 3 igneous crosscuts, 2 fault cross cuts, 2 unconformities.



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Name:	Course ID:

PASTE YOUR STRATIGRAPHIC SECTION HERE:

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LAB EXERCISE 12 - STRATIGRAPHIC CORRELATION

Name:	Course ID:

The use of index fossils is advantageous when correlation stratigraphic sections over long distances. Index fossils have a short time span of occurrence and often fall within certain geologic time periods. Figure 7.2 shows a summary of relevant index fossils used in correlation efforts. During this lab exercise you will be using these index fossils (figure 7.2) combined with your knowledge of geochronology to correlate and locate strata over an extended distance. You will also be challenged to decipher the regional geologic history and will learn how strata and geologic time can be traced from one distant location to another.

NOTE: In any stratigraphic correlation do time correlations first, then do lithologic correlations

The rule is **TIME trumps ROCK**

MATERIALS

- drawing pencils with an eraser
- 2 colored pencils (blue & red)
- copies of figures 7.2 and 7.3

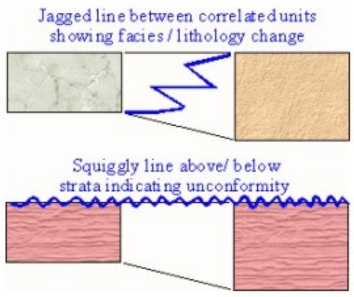
DIRECTIONS

Look at Figure 7.3. It shows three stacks of rock layers, two from outcrops more than 1,500 miles apart and one drill core strata taken from the depth of the earth between the two outcrops. Your job is to determine: a. Which layers (strata) correlate with one another AND which geologic times can be associated and traced throughout these layers.

STEP 1: Use the geochemical data from the analysis of unit u, v, w, x, y, z presented in table 7.2 to calculate the absolute times for each of these units. Transfer your calculated times to figure 7.3.

STEP 2: Identify the fossils depicted in figure 7.3 by comparing them to the Index Fossil Chart shown in figure 7.2. Write down the fossil name AND appropriate relative geologic time and absolute time span next to the fossils depicted in the rock columns (figure 7.3).

STEP 3: Using the geochronological results, the index fossil evidence, the short lithologic descriptors and visual appearance of the strata, connect the layers that appear to be the same using your blue pencil. If there is a facies change or change in lithology over distance, indicate this by a jagged line separating the two strata types in transition as in the example to the right. Also, mark each suspected UNCONFORMITY in your correlation effort with a squiggly line between the strata (see drawing on the right). Use the red pencil to show the changes in time periods across your correlated, stratigraphic sections.



STEP 4: Provide a short geologic narrative explaining how these stratigraphic columns came to be and in which particular time sequence. Deduct the environment of deposition if you can. Start with the oldest and move your way upward to the youngest or most recent event.

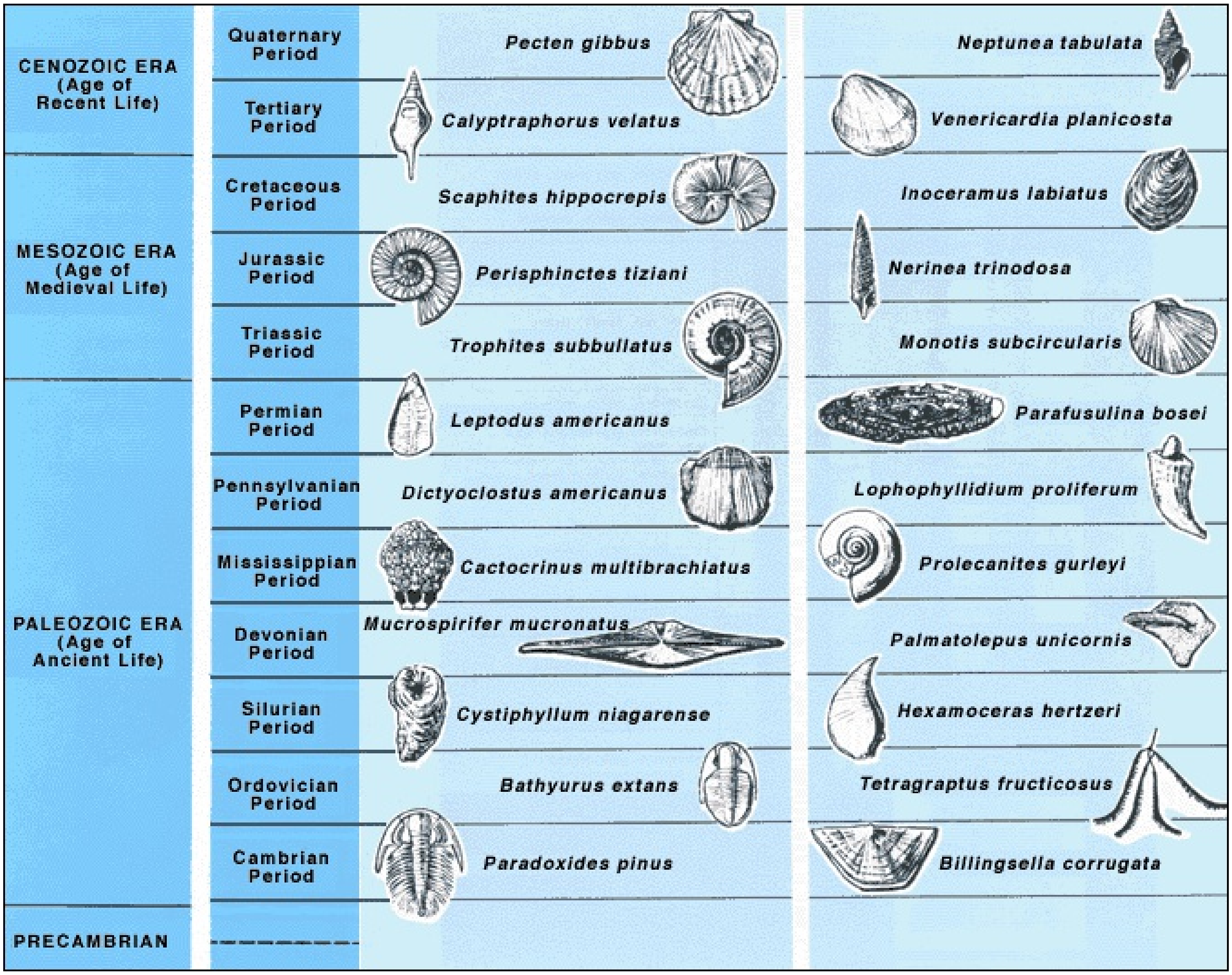
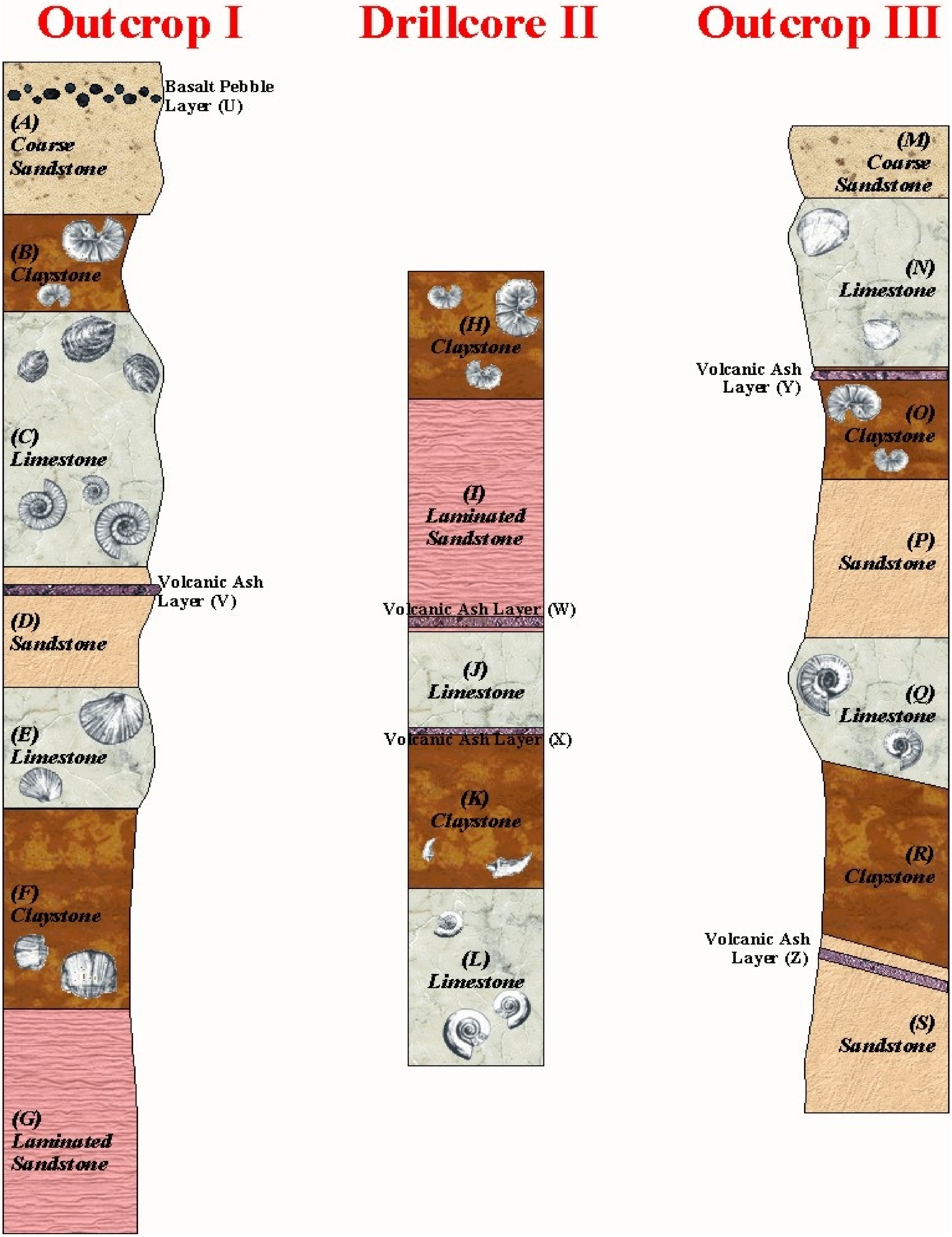


Figure 7.2 - Index Fossils for geologic time periods (Courtesy of United States Geological Survey)

Table 7.2 - Isotopic geochemical results for various igneous samples associated with Exercise 12

Unit	Description	Method	Parent Isotope (mmoles)	Daughter Isotope (mmoles)	Half-Life
U	rounded basalt pebbles	$^{87}Rb \Rightarrow {}^{87}Sr$	13.75	0.10	$48.8 \cdot 10^9$ years
V	rhyolitic ash layer	$^{235}U \Rightarrow {}^{207}Pb$	0.86	0.15	$0.703 \cdot 10^9$ years
W	rhyolitic ash layer	$^{235}U \Rightarrow {}^{207}Pb$	2.24	0.39	$0.703 \cdot 10^9$ years
X	volcanic breccia ash layer	$^{235}U \Rightarrow {}^{207}Pb$	3.99	1.10	$0.703 \cdot 10^9$ years
Y	rhyolite ash with obsidian	$^{40}K \Rightarrow {}^{40}Ar$	44.6	1.6	$1.25 \cdot 10^9$ years
Z	porphyritic rhyolite ash	$^{238}U \Rightarrow {}^{206}Pb$	6.34	0.32	$4.47 \cdot 10^9$ years

Figure 7.3 - STRATIGRAPHIC PROFILE WORKSHEET! NAME:______________________________________



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8 MAPS & MAPPING IN GEOLOGY - CONTOUR LINES

LAB EXERCISE 13 - ISOPLETHS & CONTOUR LINES

Name:	Course ID:

Isopleths are lines that connect places on a map to which the same numerical value of some measurement applies (examples: elevation, pressure, temperature). Such lines separate higher values from lower values. The spacing between the lines tells us how fast the quantity is changing with distance. This change of a quantity with distance is called a **gradient**. Often it is necessary to interpolate (estimate) the position of an isopleth from the surrounding area.

How to: In order to draw isopleths USE A PENCIL!!!!

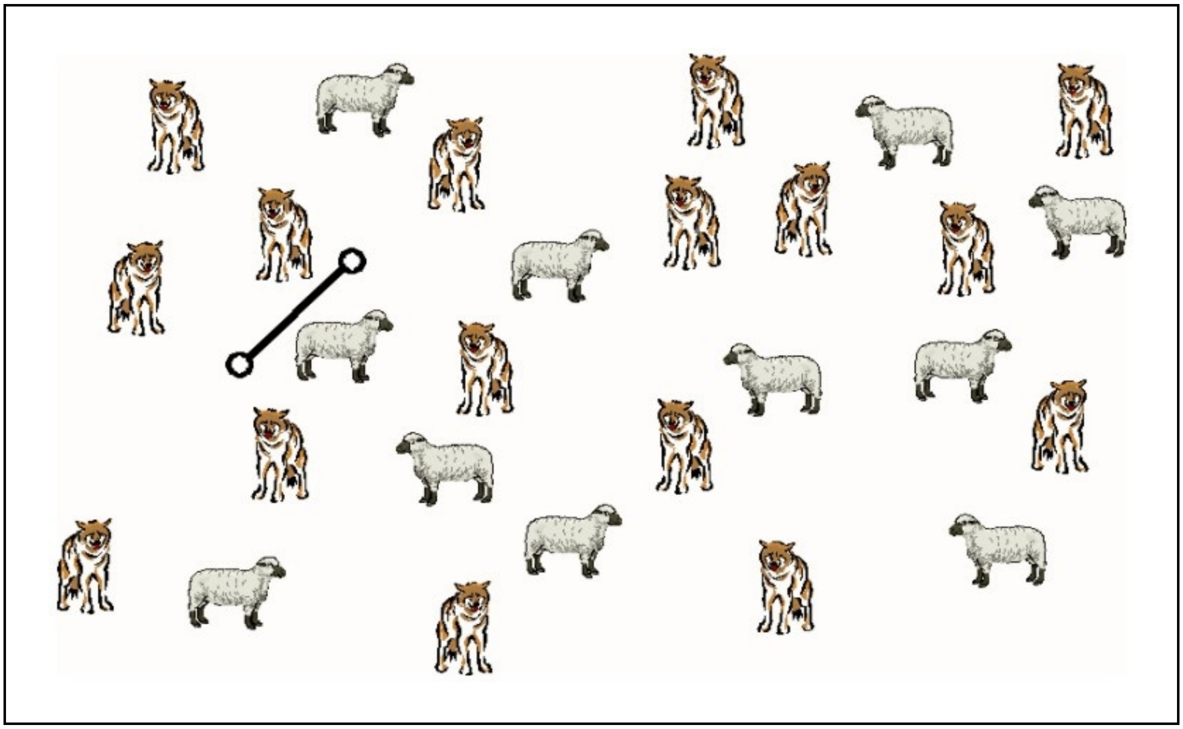
1. Scan the data to locate regions of maximum and minimum values and get an overall view of the distribution.
2. Begin with an intermediate value. Draw the first isopleth lightly preferably the one that has the most available data.
3. Lightly draw the remaining isopleths. They will follow usually the general outline of your first isopleth.
4. Do NOT draw isopleths in regions where there is no data. Every isopleth should have at least one value on each side of it.
5. Isopleths NEVER branch, merge, split, or intersect.

EXERCISE 1

Objectives: **1ST FUNCTION OF AN ISOPLETH LINE - SEPARATE DIFFERENT VALUES**

Isopleth Rule: If possible, an isopleth should make a closed loop without touching or crossing

Draw a "fence" line that separates all the wolfs from the sheep. The sheep should be on one side of the line and the wolfs on the other side. Your "fence" line should form a closed loop.



EXERCISE 2

Objectives: **1st FUNCTION OF AN ISOPLETH LINE - SEPARATE DIFFERENT VALUES**

Isopleth Rule: At the edge of the data you may stop an isopleth line

2nd FUNCTION OF AN ISOPLETH LINE - ISOPLETH LINES HAVE THEIR OWN DISTINCT VALUE

Draw a line that separates all the 5's and 4's. More than one line may be necessary to complete this exercise. What is the value of the isopleth you drew?

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EXERCISE 3

Objectives:

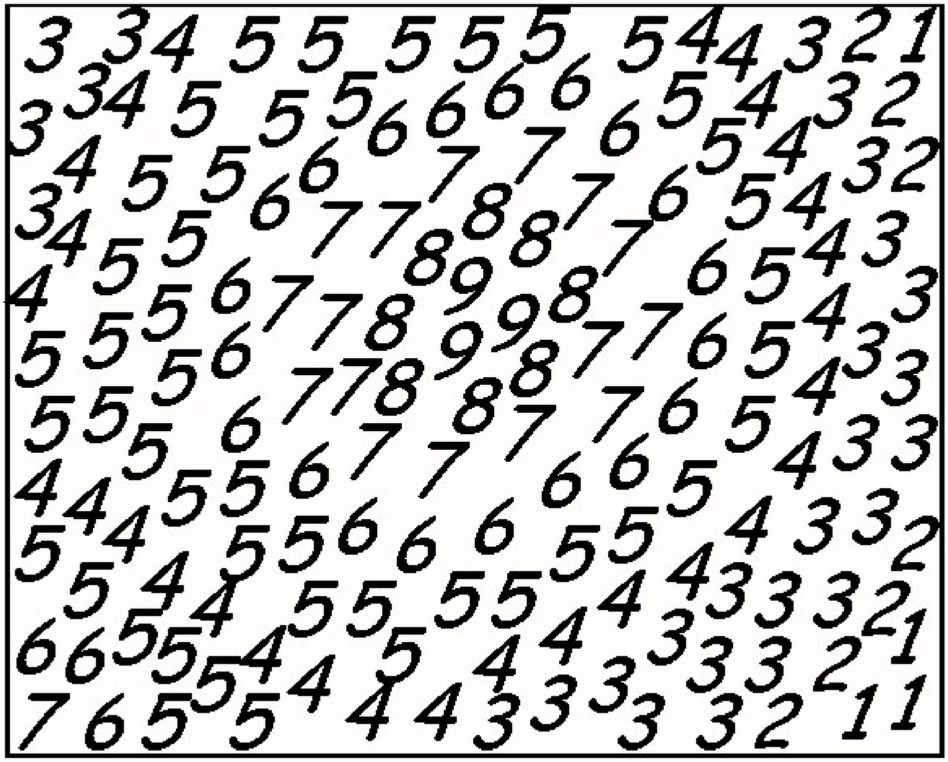
1st FUNCTION OF AN ISOPLETH LINE - SEPARATE DIFFERENT VALUES

2nd FUNCTION OF AN ISOPLETH LINE - ISOPLETH LINES HAVE THEIR OWN DISTINCT VALUE

Isopleth Rule: 1st & 2nd Function must always be satisfied, even when drawing multiple isopleth with different values.

Isopleth Rule: Isopleth lines can NOT touch or cross!

In addition to separating areas of different values, isopleths also represent places of equal values (along the isopleth line itself). In the box to the right, draw the isopleth lines for values 2, 4, 6, and 8.



EXERCISE 4

Objectives:

IF THERE IS NOT ENOUGH DATA, MORE POINTS CAN BE CREATED BY INTERPOLATION!

ISOPLETH LINES HAVE A VERTICAL DISTANCE, CALLED THE ISOPLETH OR CONTOUR INTERVAL!

1st Function of an Isopleth Line - Separate different values

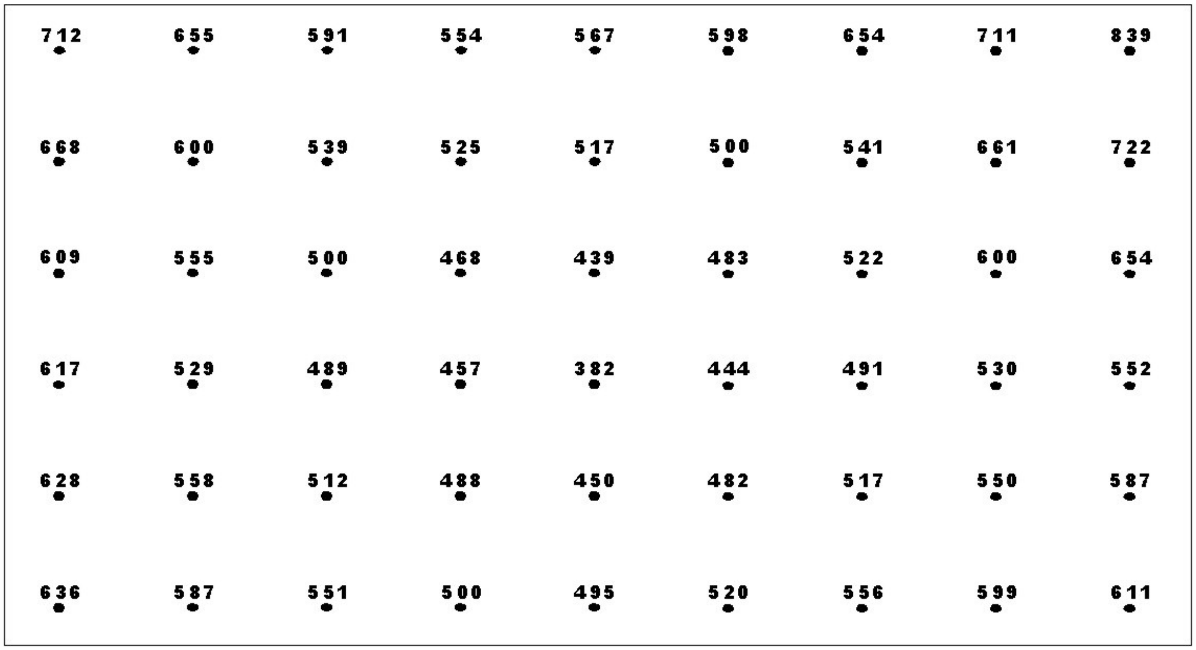
2nd Function of an Isopleth Line - Isopleth lines have their own distinct value

Isopleth Rule: 1st & 2nd Function must always be satisfied, even when drawing multiple isopleth with different values.

Isopleth Rule: Isopleth lines can NOT touch, cross, or abruptly stop in the middle of the map!

Draw isopleths at intervals of plus or minus 10. Start with the 500 isopleth line. If there are not enough data points, create more using the process of interpolation.

From the created 500 line move down at a contour interval of 50 (450, 400, etc.) as well as up (550, 600, etc.) drawing additional isopleths. Remember. You have greater control with more data points.



712	655	591	554	567	598	654	711	839
668	600	539	525	517	500	541	661	722
609	555	500	468	439	483	522	600	654
617	529	489	457	382	444	491	530	552
628	558	512	488	450	482	517	550	587
636	587	551	500	495	520	556	599	611

EXERCISE 5

Objectives:

DRAW A TOPOGRAPHIC MAP USING CONTOUR LINES.

1ST FUNCTION OF A CONTOUR LINE - SEPARATE DIFFERENT ELEVATIONS (VALUES)

2ND FUNCTION OF A CONTOUR LINE - CONTOUR LINES HAVE THEIR OWN DISTINCT ELEVATION (VALUE)

Contour Line Rule: 1st & 2nd Function must always be satisfied, even when drawing multiple contour lines with different values.

Contour Line Rule: Contour lines can NOT touch, cross, or abruptly stop in the middle of the map!

Contour Line Rule: When crossing rivers or streams, contour lines make a notch pointing upstream!

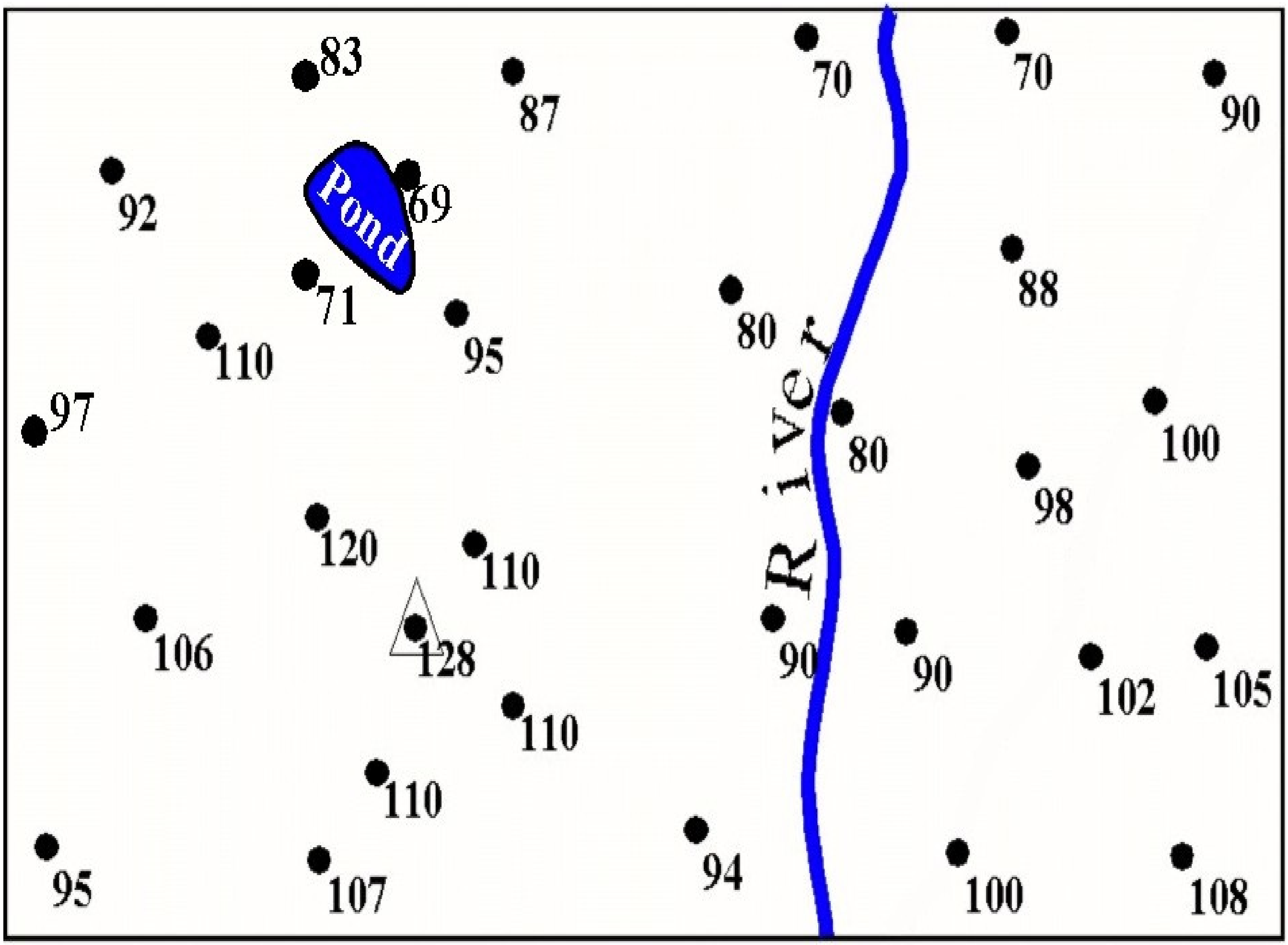
Contour Line Rule: When a steady increase in elevation is met by a sudden, often circular reverse of the usual topographic trend (e.g., sinkholes, volcanic craters, etc.), contour lines in the reverse trend are represented with the addition of tick-marks pointing downslope.

Drawing contour lines in the map below at a contour interval of 10ft. Start with a contour line of greatest resolution and extrapolate additional points as necessary. Features like rivers, ponds and mountain tops are marked as indicated.

REMEMBER ALL CONTOUR LINE RULES!!!!

Which rock type would you anticipate in the area?

____



LAB EXERCISE 14 - GROUNDWATER MAPPING

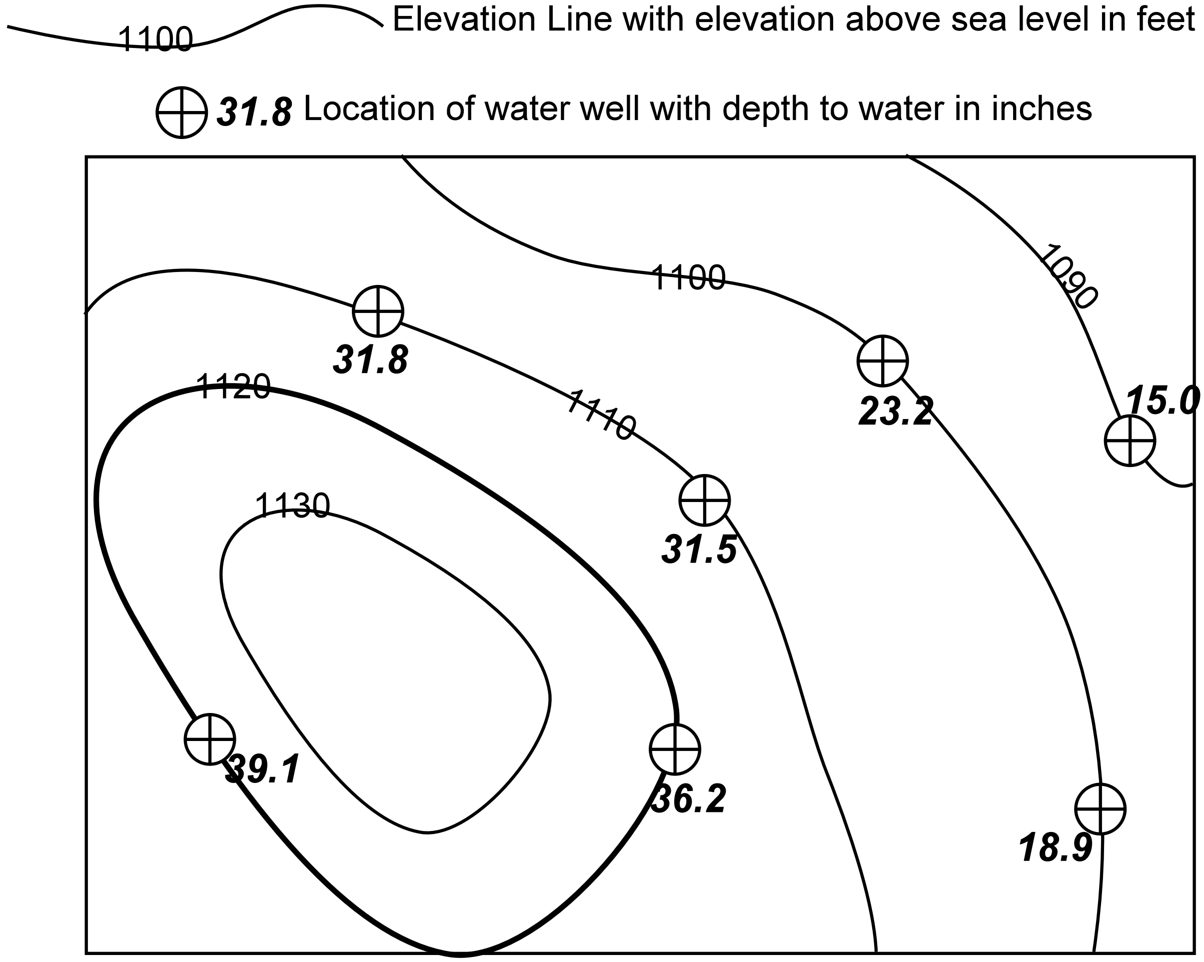
Name:	Course ID:

During this exercise you will create a second contour line map showing the contour of groundwater overlapping the elevation map of the topography as shown in the graphic. (Hint: Your secondary groundwater contours will NOT be the same as the surface contours!)

In the Map below you are given the elevation of the ground via contour lines (in feet above sea level), as well as the location of water wells. Each water well has a number corresponding with the depth of the water in inches measured from the top of the well. (*Hint: You must convert the inches of groundwater depth into feet first and then subtract this number from the indicated surface elevation to get the groundwater level in feet above sea-level. You may then proceed to construct your groundwater elevation map from the new data.*)

Which way is the groundwater flowing? (Hint: draw a contour map in blue for the elevations of the groundwater table in the subsurface)

What would happen if the well in the middle (31.5) was contaminated? (Indicate the possible consequence in red on your map!)



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9 MAPS & MAPPING IN GEOLOGY - CROSS SECTIONS

Geologists like to know what lies beneath. With a little ingenuity and some additional skills, subsurface geology can be estimated by using topographic maps. The skill to interpret what is beneath the surface starts with the interpretation of the surface contours itself. During this exercise you will learn to draw an accurate representation of a surface profile called a cross section. Drawing such cross sections involves the following steps (Refer to figure 9.1 while following the narrative below):

Materials:
-scratch paper -graph paper -colored pencils

Mark the cross section line on the map and label beginning and end in the format (X - X'). Temporarily affix a piece of scratch paper along the cross section line on the map as depicted in order to transfer elevations and other landmarks:

- Mark beginning and end points
- Make marks where contour lines cross scratch paper and label.
- Mark land marks, such as streets, rivers, hilltops, etc. on scratch paper and label

Next, transfer information from scratch paper onto graph paper and construct a cross sectional profile. First, decide on a vertical scale. It should be exaggerated compared to the map scale, otherwise your profile will lack needed detail. Use the "map scale" as a starting point. A 10x exaggeration is often sufficient and easy to construct from a map scale. You only need to drop the last zero (0) in the map scale distance, thus 1000 ft becomes 100 ft, 100 ft becomes 10 ft and so forth. Then:

- Mark the vertical elevation on the y axis of your graph paper.
- Affix the scratch paper in a horizontal fashion in the x-axis direction on the graph paper as shown.
- Transpose the "Elevation Tick marks" from your scratch paper exactly vertical to the correct elevation on the graph paper as shown.
- Do the same for landmarks and start and end points of the sectional profile.

Lastly, connect the dots! Hint: Make sure you draw a curve connecting all the dots and NOT individual straight lines.

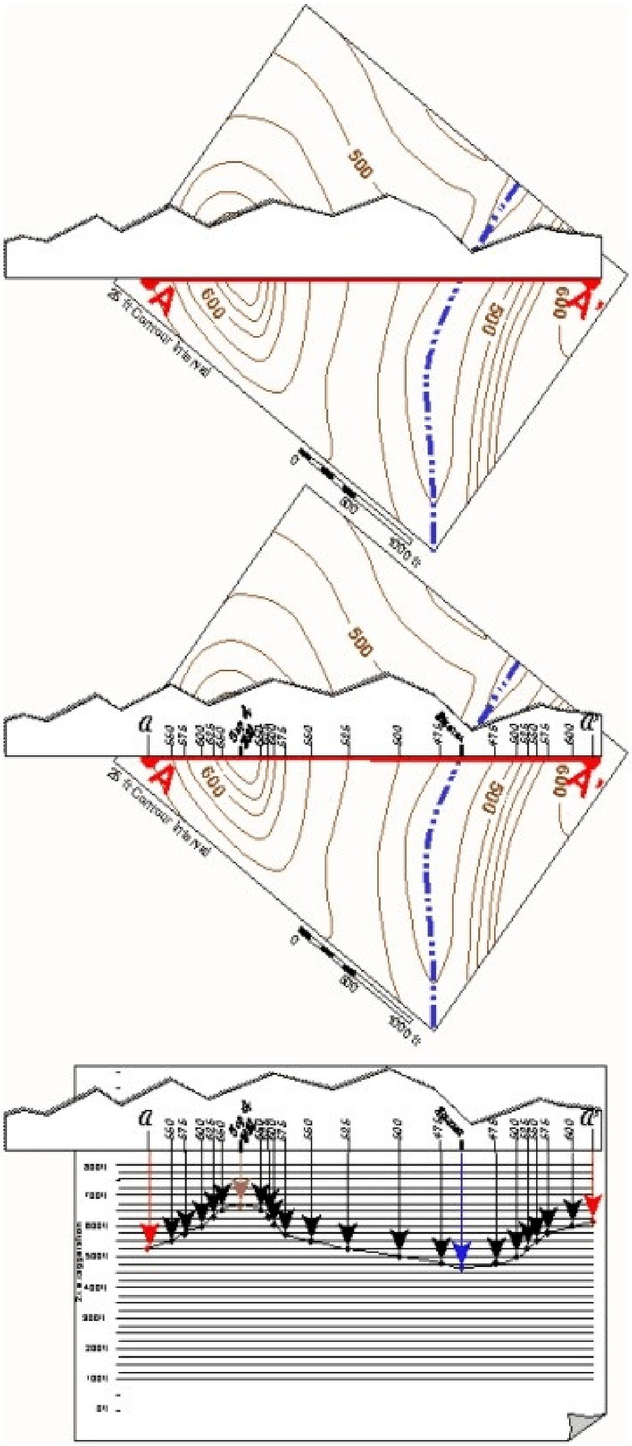


Figure 9.1 - How to construct a cross section from a topographic map

9.1 OTHER USEFUL MAP INTERPRETATION TECHNIQUES & SKILLS

MAP RELIEF: The difference between the highest and lowest elevation present in a particular map. Find the highest elevation on the map and record *(Hint: Usually hill or mountain tops)*. Then find the lowest elevation on the map and record *(Hint: Since rivers flow downhill, they often encounter the lowest elevation somewhere on the map edge, but not always!)*. Subtract the lower elevation from the higher elevation. The answer expressed in feet or meters is the relief of a map. The number is an indicator for terrain roughness. Large numbers are equivalent to very rough (mountainous terrain), while a small number corresponds to a gentle or rolling topography.

MAP SCALE & DISTANCES: *Note: Using scale ratios to determine distances works only on original standardized maps or exact copies of such maps*!

Map scales are expressed as ratios on STANDARDIZED MAPS such as 1:24,000 for example. This means that 1 length unit on the map is equal to 24 000 of the same length units on the "real" ground. In other words, 1 inch on map = 24 000 inches on ground, 1 cm on map = 24 000 cm on ground, 1 foot on map = 24 000 feet on ground, 1 mm on map = 24 000 mm on ground. The unit you chose is irrelevant as long as you use the same unit for map AND ground.

Sample Problem: The scale is 1: 60,000. You measure 3.5 inch distance on the map. How far is this distance in real life? *Note: Write the answer in a unit that makes sense, such as miles or km.* (See answer below)

ANGLE OF SLOPING STRATA: Sometimes it is necessary to access the dip angle of sloping strata from a topographic map, also called the DIP. This is possible if the sloping strata is prominently mapped (such as a hogback) and contour lines and map scale are clearly accessible on the map.

Note: While one might be tempted to read the slope directly with aid of a protractor from a cross sectional profile, remember, the vertical scale on cross sections is usually exaggerated. Hence your angular dip will also be exaggerated and will be WRONG!

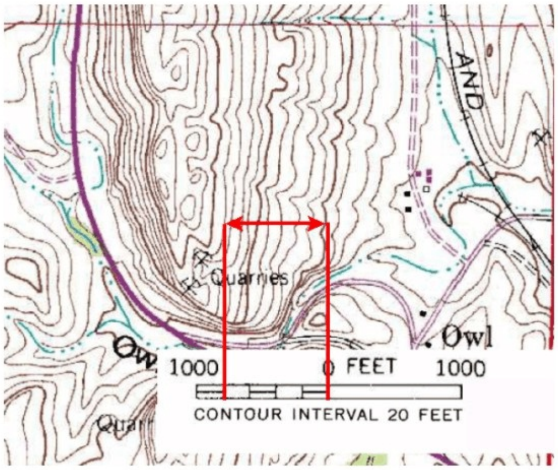


Figure 9.2 - Example for retrieving data from a topographic map in order to compute slope

Use figure 9.2 for an example. The geologic strata hogback is clearly visible on the map, but how steep does it dip into the ground? We can read the horizontal distance as 800 ft between two contour lines as indicated. The vertical change over the same distance can be readily ascertained by the given contour interval of 20 ft and the 9 contour spacings along the 800 ft horizontal distance, which is 20 ft times 9 or 180 feet!

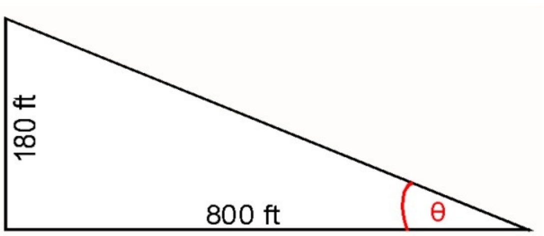


Figure 9.3 - Triangle of height vs. distance with associated slope angle

Using the right triangle given in figure 9.3 with our indicated distances we can calculate the slope or dip (angle θ) of the hogback with the following equation:

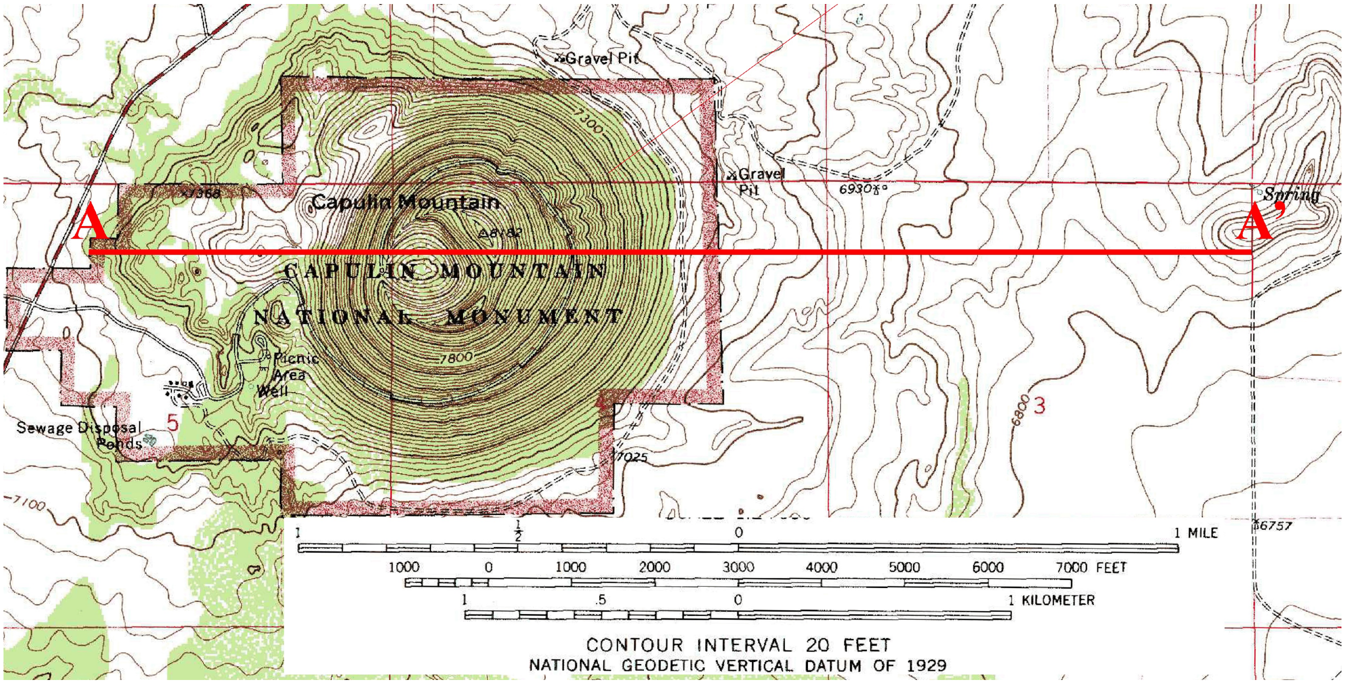
$$\theta^{\circ} = \arctan\frac{vertical}{horizontal} = \arctan\frac{180\,ft}{800\,ft} = \arctan 0.225 = 12.68^{\circ}$$

Answers: 3.5 in x 60,000 = 210,000 in. 210,000 ÷ 12 = 17,500 feet. 17,500 ft ÷ 5,280 = **3.31 miles**

LAB EXERCISE 15 - CROSS SECTIONS

Name:	Course ID:

Draw the cross-sections of the topography of the Capulin Volcano, NM as outlined! Chose your vertical scale and exaggeration wisely (Your cross sectional profile has to fit in the graphing area below.) Then answer the questions below!
Hint: For steep slopes (closely spaced lines), plot only major elevations!



1. What is the relief of this map section (Show calculations):____________________________

2. What is the average slope of the East Side and the West Side of the volcano? Calculate and mark slope on your cross sectional profile and map! (Show Calculations)

3. Measure the slope of the volcano East & West side directly from your cross section. Is there a difference? How much? Why?

10 MAPS & MAPPING IN GEOLOGY - STRIKE & DIP

A very helpful tool in geology is the indication of STRIKE and DIP on a map, aiding in the interpretation of the exposed stratigraphy and structure. While DIP and associated calculations were presented in the previous chapter, STRIKE is an indication of the compass direction of the lateral continuity of a rock outcrop or geologic formation. The STRIKE direction is measured in degrees from true North and is always at right angles to the DIP direction.

Geologists use STRIKE & DIP Symbols on maps, which look like lopsided T's with the long part indicating the STRIKE and the short part showing the DIP. The dip angle in degrees is marked right next to the short tic mark. The example in figure 10.1 shows an N30E STRIKE with a 23° SE DIP. The compass illustrated around the symbol is not plotted on the map, but is a visual aid to show how STRIKE directions are identified.

The easiest way to predict DIP direction in the field is to apply water to a rock outcropping. Since water will always flow down the steepest of all possible angles on a slope, the direction of the flow of water (from a water bottle for example), will show the true dip direction. Remember. The STRIKE is perpendicular to the dip. Figure 10.2 illustrates how a STRIKE & DIP symbol would look like if it were painted on a rock outcrop.

On a topographic map, the STRIKE is more or less parallel to the contour lines as presented in figure 10.3. Careful observation of the map shows small gullies, carved out over time by water running down the DIP of the rock slope. These gullies, represented by an array of small "V" shaped notches in the contour lines can be used to indicate DIP direction. Since STRIKE is at right angles to the DIP, such notches in a line will aid in positioning the STRIKE & DIP symbols correctly on a map.

Question: How would you write the STRIKE and DIP shown in figure 10.3 in a report for example? See below for answer.

While estimating the STRIKE and DIP from topographic maps is possible in most cases, be aware that rock strata sometimes does not erode evenly along a sloped surface. Thus the slope may actually be steeper or gentler then the true dip of the lithology. Field investigations are therefore essential in order to validate STRIKE & DIP assumptions.

Answers: Strike of N5E and a dip of 13° E

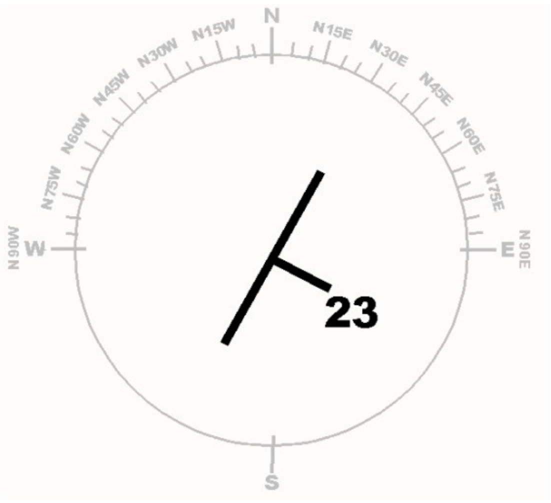


Figure 10.1 - Example of STRIKE & DIP Symbol (Note:

Figure 10.2 - Example of STRIKE & DIP on a hogback outcrop.

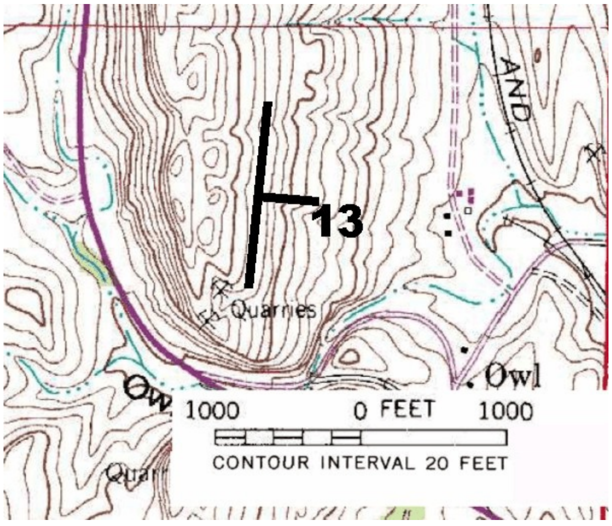


Figure 10.3 - STRIKE & DIP symbol on a topographic map.

11 MAPS & MAPPING IN GEOLOGY - LITHOLOGIES & FOLDED STRUCTURES

Lithologies can be estimated from a geologic map from surface features represented by the contour lines. Hence, interpreting contour lines will greatly assist in making sound predictions about the rocks present. Figure 11.1 summarizes examples for lithologic map interpretations.

Hard igneous or metamorphic rocks often appear more jagged with steep valleys (hard to erode) as shown on the left side of figure 11.1A while sedimentary rocks are somewhat smooth or less prominent (easier to erode). Hogbacks are a good indicator for sedimentary lithologies. They also point to a dipping or folded strata.

Soft sedimentary rocks, such as shale or siltstone will form valleys (see center of figure 11.1B), while well cemented, resilient sedimentary lithologies, such as sandstone or conglomerate will shape prominent hogbacks if the strata is tilted (see figure 11.1B left & right sides).

Limestone in the subsurface often creates sinkholes (shown by stippled contour lines), especially in wetter climates. These patches of sinkholes are known as a karst topography. Many of the holes will fill with water, allowing for an array of small lakes or ponds (see figure 11.1C). However, an abundance of still water bodies WITHOUT evident karst topography is most likely the result of impermeable clay in the subsurface.

The loose sediment of an alluvial fan in figure 11.1D is depicted by erratic contour lines, typical of unconsolidated materials. Moraines in glacial topographies or sand dunes for example exhibit similar contour line characteristics. Note that such deposits at large are often connected to high volumes of mass wasting from mountainous areas as seen to the right of 11.1D.

Landscapes carved by flowing water are indicated by "V" shaped valleys, while glaciation produces broad "U" shaped valleys as can be seen in the center of figure 11.1E. However, common sense should be employed when making glacial interpretations from topographic maps. A "U" shaped valley at low altitudes in temperate or tropical climates was probably not created by glaciation. Mountainous areas of high elevations, however, are cold enough to be sculpted by alpine glaciation as seen in figure 11.1E.

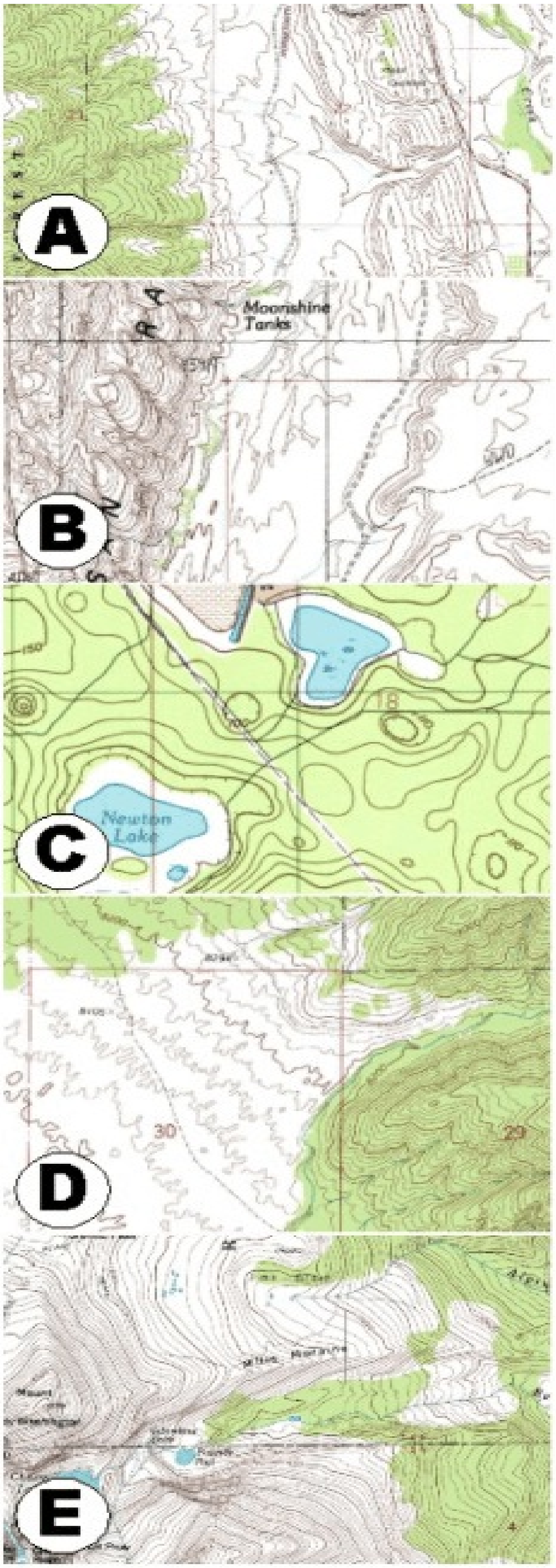


Figure 11.1 - Examples of lithologic interpretations from topographic maps.

Tectonic structures, such as folds or faults may also be interpreted from topographic maps. However, correct interpretation may require some additional tools. Folds are easiest to detect from cross sectional profiles as depicted in figure 11.2. Graphic A shows a profile of typical hogbacks, all dipping in the same direction. While folding or tilting did indeed occur, the overarching geologic structure may not be immediately recognizable.

Profile 11.2B unmistakably exhibits an anticlinal fold. Both hogbacks dip away from each other. In order to determine folding from topographic maps, long sectional profiles across a multitude of ridges are preferred. Sections of an anticline or syncline may otherwise just look like 11.2A. Figure 11.2C indicates a synclinal fold. Here, both hogbacks dip toward each other. Again, be aware that missing the center of such folds in cross sections results in nothing more than 11.2A. It should be also noted that these folds can be highly asymmetrical. Synclines and anticlines often occur in succession along such a cross sectional profile.

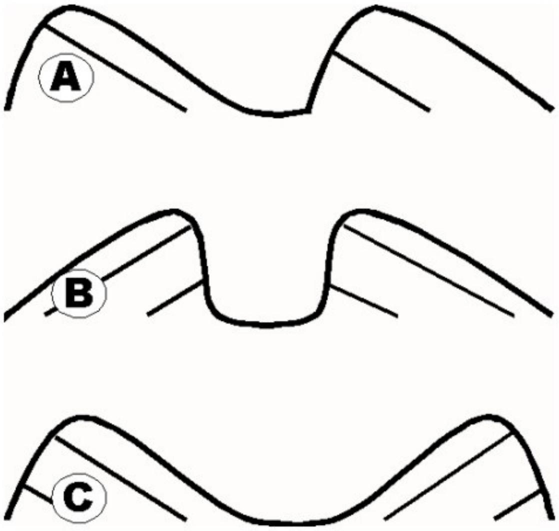


Figure 11.2 - Cross sectional profiles for interpretation of folded structures.

The presence of a fault or fault system is more difficult to extrapolate from a topographic map. However, careful observation of contour lines may strongly suggest the presence of faults. Since faults are more or less linear features, any type of lineation on a topographic map that runs contraire to the usual topographic pattern may be indicative of a fault. Figure 11.3 shows some examples of faulting as shown on a topographic map. The offset hogback in 11.3A strongly suggests the presence of a fault, marked here by the red dashed line. The two arrows show the original connection point of the hogback. The large strike slip or horizontal displacement of the geologic strata is evident.

*Question: By the way, what type of fault is shown in 11.3A? Be specific*___________________________ *(Solution below)*

Karst topographies are also useful in identifying faults. Limestone dissolves through percolation of water in the underground and water moves most likely along natural weak points in the rock. Faults or fault systems represent such weak points and sinkhole patterns may often appear in linear patterns, almost like pearls on a string as indicated in figure 11.3B. Two faults distinguished by the red dashed lines can be identified through sinkhole arrangements. The largest cave-in appears at the intersection of the faults probably created by greater subsurface water percolation at the weakest point in the limestone.

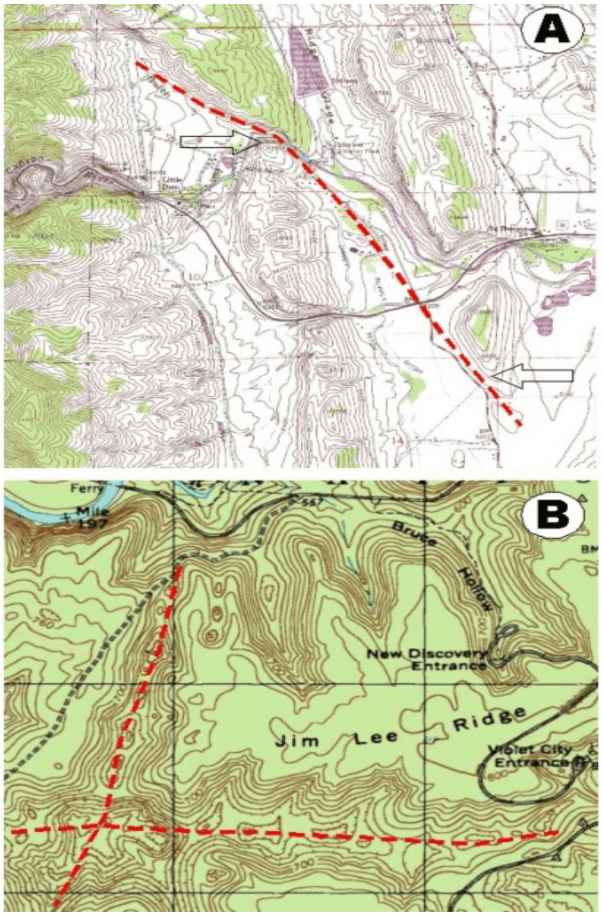


Figure 11.3 - Examples of fault identification from topographic maps.

Answers: Right Lateral Strike Slip Fault.

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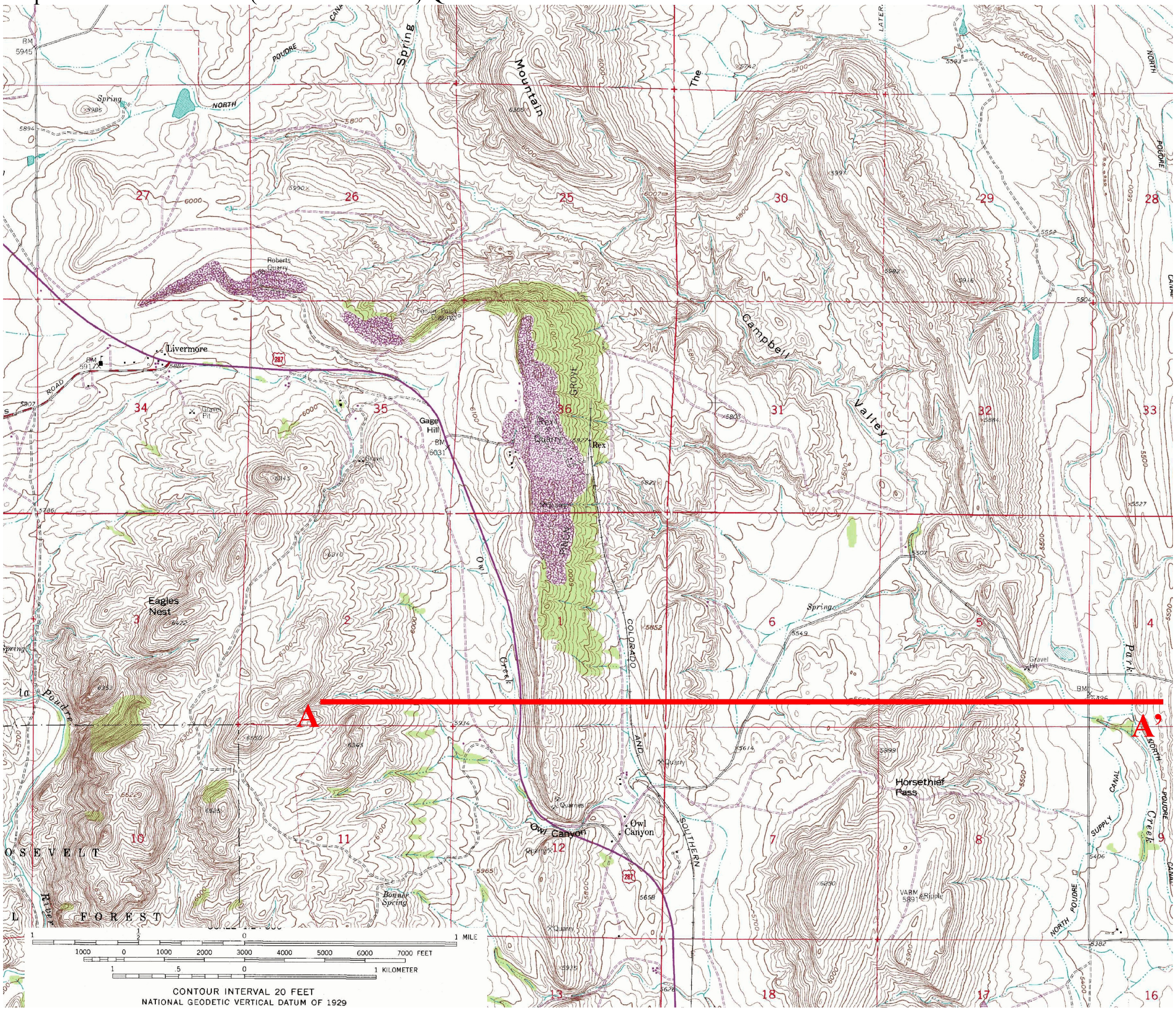
LAB EXERCISE 16 - MAP INTERPRETATIONS: DIPPING GEOLOGIC STRUCTURES

Name:	Course ID:

For each of the maps below please answer the following questions and complete the worksheet!

Map Title: LIVERMORE (OWL CANYON) QUADRANGLE COLORADO



Calculated Map Scale: ________________________________ Contour interval: ___________________________

Relief of Map (underline your answer):

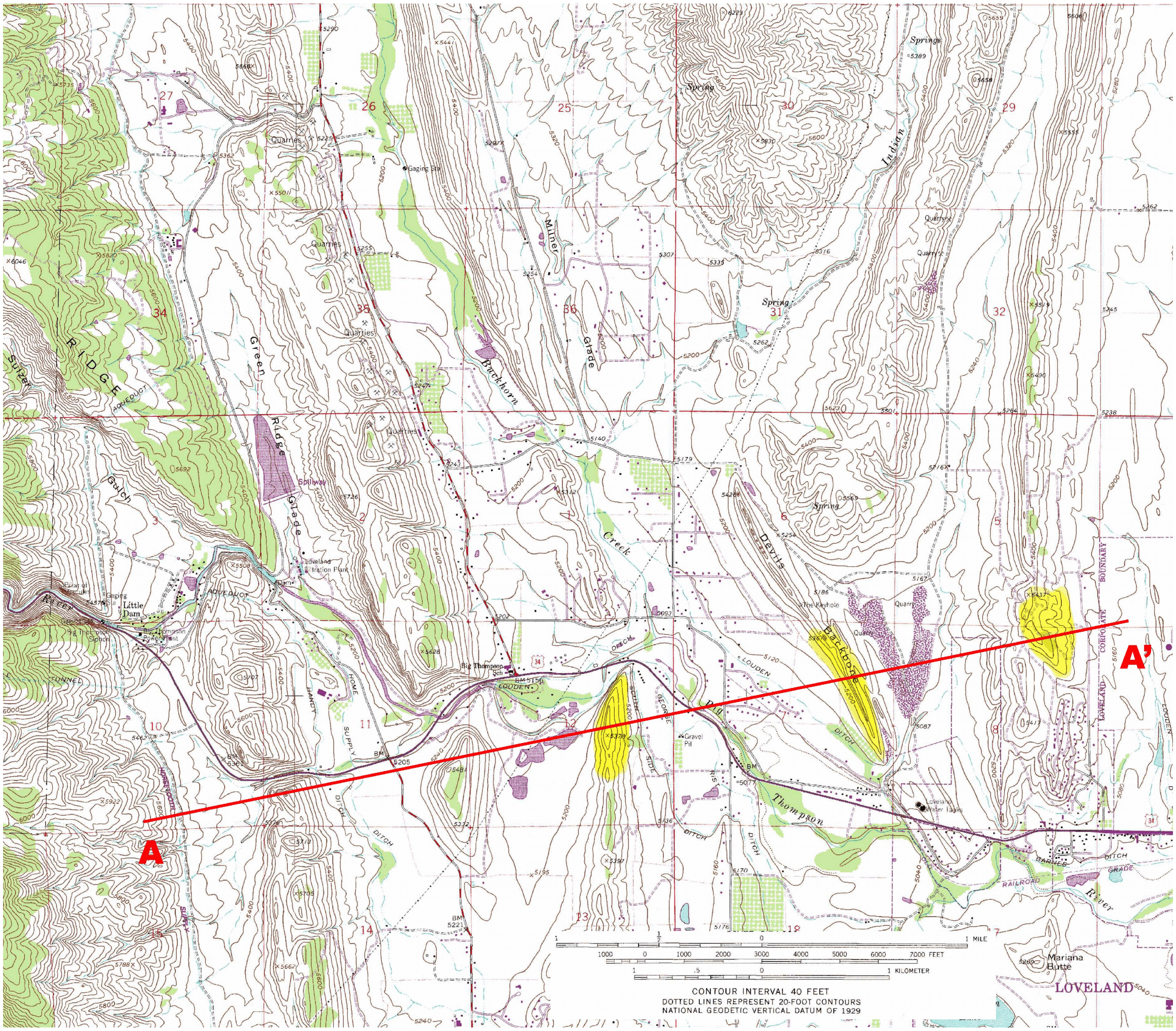
Place at least 6 STRIKE & DIP symbols on your map calculating correct dip angles.

Draw the cross section A - A' neatly on graph paper. Then use the map and your cross sectional profile to answer the following questions:

What tectonic event did most likely occur in this area? Give evidence for your conclusion:

Can you tell anything about the rock types (lithologies) present in the map? Summarize the criteria for your decision below, then use colored pencils to shade in the extent and position of your estimated lithologies on the map. (*Hint: The rocks for the eastern ~3/4 of your cross section line are sedimentary!*)

Map Title: MASONVILLE (DEVILS BACKBONE) QUADRANGLE COLORADO



Calculated Map Scale: ________________________________ Contour interval: ___________________________

Relief of Map (underline your answer):

Place at STRIKE & DIP symbols on the map at every hogback along the A-A' section showing dip angles. *(Hint: Draw cross section to find dip direction of Devils Backbone. Dip is toward the gentler slope!)*

Draw the cross section A - A' neatly on graph paper. Use map and cross sectional profiles to answer and do the following:

The yellow shaded areas on the map represent the presence of the Dakota Group comprised of very resilient conglomerates and coarse sandstones. Create a partial geologic map by completing the coloration on the map for the outcrop of the Dakota Group strata.

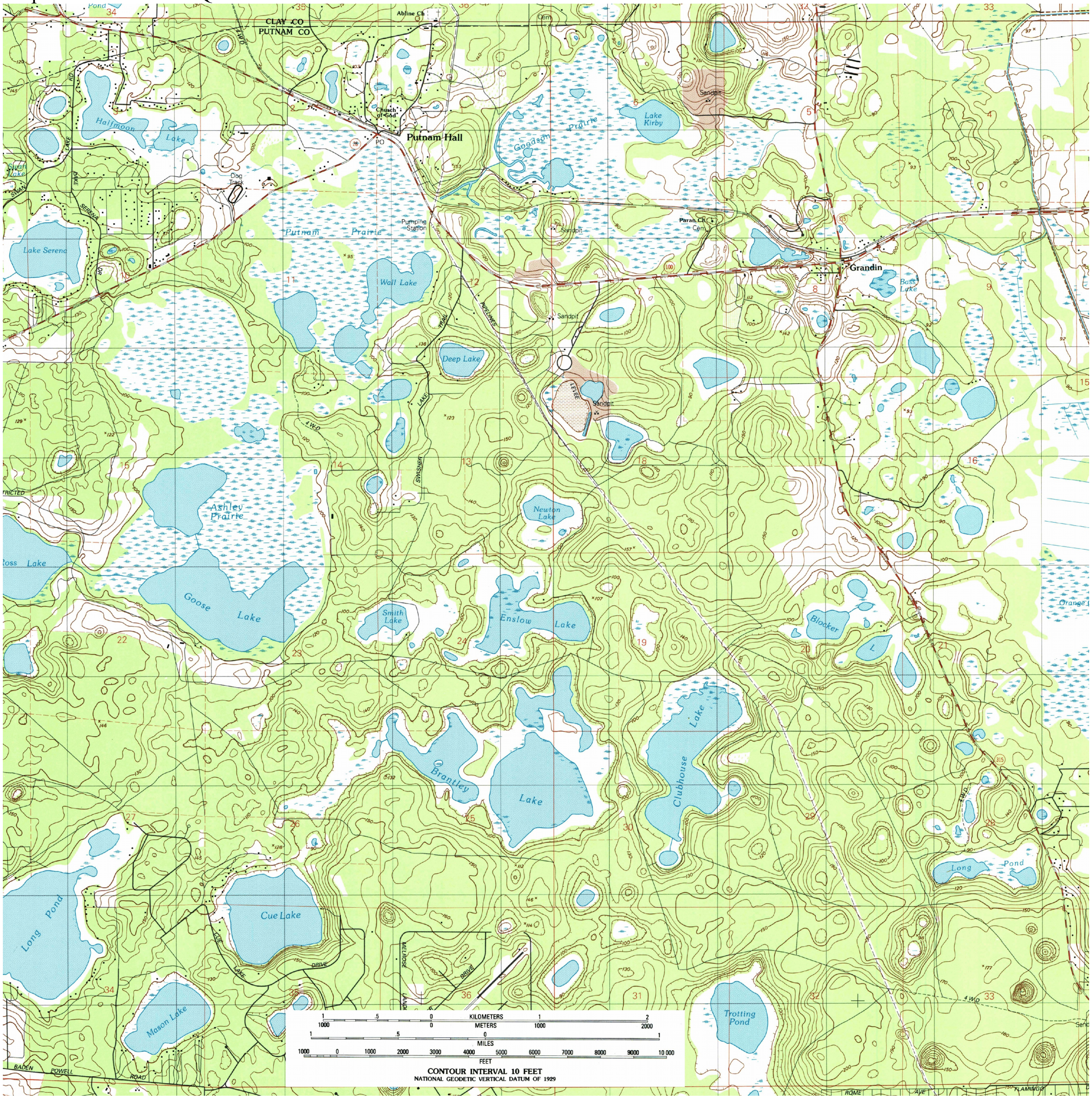
Transfer the coloration onto your cross sectional profile. Then show on your cross section how the Dakota group lithologies might be connected in the subsurface and indicate their extent above the present surface before erosion. What geologic structure is present on the map? Give evidence for your conclusion:

LAB EXERCISE 17 - MAP INTERPRETATIONS: GROUNDWATER

Name:	Course ID:

For each of the maps below please answer the following questions and complete the worksheet!

Map Title: PUTNAM QUADRANGLE FLORIDA



Map Scale: ______________________________ Contour interval: _________________________

Relief of Map (underline your answer):

What is the most likely rock-type underlying the area depicted on the map? Give evidence for your conclusion:

There is a lot of surface water on the map. The elevation of the surface of the lakes coincides with the elevation of the groundwater level in the same area. Estimate as close as possible the elevation of each lake surface and record the elevation for each like with big black letters on the map. Does the groundwater flow? If yes, in which direction? Indicate any groundwater movement with arrows on the map.

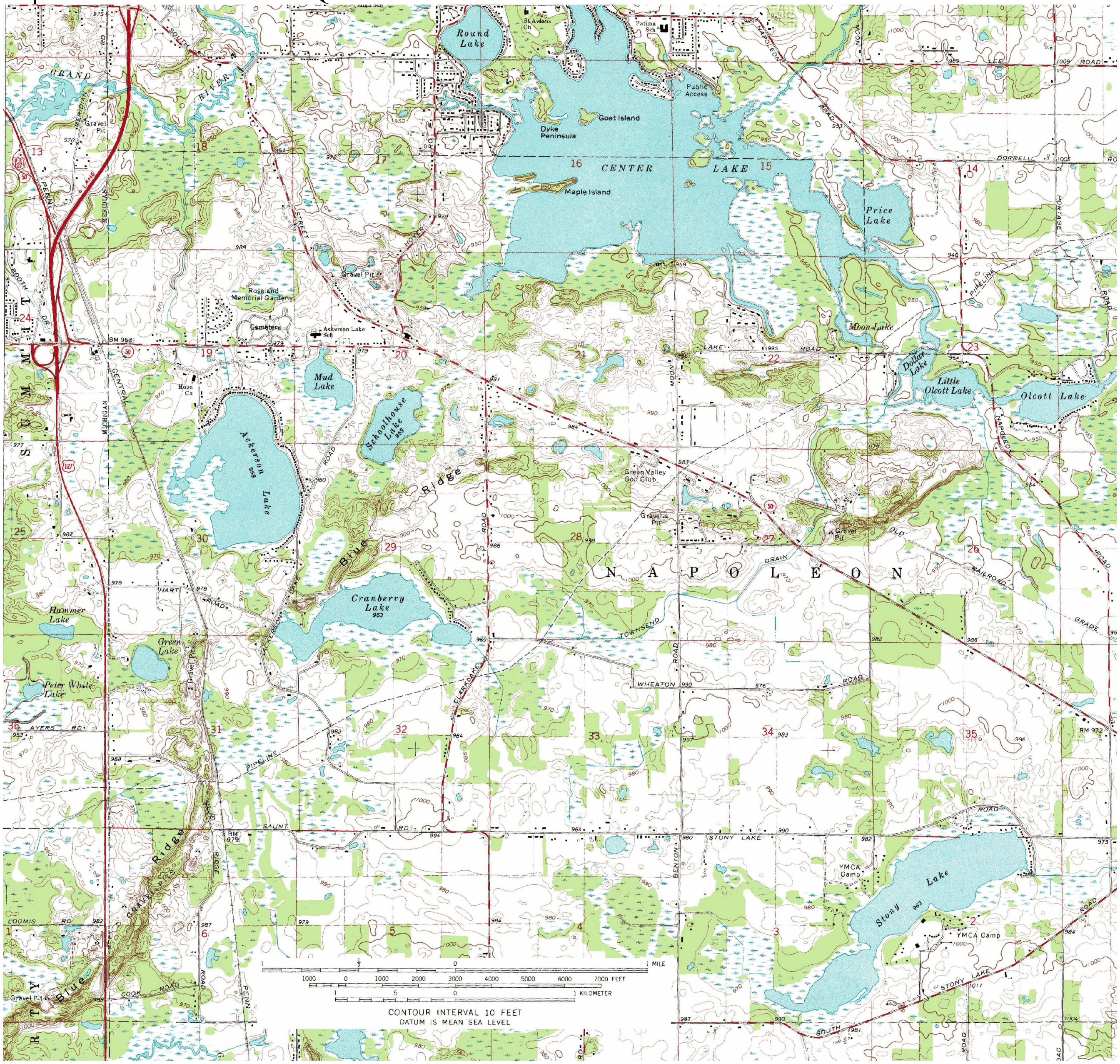
LAB EXERCISE 18 - MAP INTERPRETATIONS: GROUNDWATER / CONTINENTAL GLACIATION

Name:

Course ID:

For each of the maps below please answer the following questions and complete the worksheet!

Map Title: MICHIGAN CENTER QUADRANGLE MICHIGAN



Map Scale: ______________________________ Contour interval: _________________________
Relief of Map (underline your answer):

What is the most likely rock-type underlying the area depicted on the map? Give evidence for your conclusion:

There is a lot of surface water on the map. The elevation of the surface of the lakes coincides with the elevation of the groundwater level in the same area. For each lake / pond determine the elevation of the water surface, either by reading it directly from the lake when provided or by estimating the elevation as close as possible from the contour lines. Record each lake elevation with big black letters on the map. In which direction is the groundwater flowing? Indicate the movement with arrows on the map.

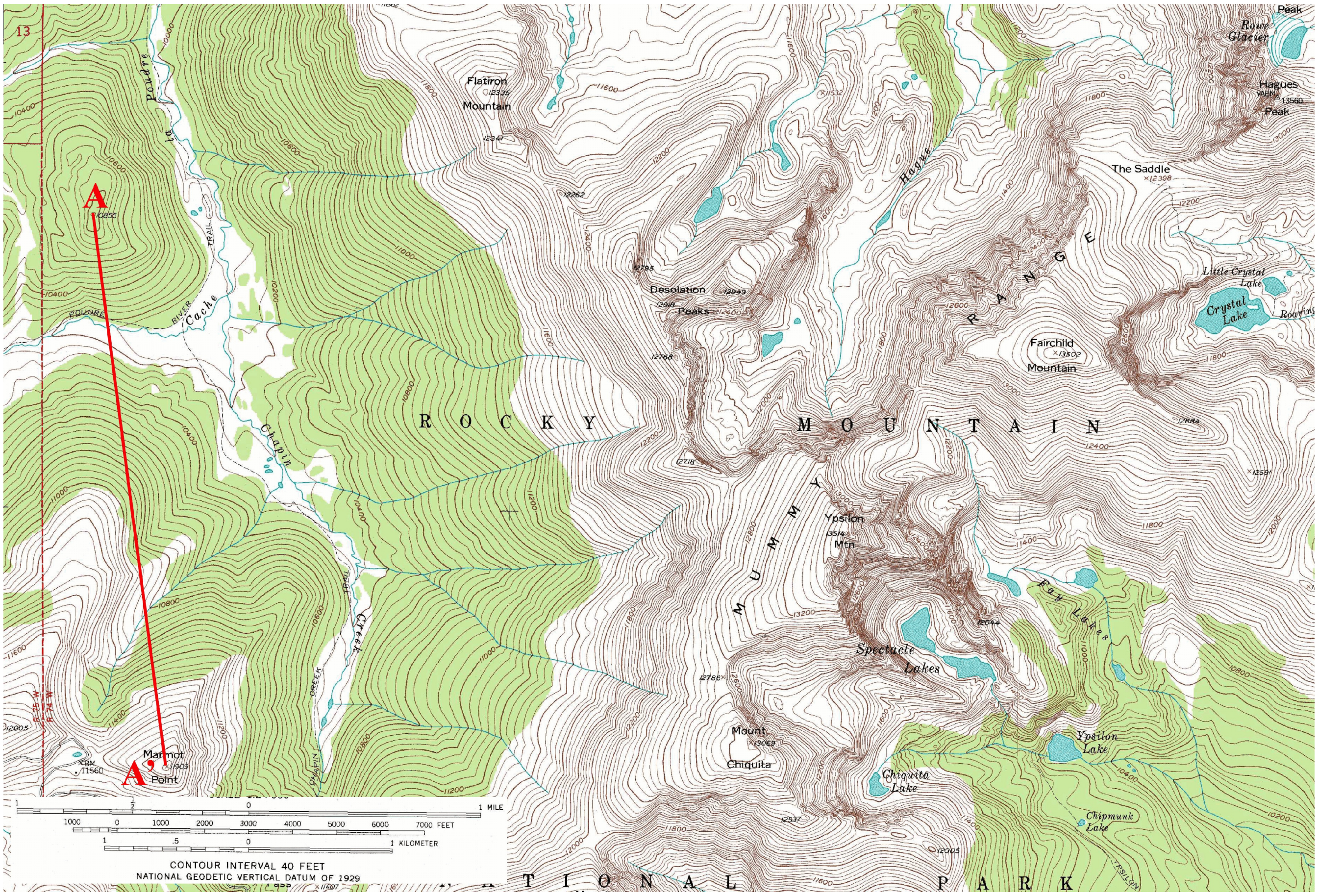
The map depicts the remnants of a continental glaciation during the last ice age. Use a colored pencil and identify as many glaciation features as possible by shading and labeling them on the map (e.g., Drumlins? Eskers? Moraines, etc.)

Why are there so many lakes in the area? Please answer in 5 sentences or less:

LAB EXERCISE 19 - MAP INTERPRETATIONS: ALPINE ENVIRONMENT & GLACIATION

Name:	Course ID:

For each of the maps below please answer the following questions and complete the worksheet!
Map Title: TRAIL RIDGE ROAD QUADRANGLE COLORADO (ROCKY MOUNTAIN NP)



Calculated Map Scale: ________________________________ Contour interval: ___________________________
Relief of Map (underline your answer):

What is the most likely rock-type underlying the area depicted on the map? Give evidence for your conclusion:

Draw the cross section A - A' neatly on graph paper. Use map and cross sectional profile to answer and do the following:

Why are there different shaped valleys on your cross section? Explain.

What processes formed the broad valley containing crystal lake just east of Fairchild Mountain?

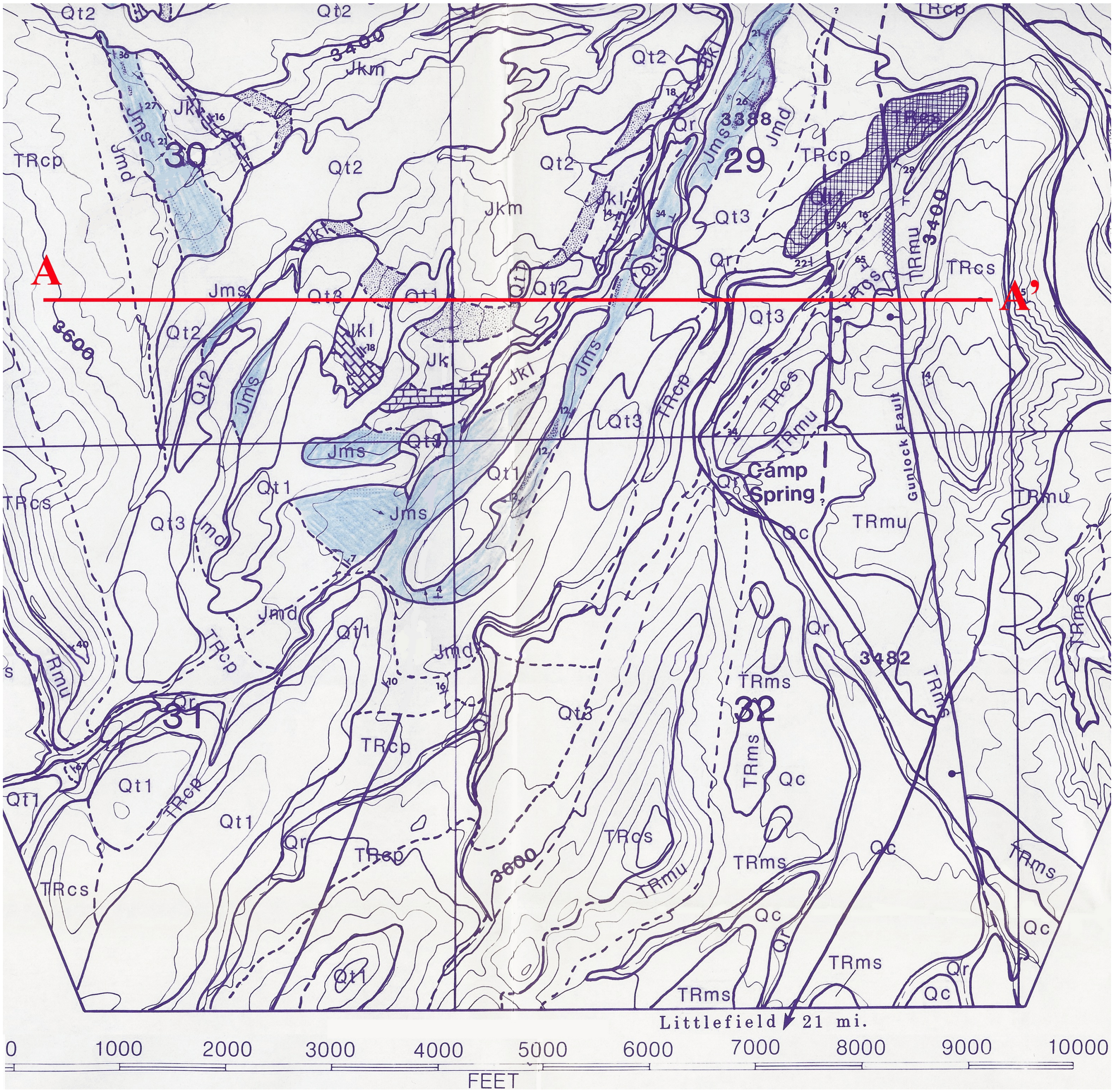
The topography on the east side of Ypsilon Mountain is strikingly different from the topography on the west side of the mountain. Why?

What is the general shape of Marmot Point and Mount Chiquita to the South of the Map? What are these type of Mountains called and how do they form? *(Hint: Flatiron Mountain to the North is in the process of becoming such a mountain!)*

LAB EXERCISE 20 - GEOLOGIC MAPPING

Name:	Course ID:

Geologic maps are a geologist's best friend. They depict the exposed surface geology. Formations and similar units are color coded to aid in identification and interpretation. The map below is an incomplete geologic map of the Shivwits area in far Southwestern Utah. A legend for the different rock formations and their geologic ages is also given.



The early Jurassic Springdale Sandstone Member of the Moenave (Jms) formation is shaded blue. Complete the geologic map by color shading all formations / members present with some differing colors of your choice. *(Hint: Mesozoic aged rocks are often colored in variations of blue or green shades)*. Use the same color scheme for the map explanation and in your cross sectional profile. Quaternary terrace deposits are often unconsolidated and horizontal, covering the underlying ancient lithologies. After completion of map, explanation legend and cross section, answer the questions listed below:

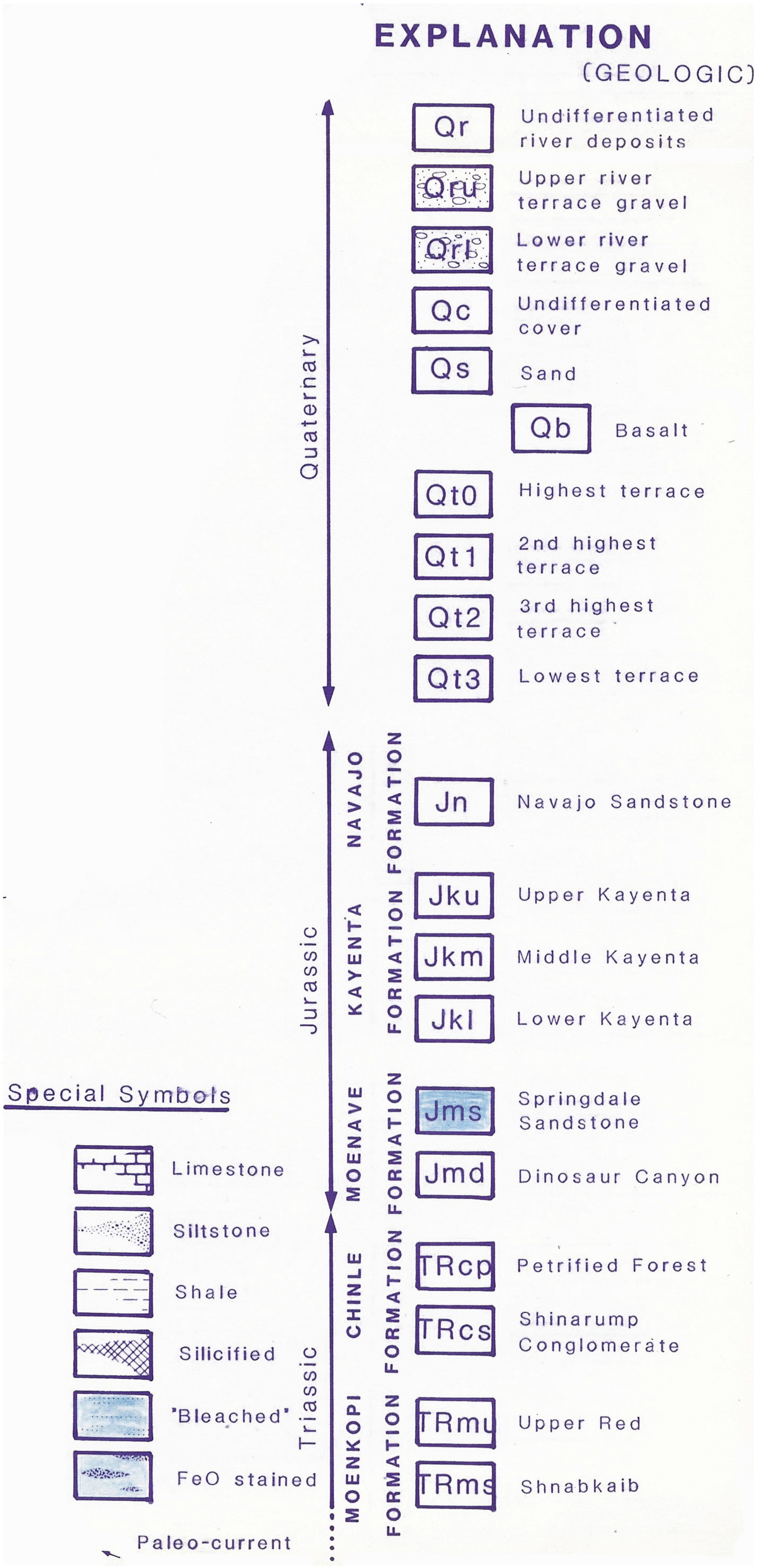
Guided by the stratigraphy given in the "Explanation," mark all possible unconformities with thick red lines on the map.

Complete the cross sectional profile A - A' as indicated on the geologic map. The contour interval is 40ft. Transfer not only elevation points but mark and transfer formation boundaries as well. Pay attention to strike and dip symbols and show extent of formations in the sub surface as much as possible.

From the map topography and the unit names, identify the possible lithologies and record them on the "Explanation" next to the appropriate unit.

What geologic structure is present on the map?

Briefly state the suggested geologic history of the area. (In 5 sentences or less.)



EXPLANATION

(GEOLOGIC)

Quaternary		Qr	Undifferentiated river deposits
		Qru	Upper river terrace gravel
		Qrl	Lower river terrace gravel
		Qc	Undifferentiated cover
		Qs	Sand
		Qb	Basalt
		Qt0	Highest terrace
		Qt1	2nd highest terrace
		Qt2	3rd highest terrace
		Qt3	Lowest terrace
Jurassic	NAVAJO FORMATION	Jn	Navajo Sandstone
	KAYENTA FORMATION	Jku	Upper Kayenta
		Jkm	Middle Kayenta
		Jkl	Lower Kayenta
	MOENAVE FORMATION	Jms	Springdale Sandstone
		Jmd	Dinosaur Canyon
Triassic	CHINLE FORMATION	TRcp	Petrified Forest
		TRcs	Shinarump Conglomerate
	MOENKOPI FORMATION	TRmu	Upper Red
		TRms	Shnabkaib

Special Symbols

- Limestone
- Siltstone
- Shale
- Silicified
- 'Bleached'
- FeO stained
- Paleo-current

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