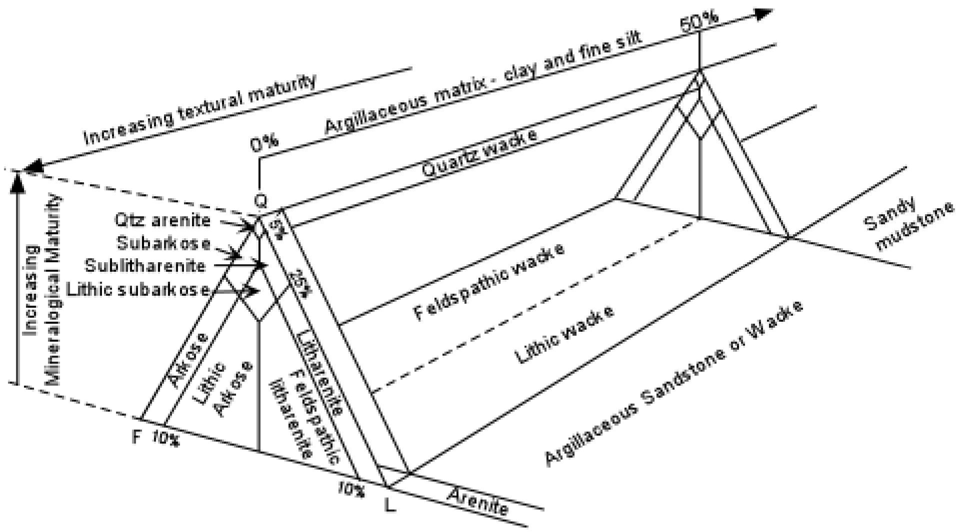
Sandstones

Sandstones make up only about 25% of the stratigraphic record, but have received the most attention in studies of sedimentary rocks. There are basically two reasons for this. First, sandstones are easily studied because they contain sand sized grains that can easily be distinguished with a petrographic microscope. Second, most of the world's oil and natural gas is found in sands or sandstones because of their generally high porosity.

Classification
For this course we will use a classification of sandstones that is partially based on Blatt and Tracey (p. 257) and partially based on Williams, Turner, and Gilbert (p. 326).

Sandstones that contain less than 10% clay matrix are called arenites (note that the Spanish word for sand is arena). These can be subdivided based on the percentages of Quartz, Feldspar, and unstable lithic fragments (fragments of preexisting rock).



A feldspar-rich sandstone is called an arkose. Lithic rich sandstones are called litharenites. Further subdivisions are shown in the diagram. If the rock has between 10 and 50% clay matrix, the rock is called a wacke. Quartz wackes have predominantly quartz surrounded by a mud or clay matrix. In a feldspathic wacke, feldspar is more abundant, and in a lithic wacke, lithic fragments are more abundant. The term ***graywacke*** is seldom used today, but was originally used to describe a lithic-rich sandstone with between 10 and 50% mica, clay, or chlorite matrix. Rocks with greater than 50% clay matrix are called sandy mudstones, and will be discussed in the lecture on mudrocks.

As the percentage of quartz increases, the mineralogical maturity of arenites increases. Also, as the percentage of clay matrix decreases the degree of sorting increases, and thus the textural maturity increases. Textural maturity also increases in the opposite direction as the % clay matrix increases from 50 to 100%.

Mineralogic Composition of Sandstones
As seen in the classification scheme, sandstones are composed of mostly quartz, feldspar, and lithic fragments. Other minerals also occur, depending on the mineralogical maturity of the sandstone. It is these minerals that make studies of the ***provenance*** (origin of the grains) possible in the study of sandstones. Here we discuss the common minerals in sandstones as well as the less common (accessory) minerals.

- **Quartz**. Greater than 2/3 of the minerals found in sandstones is quartz. There are several reasons for this:

  1. Quartz is one of the most abundant minerals in crystalline rocks like granitoids, schists, and gneisses.
  2. Quartz is mechanically durable due to its high hardness and lack of cleavage.
  3. Quartz is chemically stable under conditions present at the Earth's surface. It has a very low solubility in water.

  Quartz occurs as both monocrystalline grains and polycrystalline grains, and usually shows undulatory extinction (see figure 13-6, p. 247 in Blatt and Tracy). The undulatory extinction is due to deformation either of the preexisting rock from which the grains were derived or results from deformation of the sandstone itself. Thus, even though some workers claim that quartz showing undulatory extinction is derived from a metamorphic source, such quartz cannot be a reliable indicator of a metamorphic source.

  Polycrystalline quartz of sand size, especially if more than five individual crystals are present, is a better indicator of a metamorphic source.

  Milky quartz is not very common in sandstones, but when it does occur it is likely an indicator that the quartz was derived from a pegmatite or vein quartz. The milky color of such quartz is due to fluid filled bubbles within the quartz.

  Milky quartz, polycrystalline quartz grains, and quartz with undulatory extinction are less stable in the sedimentary environment than monocrystalline non-undulatory quartz. Thus, a sandstone consisting of monocrystalline quartz that does not show undulatory extinction is mineralogically the most mature.

- **Feldspar.** Although feldspars are the most common minerals in igneous and metamorphic rocks, feldspars are less stable than quartz at conditions near the Earth's surface. Thus feldspars make up only 10-15% of all sandstones. Feldspars in sandstones consist of the following:

  - Plagioclase - usually showing albite twinning. Such plagioclase can be derived from both igneous and metamorphic sources. If the plagioclase also shows zoning, then it is likely from a volcanic source.
  - Alkali Feldspar - Orthoclase and microcline are derived from both igneous and metamorphic sources. Sanidine is derived from volcanic sources. Microperthite, the intergrowth of K-rich and Na-rich alkali feldspars, is likely derived from a plutonic igneous source.

Because feldspars are unstable in the sedimentary environment, most feldspars in sandstones show the effects of alteration. This is usually evident as growths of microcrystalline clay minerals along cleavage planes and on the surfaces of the feldspars.

- **Lithic Fragments.** With the exception of fragments of polycrystalline quartz, lithic fragments are generally unstable in the sedimentary environment, yet, if present in a sandstone give the best clues to provenance. Any type of rock fragment can be found in a sandstone, but some kinds are more common due to the following factors:

    1. Areal extent in the source drainage basin. The greater the outcrop area of the source that produces the lithic fragment, the more likely it is to occur in sediment derived from that source.

    2. Location and relief of the drainage basin. If the source is located close to the depositional basin, lithic fragments derived from the source are more likely to occur in the sediment. If the source area has high topographic relief, rates of erosion will be higher, and lithic fragments derived from the source will be more likely to occur in the sediment.

    3. Stability of the rock fragment in the sedimentary environment. Fragments of mudrocks are relatively rare due to their mechanical weakness during transport. Similarly fragments of gabbros are rare in sandstones because the minerals they contain are chemically unstable in the sedimentary environment. Because sandstones are usually cemented together with calcite or hematite, sandstone fragments break down easily during transport. The minerals that occur in granites, however, are more stable under conditions present near the Earth's surface, and thus granitic fragments are more common in sandstones. Volcanic rock fragments, with the exception of crystalline rhyolites, are generally unstable, but may occur if factors 1, 2 and 4 are favorable.

    4. Size of the crystals in the fragments. In order to be present in a sandstone as a lithic fragment, the grain size of the minerals in the lithic fragment must be smaller than the grain size of the sediment. Thus, granitic fragments will be expected to be rare, except in coarse sands, and volcanic and fine-grained metamorphic fragments will be expected to be more common.

- **Accessory Minerals.** Since it is possible that any mineral could be found in a sand or sandstone depending on the degree of mineralogical maturity, a variety of other minerals are possible. Some of these can be useful in determining provenance of the sand. The more common minerals in sandstones, quartz and feldspar, have densities of less than 2,700 kg/m^3, but most accessory minerals, with the exception of muscovite, have densities greater than 3,000 kg/m^3. Thus the accessory minerals are usually referred to as ***heavy minerals***. This is convenient because if the sandstone can be desegregated, then the heavy minerals can easily be separated from the quartz and feldspar on the basis of density.

The heavy minerals can be divided into three groups, as shown in the table below. Using this list, provenance of the sand can sometimes be determined to be from an igneous source or a metamorphic source.

Provenance of Accessory Minerals in Sandstones		
Igneous Source	Metamorphic Source	Indeterminate Source
Aegerine Augite Chromite Ilmenite Topaz	Actinolite Andalusite Chloritoid Cordierite Diopside Epidote Garnet Glaucophane Kyanite Rutile Sillimanite Staurolite Tremolite	Enstatite Hornblende Hypersthene Magnetite Sphene Tourmaline Zircon

- **Glauconite.** Glauconite occurs as green or brown sand-sized pellets in some quartz arenites, although sometimes the glauconite pellets make up a substantial portion of the rock. Glauconite has the chemical formula - $(K,Na,Ca)_{1.2-2.0}(Fe^{+3},Al,Fe^{+2},Mg)_4(Si_{7-7.6}Al_{1-0.4})0_{20}(OH)_2 \cdot nH_2O$, although some so-called glauconite sands are composed of such minerals as smectite clays, serpentine, and chlorite. The pellets are thought to originate as fecal pellets. They commonly occur in sands deposited in shallow water (up to 2,000 m) and are most common in Cambro-Ordovician and Cretaceous marine rocks, times when sea level was unusually high and the continents were flooded with epiric seas. Because glauconite contains K, the sands can sometimes be dated by the K-Ar method of radiometric dating.

Diagenesis of Sandstones
Once sand has been deposited and buried by more sediment, it begins to undergo diagenetic processes which can turn the unconsolidated material into a sedimentary rock. There are seven main diagenetic processes:

1. Compaction
2. Recrystallization
3. Solution
4. Cementation
5. Authigenesis
6. Replacement
7. Bioturbation

Note that diagenesis is not restricted to sandstones and conglomerates, but occurs in carbonates and mudrocks as well.

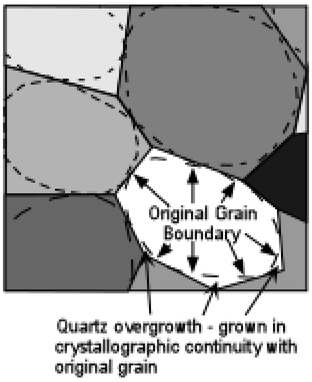
- **Compaction.** The first stage of diagenesis is compaction of the sediment. Compaction is due to the weight of the overlying sediment and first results in the reduction of porosity by forcing the grains closer together, and thus expelling fluid, usually water, from the pore spaces. Pure quartz sands that are well sorted can rarely be compacted to any large extent, and compaction in these sands will not result in lithification. Poorly sorted sands, one the other hand, may contain a significant fraction of clay minerals. Clay minerals are ductile, and can deform around the sand grains during compaction, thus reducing the porosity and starting the process of lithification.

- **Recrystallization.** Due to changes in pressure, temperature, and composition of the fluid phase, some minerals recrystallize, i.e. dissolve and reform, changing the orientation of their crystal lattice. Such textural changes may result in stronger lithification of the sediment.

- **Solution.** Solution is the process of dissolving mineral matter. As fluids pass through the sediment, unstable constituents may dissolve and are either transported away or are reprecipitated in nearby pores where conditions are different. One processes whereby grains are dissolved is called ***pressure solution.*** Pressure solution occurs at zones of grain-to-grain contact where pressure is concentrated. Dissolution of the grains preferentially occurs along these higher pressure areas and the dissolved ions migrate away from the point of contact toward areas of lower pressure where the dissolved ions are reprecipitated.

- **Cementation.** Most lithification is the result of new authigenic minerals forming in the pore space to create a cement which holds the grains together. The most common cements are quartz, calcite, clay minerals, and hematite, although other minerals like pyrite, gypsum, and barite can also form cements under special geologic conditions.

    - **Quartz Cement.** Quartz cement is most common in nearly pure quartz arenites. Such rocks generally only form in environments of high energy currents, such as beach deposits, marine bars, desert dunes, and some fluvial sandbars. Thus, it appears that most of the quartz cement is derived from the sands themselves or quartz sands in other parts of the section.



Quartz cement often occurs as ***overgrowths*** on the original quartz grains. These overgrowths grow in crystallographic (and optical) continuity with the original quartz grains. The overgrowth cement grows outward from the original grain until it runs into cement growing outward from an adjacent grain. Thus, the rock attains a texture of interlocking grains similar to an igneous crystalline granular texture. If the grain has small specs of clay or other fine grained dirt forming an irregular coating on its surface, the coating may be preserved and show the original outline of the grain. (see also fig. 14-2 p. 267 in your text)

- **Calcite Cement.** Calcite is the most common cement in sandstones, although when present, is doesn't tend to fill all pore spaces completely, but occurs as patchy cement. Calcite is soluble in surface waters, therefore calcite cemented sandstones often have their cement partially dissolved. Dissolution of the calcite cement results in ***secondary porosity***.

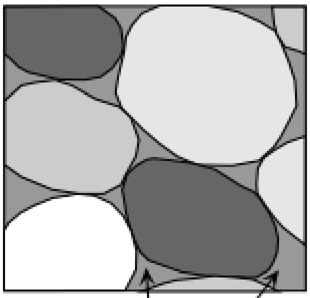
  In order to form a calcite cement a source of Ca^{+2} ions and CO_3^{-2} (carbonate) ions is required. Ca^{+2} occurs in abundance in most surface and groundwater as a result of chemical weathering of rocks. Carbonate ion also occurs in abundance in surface and groundwater, but is either derived by dissolution of carbonate minerals, or from bicarbonate ion (HCO_3^-) that results from dissolution of CO_2 gas in the atmosphere by H_2O

$$H_2O + CO_2 <=> H^+ + HCO_3^-$$

- **Hematite Cement.** In rocks and minerals Fe occurs in two oxidation states (Fe^{+2}, ferrous and Fe^{+3}, ferric). In most igneous and metamorphic minerals there is little free oxygen, so the most common oxidation state is Fe^{+2}. When such minerals are brought near the surface of the Earth where there is a greater abundance of free oxygen, the iron oxidizes to Fe^{+3} and can be carried away by hydrous fluids. Precipitation of Fe^{+3} from such fluids results in forming hematite (Fe_2O_3). Only small amounts of hematite coating a mineral grain or rock surface is sufficient to give a red colored stain. Once the hematite precipitates it is very insoluble in water unless the water becomes highly reduced. Thus, the presence of hematite cement indicates an oxidizing environment during diagenesis.

- **Other Cements.** Other cement forming diagenetic minerals can occur under special circumstances. For example, pyrite (FeS_2) can precipitate from fluids rich in sulfur under reducing conditions, barite ($BaSO_4$) can form if the fluids are rich in Ba, and Gypsum ($CaSO_4 \cdot H_2O$) can from if the fluids are oxidizing and rich in sulfur.

Often times when these cements form near the Earth's surface, the cementing minerals form crystallographically continuous crystals in the cement, resulting in ***Sand Crystals.*** Such crystals are usually made mostly of grains of quartz sand, but have the appearance of a crystal (like a barite rose, a gypsum rose, or calcite crystal) only because the cement between the grains forms a crystal. If you were to cut a thin section of such a sand crystal you would see that the cement is optically continuous between the grains (i.e. it would all go extinct at the same time).



- **Authigenesis.** Authigenesis is when new minerals are crystallized in the sediment or rock during diagenesis. These new minerals may be produced by reactions involving phases already present in the sediment (or rock), through precipitation of materials introduced in the fluid phase, or a chemical reaction between primary sedimentary minerals and ions introduced by the fluids.

  This process overlaps with weathering and cementation, usually involves recrystallization, and may result in replacement. Authigenic phases include silicates such as quartz, alkali feldspar, clays and zeolites; carbonates such as calcite and dolomite; and evaporite minerals such as halite, sylvite and gypsum. If the growth of these authigenic minerals fills the pore space or starts to connect the original grains together, they can form a cement and help lithify the rock.

- **Replacement.** Replacement occurs when a newly formed mineral replaces a preexisting mineral in place. Replacement may be:

  - ***neomorphic*** where the new grain is the same phase as the old grain, or is a polymorph of it. Albitization is one such process where albite replaces a plagioclase in a grain.

  - ***pseudomorphic*** where an old grain is replaced with a new mineral but the relict crystal form is retained,

  - ***allomorphic***: where an preexisting mineral is replaced with a new minerals that has a different crystal form.

  Although there are many replacement phases, dolomite, opal, quartz, and illite are some of the most important. Petrified wood is an excellent example of replacement.

- **Bioturbation.** Bioturbation refers to physical and biological activities that occur near the sediment surface which cause the sediment to become mixed. Burrowing and boring by organisms can increase the compaction of the sediment and usually destroys any laminations or bedding. During bioturbation, some organisms precipitate minerals that act as cement.