The Chemistry of Rocks in the Wissahickon Valley

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Problem Statement

The majority of my students are sophomores who have had little to no science during their middle school years. This lack of a comprehensive science program in their formative years explains much of their difficulty connecting science to their daily life. This is most evident when I introduce the periodic table of elements and attempt to explain how elements combine to form the many compounds that are necessary in our lives.

Although I use many common household chemicals to illustrate the importance of elements and compounds, students still fail to fully appreciate the role that chemistry plays in our understanding of the physical world. I have often attempted to use the chemistry of the rock cycle to connect our class to the real world but many students are unaware of the rock cycle, or have had a cursory general survey of rocks. Understanding the role that elements play in the formation of minerals and how those minerals combine to form the many rock types and materials in our world would create a vibrant connection between the static elements on the periodic table and the world in which we live.

In our conversations of the world around us, I have noticed that many of my students have had little or no experiences in natural settings where they could explore and make connections between the concepts learned in the classroom and their environment. This is most evident when we discuss science concepts that depend on their knowledge of ecosystems (such as forests, mountains, or river systems), as many have lived only in urban centers and have little awareness of non-urban environments.

This is an easily remedied problem as our city has an extraordinary “urban wilderness” that can provide my students the opportunity to explore their natural environment. The Wissahickon Valley

Park, located in northeast section of the city, offers a beautiful natural classroom wherein students can explore the chemistry of rocks and minerals and the geological processes that transform them.

The evidence of the valley's geological history is evident in the many formations, outcropping and metamorphic rocks found throughout the park. It is important that students see this evidence because there is a sense among many that the geology of our planet is static and unchanging. Most students know about the ongoing evolution of living organisms, but few truly appreciate that the earth has radically transformed (and continues to transform) over its 4.6 billion year history. The rich geological history stored within the valley will provide an opportunity to witness and study the evidence of the geological changes that have occurred and continue to reshape the geology of this area.

Rationale

Exploring the chemistry of the rock cycle will provide an opportunity to analyze how elements react to form minerals and how these minerals combine to form rocks. Analyzing the conditions that created the many types of igneous, sedimentary, and metamorphic rocks provides a forum in which to discuss how temperature, pressure, and time transform the chemical and physical properties of the minerals in rocks. Understanding the chemistry of metamorphic and sedimentary rocks will help us to more fully comprehend the nature of the ongoing changes in the geology of the earth.

While many of the past geological transformations have been altered or obscured by periods of glaciation, the geological record of the Wissahickon is relatively well preserved, as it was not affected by the most recent ice age (West, 1993). As a result, millions of years of geological history are evident in the formations, outcroppings, folds and fractures that are readily observed throughout the valley.

The valley and its waterway (the Wissahickon Creek) will provide the opportunity to study the interaction between chemistry, geology, ecology and the real world as we can learn how rocks form, how tectonic processes transform those rocks, and how present day activities threaten the sustainability of the many ecosystems found within the valley.

Proposed Unit of Study

This unit will begin in early September when the class surveys the sciences involved in environmental science. The unit will allow me to illustrate the important intersection of chemistry, geology, and ecology in our efforts to protect the environment. The unit will begin with a focus on the chemistry and geology of the Wissahickon rocks and end with a discussion on how to address the environmental risks that threaten the sustainability of the area.

The initial days of the unit will review elements, compounds, the periodic table and bonding theory. I will introduce the concept of minerals as compounds with specific chemical and physical properties that combine to form rocks. The class will review the rock cycle beginning with sedimentary and the processes that change sediments into sedimentary rocks. We will then explore how pressure, heat, and time transform the sedimentary rocks into metamorphic rocks. Students will be shown the various types of geological formations geological events and how these events affect rock strata. The class will learn how to identify these formations and where they exist within the Wissahickon.

Once students have an understanding of these concepts, a trip to the Wissahickon will allow them to experience these formations and the rock samples that exist there. Students will complete the unit by creating a walking tour guide to the rocks and geology of the Wissahickon.

Objectives

Students Will Be Able To:

- Describe the elements and compounds that make up minerals
- Explain how minerals create the physical / chemical properties of rocks
- Describe how geological processes transform the physical / chemical properties of rocks.
- Identify given rock samples and geological formations
- Create and make a presentation on a given rock sample or formation of importance in the Wissahickon Valley Formation.
- Create a walking tour of the formations and rocks in the Wissahickon valley

Background

The Wissahickon Valley in Philadelphia

The word "Wissahickon" comes from the language of the Lenni Lenape Nation. Members of this ancient group of Native Americans refer to themselves as "first or original man" because they settled in the area as far back as the 14th century (Munsee Delaware Indian Nation-USA, 2014). Wissahickon is a "combination of two words from their language: "Wisauckisickan" which means "yellow colored- creek," and "Wisamickan' which means "catfish creek" (Gasiorowski, 1997, p. 46).

The Wissahickon Creek emerges from an area known as the Stockton Formation which lies to the north of Philadelphia in Montgomery County. Its waters flow through Chester Valley across the Rosemont and Huntingdon Valley Faults and into the Wissahickon Valley in northwest Philadelphia. The faults separate the rocks of the valley (predominantly metamorphic schist and quartzite) from deposits of Baltimore Gneiss to the west and carbonate formations to the north (West, Gems of the Wissahickon, 1998). The creek runs through the valley; which is known to local residents as the Wissahickon Valley Park. It is a densely wooded area with abundant wildlife, fish and many miles of scenic trails. It is renowned as one of the most scenic urban landscapes in the country. (Friend of the Wissahickon, 2016).

Wissahickon creek played an important role in Philadelphia's pre industrial history as it provided energy for its mills (approximately 50 mills lined the banks of the creek during the 17th and 18th century) and abundant supplies of rock (West, 1993). The valley is perhaps more well known for those rocks, which have become synonymous with the area. The name "Wissahickon Schist" was coined by Florence Bascom in 1907 to describe the rocks that were were used extensively

throughout the region for construction and landscaping. Wissahickon schists are still seen in buildings and landscapes throughout the region.
(See Figure 1**).**

It is important to note that "Wissahickon Schist" does not refer to a single type of rock but to a class of rocks. Within the valley one finds an array of schist type rocks each with a distinctive composition and geological history. The variety of metamorphic rocks in the valley are the result of geological processes that shaped and reshaped the topography of the area over the past billion years (West, 1993). To fully understand the chemistry of the Wissahickon rocks, one must explore the geological history of Pennsylvania.

[1]*Geological History*

The rocks that form the foundation of Pennsylvania began to form billions of years ago during the Proterozoic Eon. During that time climatic conditions allowed the molten magma covering the earth to cool and harden forming solid slabs of igneous rock (continental crust). As time progressed these small land masses came together to form cratons (large sections of continental crust). Toward the middle of the Proterozoic Eon (around 1.1 Bya) these cratons came together to form the supercontinent known as Rodinia (See Figure 2). One section of Rodinia (Laurentia) contained the early formations of what would become the North American continent. The geological history of the rocks in the Wissahickon Formation begins when the state of Pennsylvania was but a small area of this super continent. During this period of accretion, considerable deposits of gneiss, serpentinite and metabasalt formed in an area of the craton that would underlay the eastern coast of the United States. Of these early rocks, gneiss (a metamorphic rock) remains as the principal "basement rock" of the state of Pennsylvania (Barnes & Sevon, 2016).

Although some of the earth's magma had solidified much of it remained in the molten liquid in a superheated state within the earth's mantle. Convection currents within the magma would keep the newly formed land masses (tectonic plates) in the continual motion that has resulted in the ongoing geological transformation of the planet's oceans and continents. These tectonic forces would initiate the breakup of Rodinia. As the supercontinent broke apart, rift valleys, basins and small seas formed at the margins of the separating land masses. Eroded sediments and volcanic ash were deposited in these areas forming a variety of sedimentary rocks: fine mud particles formed mudstones, coarser sediments formed sandstone, and volcanic ash dissolved in the early seas and gave rise to carbonate based rocks. Towards the end of the eon (around 570-500 mya), the Iapetus ocean formed to the east of Laurentia and the North American craton. It is interesting to note that the North American craton and the Iapetus ocean basin were situated at the equator at this time.
(See Figure 3)

During the Cambrian Period water from the Iapetus Ocean covered much of the North American craton. Carbonates formed in the tropical waters near the shore, while mud, silt, and sand were deposited farther into the ocean. These early sediments would form some of Pennsylvania's first rocks: dolomites would form from the carbonate depositions, mudstones would become shales, and schists, while sandstones would transform into quartzite. Millions of years later during the

[1] A diagram of the Geological Time Line is located in the Appendix

middle to late Ordovician period the Iapetus ocean (and a series of arc volcanoes to the east of North America collided with Laurentia. The convergence of continental and oceanic crust (known as the Taconic Orogeny), formed the Taconic Mountains (which still exist today in northern New York and Vermont). The mass of the newly formed mountains depressed the continent and a series of foreland basins (one known as the Appalachian Basin) formed ranging from what is now central and western Pennsylvania to as far south as Virginia and the Carolinas (Gasiorowski, 1997). As time progressed, large rivers eroded the mountains and deposited immense amounts of sediment into the basins. The nature of the sediments deposited in the basins were determined by the water flows. As noted earlier, less energetic flows carried smaller (mud, silt, clay) particles while stronger flows carried sand and gravel: these differential water flows created the alternating layers of shale and sandstone that would become the schist and quartzite found in Wissahickon schist (West, 1993).

Two other mountain building events would contribute to the geology of the Wissahickon Valley: the Acadian orogeny occurred during the Devonian period, when the landmasses Avalonia, Europe, and the North American craton converged to form the super continent Euramerica (see figure 4). The convergence formed the Acadian mountains located in eastern Pennsylvania. As the mountains eroded, sediments once again collected in the Appalachian Basin. The sediments (fine clays and mud) from this event formed mudstones that became the shales known today as the Marcellus shales (Barnes & Sevon, 2016).

Tectonic forces would once again force the earth's plates together into a supercontinent known as Pangaea. The continents of Europe, South America, and North America came together near the equator. The convergence of Africa, South America, and North America (known as the Alleghenian Orogeny) created the Alleghenian mountains in Western Pennsylvania. See figure 5. The impact began North America's movement away from the equator and towards its final position in the northern hemisphere. Sometime in the Triassic period (around 220 mya) magma began to flow out of a divergent boundary in the middle of the Atlantic Ocean. As the magma forced the seafloor to spread, the continents of Pangaea began to separate. Over the course of the ensuing millions of years, the continents have reached their current positions. The Alleghenian Orogeny was the last major mountain building event in Pennsylvania's history.

The underlying material of our continents and oceans are rock formations created during a billion years of geological events. Processes of erosion, sedimentation and metamorphism transformed those rocks into the schists and gneiss found in the Wissahickon Valley.

Chemistry of Wissahickon Valley Rocks

Rocks are composed of combinations of differing elements and minerals. A rock can be defined as any large continuous portion of the lithosphere that has specific physical and chemical properties. These properties depend on the proportions and geometrical arrangement of the minerals of which they are composed (Tarbuck, 2006). Although there are many differing ways to classify and analyze rocks, they are generally classified into three broad categories: igneous, sedimentary, and metamorphic. This unit will initially use the major categories of igneous, metamorphic, and sedimentary rocks as a reference point. Classifications that are more specific will be used as our study progresses.

Types of Rocks

Igneous rocks are formed within the magma of the earth where they exist in a molten state known as magma. Within the magma, differing minerals combine to form rocks with specific chemical and physical properties. Factors within the magma such as heat, pressure, and water content determine the manner in which minerals crystalize which determines the type of igneous rock that forms. Where the magma cools; (inside the earth: intrusive) or (outside the earth: extrusive) and the rate of cooling also influence the physical and chemical properties of the rock.

Igneous rocks are also described by the proportions of given mineral they contain. Granitic igneous rocks are composed of light colored silicate minerals (potassium feldspar, quartz (silica), and the dark silicates biotite mica and amphibole). They are also referred to as felsic rocks because many are primarily composed of feldspar (fee) & silica (sic). Basaltic igneous rocks are primarily dark colored rock composed mainly of olivine, pyroxene, and plagioclase (calcium-feldspar). These rocks are also described as mafic because their minerals have a high proportion of magnesium (ma) and iron (ferrum). Andesitic rocks have a composition that is between felsic and mafic rocks. The minerals in these rocks are a combination of light minerals and dark minerals: amphibole, pyroxene, and plagioclase feldspars.

At the extreme end of this spectrum are the ultramafic igneous rocks. These rocks are mainly very dark as most rocks in this category are composed of the dark minerals olivine and pyroxene. Two igneous rocks found in the valley are granite and pegmatite (West, 1998). Granite is an intrusive, mafic rock composed mainly of silica (quartz); pegmatite is a coarse grained, intrusive, felsic rock composed primarily of quartz, feldspars and mica. Most of the rocks in the valley are the metamorphosed products of sedimentary rocks. However, one important metamorphic rock in the valley is an amphibolite which is formed from the igneous rock: basalt. Amphibolite is is called an amphibolite because it contains the mineral hornblende, (which is part of the family of minerals known as amphiboles) (Alcock, 2012).

There are two major categories of **sedimentary rocks**: clastic (or detrital) and chemical. Clastic sedimentary rocks form as a result of weathering processes that erode and break up rocks and other substances into smaller particles. The rock particles are deposited on the land or in bodies of water where they are buried and transformed into rock. Sediments become rock through the process of compaction (where the weight of overlying material compresses particles into a solid phase). Sediments can also be cemented together by minerals in water such as calcite, hematite, or silica. As water passes through buried sediment, these minerals precipitate out of the solution and bind the sediments together. Chemical sedimentary rocks result from the rock minerals that are dissolved by water and carried to receiving bodies of water. As conditions change, these chemical precipitate out of solution and are deposited as sediments. With time these sediments become sedimentary rock (Tarbuck, 2006).

The properties of the minerals and the size of the sediment determines those of the resulting sedimentary rock. Conglomerate sedimentary rocks are composed of large grains of rock cemented together, while shales are composed of fine grains of clay that have been compacted together. A range of rock types exist between these two extremes. The major types of sedimentary rock in the Wissahickon are mudstones, shales (from clay), and sandstones (from sand).

As sedimentary rocks are exposed to heat and pressure over long periods of time, their physical and chemical properties are altered. The resulting **metamorphic rocks** exhibit different chemical and physical properties which can provide valuable clues as to geological history of a given environment. The principal rocks found in the Wissahickon are schist, quartzite, gneiss, and pegmatite. Schist, quartzite and gneiss are (as mentioned earlier) formed from sedimentary rocks. Schist is formed from shales and quartzite, which in time become gneiss.

Wissahickon Rocks

The predominant rock types found today in the Wissahickon are the metamorphic rocks: quartzite, schist, gneiss, amphibolite, and the igneous rocks pegmatite and granite. The composition of these rocks, along with the fractures, folds, and joints found in the rock formations tells the story of the tectonic forces that formed the Wissahickon. Quartzite is a hard metamorphic rock that is not easily eroded, for this reason it can still be found in outcroppings in the valley. The schists in the valley offer a different story as they are softer rocks that erode and cleave easily. Schists contain a variety of silicate minerals: micas (chlorite, muscovite, biotite), along with visible minerals such as tourmaline, garnets, and staurolite. Gneiss is a harder rock than schist, because it contains feldspar from the igneous rock pegmatite. It is believed that molten pegmatite combined with molten layers of schist to create the banded layers of the gneiss.

Classes of Wissahickon Rocks

Name	Type of Rock	Source	Minerals
Schist (Mica and Garnet)	Metamorphic	Mudstone and Shale	Chlorite, Muscovite, Biotite, Garnet, Feldspar Quartz
Gneiss	Metamorphic	Shale, Sandstone, and Schist	Feldspar, quartz, garnet,
Amphibolite	Metamorphic	Basalt	Amphibole, plaglioclase feldspar
Quartzite	Metamorphic	Sandstone	Quartz (Silicon Dioxide
Pegmatite	Intrusive Igneous		Quartz, Feldspar, Mica
Granite	Intrusive Igneous		

The principal rock type however is Wissahickon Schist which is a combination of schist (primarily mica schist) intermixed with quartzite. The minerals found in the rocks provide further evidence of the conditions of metamorphism. Since different minerals form at differing pressures and temperatures the presence of a given mineral tells the depth at which a rock was formed. The sequence of these index minerals found in the "Wissahickon schist is as follows: biotite, garnet, staurolite, kyanite, and sillimanite) (Crawford, 1987).

Chemistry of Wissahickon Schist

"Wissahickon Schist" is composed of layers of schist intermixed with quartzite. Schists (as noted earlier) are a class of metamorphic rocks composed mainly of thin silvery layers of minerals (mainly micas), that foliate easily. Quartzite is a harder rock formed from larger silica rich sand particles found in sandstone. In figure 6 **,** one can the schist (the crinkled wavy layers), while the quartzite is the uniform, harder, smoother surface protruding from the rock body. The different types of rock within the one body are the result of the differing flows of water that deposited sediments in the basins and alluvial plains of the area. Faster more energetic flows carried heavier particles sand and gravel (that became sandstone), while less energetic flows carried finer mud, clay and silt particles, (that became mudstone).

These differing water flows meant that alternate layers of sediments were deposited at differing times, hence the intermixed layers of metamorphic rocks (West, 1993). The minerals in the schist and the folding of its layers provide evidence of the tectonic stresses and chemical conditions that metamorphosed the sedimentary rocks.

The type of mineral in the rocks are micas but other minerals in the rock (index minerals) are indicative of the temperature (and hence the pressure and depth) at which metamorphosis occurred. Geologists use index minerals to map the progression of increasing metamorphic character of sedimentary rocks. The sequence named after George Barrow (who first analyzed the gradual transformation of sedimentary rocks in the late 19th century) is referred to as Barrovian Metamorphism (Fichter, 2000). It should be noted that several minerals might be present in a rock sample: when this occurs the mineral with the highest grade is used to determine the metamorphic grade of the rock. Figure 7 illustrates the relationship between the pressure, temperature, and depth at which these index mineral form.

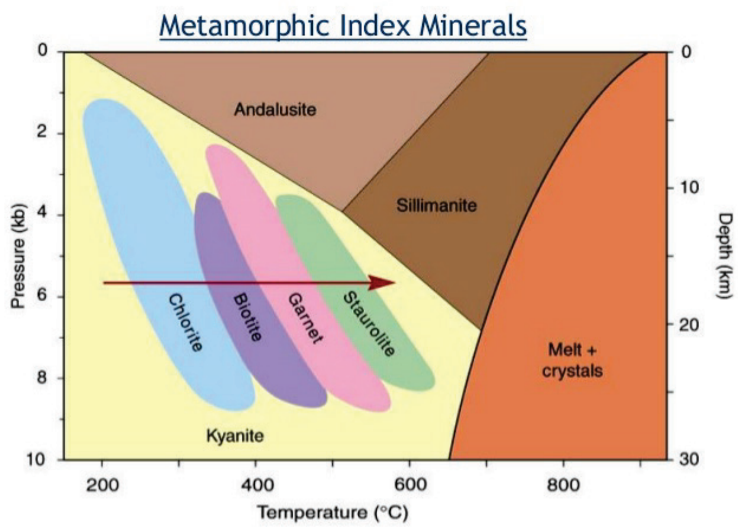


Figure 7: Temperature/ Pressure Gradient Index Minerals: Source: http://geopick.uncc.edu/geologyWeb/physicalGeology/Topics/530metamorphicRocks/imagesMeta/FIG06_013

Schist may contain any of the following minerals (muscovite, chlorite, biotite, staurolite, kyanite, and garnet, or sillimanite intermixed with quartzite. Of these, chlorite, biotite, garnet, staurolite, and kyanite, (in order of increasing metamorphic grade) are used to determine the schist's degree of metamorphism, (sillimanite typically indexes gneiss) (Fichter, 2000). It is necessary to note that the Berkovian sequence can be applied to any rock type (igneous, sedimentary, even metamorphic). The sequence of minerals is different for each of these parent rocks. When shales are the parent rock, the sequence is divided into three metamorphic facies (or grades): (Greenschist, Amphibolite, and Granulite) that correspond to the degree of metamorphism (low, intermediate, and high respectively).

Table 1 summarizes these transitions beginning with the sedimentary processes that produce the parent shale, moving to schist, then gneiss, ending with igneous processes that convert the metamorphic rocks back to magma. The minerals present in the Wissahickon schist (biotite, garnet, staurolite, and kyanite) suggest that metamorphism occurred at depths of 20-25 km (12 -16 miles) below the surface: gneiss would transform at even greater extremes. The presence of rocks (that were once buried deep within the earth) at the surface provides yet more evidence of great tectonic events that uplifted and exposed them. Patterns of folding, fractures, and realignment of layers are indicative of the geological forces acting on the differing rocks. The patterns and orientations of schist and quartzite in Wissahickon schist are the result of the manner in which the rocks responded to heat and pressure. The geometrical orientation of the minerals in quartzite are more "symmetrical" and are able to maintain their shape when stress is applied. Thus, the quartzite layers (when heated and under uneven stresses) will fold in the direction of the applied stress. Mica minerals however tend to dissolve in response to heat and pressure. They will then re-crystallize (when they cool) in linear layers that are aligned perpendicular to the applied stress: thus folding is not evident in the mica rich schist layers of the rock (Gasiorowski, 1997).

Fractures (cracks) in rocks occur as a result of tectonic forces. If rocks are hot and pliable the folding, or realignment can occur. If rocks are solid and brittle, then they will crack in response to stress. These "cracks" can be described as either joints or faults: a fault occurs if the rocks on either side of the separation have moved relative to each other; a joint occurs if the rocks have the same position on either side of the separation (Alcock, 2012).

While the majority of rocks in the valley were originally sedimentary rocks, there are many rocks that are igneous in origin. In several areas, one finds (granite and pegmatite (intrusive igneous rocks) and amphibolite (the metamorphic rock formed from basalt). Their location and orientation relative to schist helps explain how they formed and when (and how) the rock types came into contact with each other.

Minerals

Minerals are defined as naturally occurring inorganic solids with specific crystalline structures and definite chemical composition (that vary within a given range). Minerals are typically identified by their physical properties; (luster, color, streak, hardness, cleavage, specific gravity, and crystal form). The chemical composition of minerals is extremely varied. Some minerals such as native elements consist of a single element: i.e., (the allotropes of carbon: graphite and diamond, gold, copper, and aluminum, etc.).

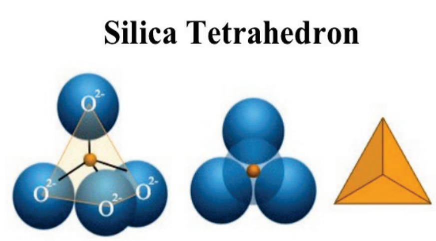
Most minerals are however ionic compounds consisting of a metallic cation and a mono or polyatomic anion in specific ratios. For example, pyrite: Fees, is composed of the Fe^{2+} cation and the Sulfide S^{2-} anion, while Gypsum ($CaSO_4$-$2H_2O$) is composed of the calcium cation Ca^{2+} the sulfate polyatomic anion $SO_4{}^{2-}$, and two waters of hydration. Note that ratio of ions gives the mineral an overall neutral charge (Nelson, 2013).

A mineral's chemical composition and physical structure depends on the number of ions, the charges on each constituent of the mineral, and their geometrical arrangement. Although minerals have a definite chemical composition, the ratio of ions can vary within a given range. The relative abundance of ions present in the melt (the magma where minerals are formed), and the physical conditions (heat, pressure, water content) of the magma determines how minerals form and how they interact with other chemicals in the melt.

Thus when minerals form a wide range of possible combinations is possible. This variance in chemical composition is known as a solid solution. In a solid solution specific sites in the minerals structure are occupied by differing elements or chemical groups (Rakovan, 2005). An example is the mineral dolomite $(Ca^{2+,}\ Mg^{2+},CO_3)_2$. The carbonate ion has a $^{2-}$ oxidation state, which can accommodate either the $Ca^{2+,}$ or the $Mg^{2+,}$ cation. However, either cation can coordinate with the carbonate ion in various combinations to produce a wide range of minerals. The most different variations are called the end members of the mineral. In the case of dolomite, the two end members are $CaCO_3$ (either aragonite or calcite depending on the crystal structure) and $MgCO_3$ (magnesite). A wide range of possible combinations exists between the two end members. This variation gives rise to wide array of possible dolomites.

Substitutions generally occur between ions of similar charge and size, however when ions are of different charges, coupled substitutions occur in order to maintain the mineral's charge neutrality. For example, in the solid solution for the mineral plagioclase feldspar, the end members are (albite $NaAlSi_3O_8$) and (anorthite $CaAl_2Si_2O_8$). In anorthite a $Ca^{2+}$and an Al^{3+} replaced the Na^{1+} and Si^{4+} in the albite: Note that the overall charge of the substituting ions is the same: 5^+ (Nelson, 2013). The variability that exists in the chemical composition of other minerals given rise to a vast array of minerals. As a result, there are thousands (over 4,000) differing mineral combinations. Given this complexity, I will limit this unit to those minerals that form Wissahickon rocks.

Silicates: The most abundant elements in the earths' crust are oxygen (48.4 Wt.%) and silicon (28.2 Wt.%). As a result, the most common minerals are the silicates, which are coordinate complexes of oxygen, silicon and other elements arranged in various geometrical structures.



The Silica Tetrahedron is the basic building-block of silicate minerals. It is composed of one silicon ion (Si^{4+}) surrounded by four oxygen ions (O^{2-}). Silica Tetrahedrons link up in various patterns and bond with metal ions to form specific silicate minerals.

Source: http://image.slidesharecdn.com/mineralsgreg-120215121846-phpapp02/95/minerals-physical-properties-14-728.jpg?cb=1329309258

The simplest arrangement of the silicon and oxygen atoms is the silicate tetrahedron. This arrangement is the result of the bonding between a silicon atom (Si^{4+}) covalently bonded to four oxygen atoms (O^{2-}). The resulting compound has an overall charge of 4- thus the formula SiO^{4-}.

The tetrahedral arrangement is shown in figure. The four oxygen atoms are arranged at the vertices of a tetrahedron, with the silicon atom at the center. Each of the oxygen atoms carries a negative charge making it available for bonding with other silicates and / or other metal atoms to form a variety of silicate mineral structures. The principal metal used in these silicate complexes are sodium, magnesium, calcium, and iron (Tarbuck, 2006).

Silicate Crystal Structures

Silicate tetrahedra can form a variety of geometrical structures based on the number of bonds formed with other silicate tetrahedra. The array of structures results from linkages between individual tetrahedron formed by covalently bonded oxygen atoms. The resulting geometrical structures determine the physical and chemical properties of the minerals formed: Figure 8 illustrates the possible structures of the silicates. If no linkages occur, then the tetrahedron coordinates with metal cations: these single tetrahedron complexes are known as nesosilicates (or island tetrahedrons).

An important group of nesosilicates in the Wissahickon are the garnets. The general formula for these minerals is $A_3B_2(SiO_4)_3$). The A site usually contains divalent cations such as Ca^{2+}, Fe^{2+} or Mg^{2+}, the B sites contain trivalent cations: Al^{3+}, Fe^{+3}. Garnets are classified into two series based on the presence of Ca in the A site: as either pyralspite series: (no Ca in the A site) or ugrandite series: (Ca in the A site) (Nelson, 2013). Garnets are usually found in metamorphic rocks. They are also index minerals found in rocks that have a high degree of metamorphism: such as schist. Almandine is a garnet that is found in many samples of Wissahickon schist (West, 1998).

Single and double chains (inosilicates) occur when tetrahedra form multiple bonds: a single chain forms when tetrahedron share two of their oxygen atom with neighboring oxygen atoms: a double chain forms when tetrahedrons share three of their oxygen atoms with neighboring tetrahedra. When tetrahedra share four of their atoms they form a structure known as a phylosilicate (sheet silicate). A ring is composed of six tetrahedra covalently bonded. A sheet is composed of an indefinite number of rings with a hydroxyl ion (OH^-) at the center of each ring
See Figure 9.

The basic unit of the tetrahedral layer is an $(Si_2O_5)^{-2-}$ group (or with the hydroxyl ion $(Si_2O_5)(OH)^{-3}$) (note the charge on the group). In order to maintain charge balance, cations (either Mg^{2+},Fe^{2+}, or Al^{3+},) coordinate with the tetrahedra in an octahedral arrangement: this layer of cations forms an octahedral layer (Nelson, 2013). Tetrahedral (T) and Octahedral (O) layers can stack in sets of two (T-O) or three (T-O-T) to form the phylosilicate sheets. The differing arrangements are determined by the number of hydroxyl or oxygen atoms present in the tetrahedral layer, and the valence of the coordinating cations in the octahedral layer. The differing arrangements determine the chemical and physical properties of the various phyllosilicate minerals (Mitchell & Kenich, 2005).

Parallel sheet layers (whether T-O; or T-O-T) are joined together by weak van der Walls forces (as in the case of the Talc), by monovalent ions (such as K^{1+}in Muscovite) or divalent cations (such as Ca^{2+} in Clintonite) (Nelson, 2013) that form a vast array of phylosilicate structures (See Figure 10). There a many more facets of crystal structure that are central to the study of minerals, but such an analysis is beyond the scope of this paper.

We have (briefly) explored crystal structure because it helps explain the cleavage pattern of minerals. Cleavage is the tendency of a mineral to break along planes of weak bonding when stress is applied. It is important to note that crystal structure does not determine cleavage pattern for all minerals: as some minerals (quartz for example) have a well-defined crystal structure but no cleavage (Tarbuck, 2006). Cleavage is an important topic to this unit because it is one of the more distinctive physical property of the mica mineral family.

Micas (specifically muscovite and biotite) are the main components of Wissahickon schist. These mica minerals have what is called perfect cleavage because they break into very thin, symmetrical sheets. They cleave in this manner because each the layers of the sheet are held together by potassium ions (the yellow ions in figure 11). When stress is applied the layers split apart because the potassium bonds relatively weak.

> Mica has a sheet structure composed of tetrahedral and octahedral units. Sheets are stacked one on the other and held together primarily by potassium ions in a coordination that provide an electrostatic bond of moderate strength. In comparison with the intralayer bonds, however this bond is weak, which accounts for the perfect basal cleavage of mica[s]. pg.48 (Mitchell & Kenich, 2005, p. 48)

Minerals can be distinguished by other physical characteristics. Table 2 summarizes the properties of the major minerals in the Wissahickon.

Table 2: Minerals in Wissahickon Rocks

Name	Composition End Members	Cleavage	Luster	Color	Hardness Mohs Scale
Amphibole	$NaCa_2(Generals)_8O_{22}(OH)_2$	Two directions Uneven Fracture	Glassy to dull	Dark Green, Dark Brown, Black	5-6 Harder than Glass
Biotite (Mica)	$K(Mg),Fe)_3AlSi_3O_{10}(OH)_2$	Single perfect: thin sheets	Pearly; translucent	Brown-Black	2.5 -3.0
Muscovite (Mica)	$KAl_3Si_3O_{10}(OH,F)_2$	Single perfect: thin sheets	Glass-like, pearly	Colorless, White-Silver	2.- 2.5
Feldspar Potassium	$KAlSi_3O_8$			White -Gray	
Feldspar plagioclase	$NaAlSi_3O_8$ (Albite) - $CaAl_2Si_2O_8$(Anorthite)	Two planes at 90^0	Glass like	White-Gray	6-6.5 Harder than Glass
Garnet	In Wissahickon Schist: Almandine ($Fe_3Al_2(SiO_4)_3$	None	Glass like	Dark Red to Reddish Brown	6.5 -7.5
Quartz	SiO_2	No Cleavage	Glass like	Clear to White	7.0

Source: (Department of Geology at the University of Minnesota, 2009)

The information in this introduction is meant to provide the class with sufficient background information to begin the study of Wissahickon rocks. Given the complexity of this subject matter students will need to engage in additional independent research and field study in order to fully understand the geological history and chemistry of the Wissahickon. The following unit plan is meant to provide the foundation for this study.

UNIT: CHEMISTRY OF WISSAHICKON ROCKS UNIT

Standards Used in the Unit

Common Core literacy standards:

- Ccss.Ela-Literacy.Rst.11-12.8 Evaluate the hypotheses, data, analysis, and conclusions in a science or technical text, verifying the data when possible and corroborating or challenging conclusions with other sources of information.
- Ccss.Ela-Literacy.Rst.11-12.9 Synthesize information from a range of sources into a coherent understanding of process, phenomenon, or concept, resolving conflicting information when possible.

Next Generation Science Standards

- HS-PS1-1.Use the periodic table as a model to predict the relative properties of elements based on the patterns of electrons in the outermost energy level of atoms
- HS-ESS2-1. Develop a model to illustrate how Earth's internal and surface processes operate at different spatial and temporal scales to form continental and ocean-floor features.
- HS-ESS2-2. Analyze geoscience data to make the claim that one changes to Earth's surface can create feedbacks that cause changes to other Earth systems

Lesson Plans

Day One / Day Two **Topic: Chemical Bonding**
Essential Question
Objective: SWBAT: Analyze elements and ions in rock forming minerals
Standards: HS-PS1-1, Cssa-Ela. Rst11-12.9
Narrative: Part of this day's lesson will be a review of the principals of bonding as most students have already had a year of chemistry. The focus of the review will be on the reasons why bonding occurs, the type of bonds formed, and the chemical composition of minerals. This will lead to a discussion of the chemical structure of rock forming minerals (silicates), solid solutions, and the molecular geometry of silicates. **Strategies:** Students will review principles of chemical bonding by determining the formula for molecular & ionic compounds, and determining the ratio and charges of ions (mono and polyatomic) ionic compounds. **Direct Instruction:** Definition of elements, compounds, the octet rule, and bonding principles. Review of charges on anions, cations and charge neutrality in bonds. Minerals will be defined as naturally occurring solid compounds with definite chemical compositions. **Classroom Activity**: Students will use octet rule (and Lewis dot structures) to determine ratio of ions (and polyatomic ions) in ionic bonds. Students will then analyze the ratio of elements, mono-atomic and polyatomic ions in rock forming minerals. Students will also analyze the structure of end members in solid solutions of minerals
Materials: Periodic tables, list of common rock forming minerals; list of solid solution end members.

Day Three / Four: **Topic: Chemistry of Rock Forming Minerals**
Essential Questions: How does the geometry of rock forming minerals affect their physical / chemical properties?
Objective: Describe geometry of rock forming minerals IOT analyze the relation between geometry and physical property
Standards: HS-PS1-1, & 2.2: Cssa-Ela. Rst11-12.8
Narrative: The lesson will explore the tetrahedral geometry of silicates and examine the variations that arise when silicate tetrahedra link together. **Strategies:** Students will diagram the bonding and shape of given minerals that form, islands, single / double chains, sheets, and three dimensional networks. **Direct Instruction:** Explanation of how bonds are formed between individual silicate tetrahedra to form the various structures. Cleavage is the tendency to break along planes of weakest bonding; thus silicate geometry can explain a mineral's cleavage pattern. **Classroom Activity**: Students will diagram individual tetrahedra, determine how structural variations are made, then explain where / how cleavage will occur. Students will engage in the Architecture of Silicate Minerals Lab. Students will relate activity to geometry and cleavage patterns of specific minerals found in Wissahickon rocks.
Materials: Illustrations of silicate structures, list of minerals in each structural class, illustration of bonding in silicate minerals, Architecture of Silicate Minerals lab handout. Lab located at: http://academic.brooklyn.cuny.edu/geology/powell/courses/geol7040/GEOL7040-Silicate%20Structures%20Activity.pdf

Day Five: **Topic: Rock Cycle**
Essential Questions: How are the three types of rocks related? Why is it referred to as the "Rock Cycle"?
Objective: To analyze the three rock types and explain how they interchange form.
Standards: HS-PS 2.2: Cssa-Ela. Rst11-12.9
Narrative: Today's lesson will focus on how physical and chemical conditions affect the properties of rocks. The lesson begins with a general review of rocks and the rock cycle followed by a discussion of the minerals present in sedimentary and metamorphic rocks found in the Wissahickon. Students will use index minerals to analyze the conditions under which metamorphism occurred. **Strategies:** Students will explore samples of igneous, sedimentary, and metamorphic rocks: they will note identifiable characteristics of each type of rock. They will then be given unknown samples and asked to identify them based on their observations. **Direct Instruction:** Description of the classes of rocks: igneous (intrusive, extrusive), sedimentary (clastic and chemical), and metamorphic rocks. Explanations of how differing rock types form; (how chemical / physical conditions affect their physical chemical properties) and how index minerals are used to determine the pressure, temperature, and depth of metamorphism. **Classroom Activity**: Comparing properties of rock samples, identifying different types of rock. Identifying unknown rock samples. Students will engage in a classification of

rocks interactive video. Students will use the video overview to note general characteristics of the three types of rocks. Students will then analyze real samples of rocks and attempt to identify the rock type.
Materials: Rock samples kit, samples of each type of rock, computer cart for interactive video, rock properties handout, Graph of index minerals vs (heat, pressure and temperature). Lab located at: http://www.glencoe.com/sites/common_assets/science/virtual_labs/ES04/ES04.html and rock classification key handout.

Day Six	**Topic: Rocks and Minerals of the Wissahickon**
Essential Questions: What are the main rock types in the Wissahickon? What minerals are in these rocks	
Objective: To analyze the major classes of Wissahickon rocks, their minerals, and their physical properties.	
Standards: HS-PS1-1, & 2.2: Cssa-Ela. Rst11-12.8	
Narrative: Today students will use what they've learned to identify the major types of rocks in the Wissahickon. They will identify the minerals present and begin their explanation of how the rocks were formed. This is the first day of the Chemistry of Wissahickon rocks. **Strategies:** Students will view an interactive virtual tour of the Wissahickon rocks and attempt to identify the type of rock, its formation, and the minerals present in the rocks. **Direct Instruction:** Review of the physical properties of rock types, their physical / chemical properties, as well as the manner in which they formed (sedimentary / metamorphic). Review of the rock cycle and properties of rocks. **Classroom Activity**: Students will view the Virtual Tour of the Wissahickon which illustrates Wissahickon rocks. Students will note the physical features of each sample and determine the type of rock, how it was formed, the minerals present in the rock, the chemical structure, and physical properties (cleavage, hardness) of the rock. This day's activity will serve as a formative assessment of learning to date.	
Materials: Virtual Tour of Wissahickon located @ http://www.personal.psu.edu/faculty/j/e/jea4/VWiss/Wisstopo.html	

Day Seven / Day Eight:	**Topic: Geological History / Radiometric Dating**
Essential Questions: What are the ages of man? How do we date fossils? How do we date rocks? How do we know how old the Earth is?	
Objective: SWBAT Use half-life data of radioisotopes to explain methods of dating rocks and fossils.	
Standards: HS-PS1-1, & 2.2: Cssa-Ela. Rst11-12.8	

Narrative: The history of the Wissahickon rocks extends into the Paleozoic eon. In order to analyze the geological record, students need to have a firm grasp of Geological Time Periods and the manner in which we date material from the past. **Strategies:** Students will complete a historical time line activity, which relates biological and geological events to specific time periods. Students will also complete a lab that explores radiometric decay of carbon isotopes. **Direct Instruction:** The earth's history is divided into eons, eras, periods, epochs, and ages. Each time period is characterized by type of living organisms and major geological events: (for this unit we will include the major landmasses and types of rocks formed) Fossils and rocks provide information used to establish the geological record and geography of landmasses. Radiometric dating uses the half-life decay rate of isotopes to determine the age of artifacts from the distant past. Isotopes are atoms of an element with the same atomic number but a different number of neutrons. Isotopes decay into other atoms at well-known rates. Scientists can use the half-life of isotopes to date rocks and fossils. **Classroom Activity**: Students will create a geological timeline that relates information living organisms and geologic events. Special attention will be given to the time of the Taconic, Arcadian, and Alleghenian Progenies, and the formation of the supercontinents of Rodinia, Euramerica, and Pangaea. Students will then engage in a lab activity that explores the concept of radiometric dating using the C_{14}- N_{14} decay series (half-life = 5730 years). Once completed students will analyze the half-life data of other isotopes used to date older rock samples.
Materials: Large diagram of geological time periods, individual handouts with data for each time period, and construction paper: Radiometric dating lab handout, lab materials (100 pennies, boxes, graph paper); lab available @ http://kenstonlocal.org/wilk/wp-content/uploads/2016/01/Radiometric-Dating-Activity.pdf

Day Nine / Day Ten: **Topic: Plate Tectonics**
Essential Questions:
Objective: SWBAT Use theory of plate tectonics to explain the formation and rifting of the supercontinents throughout time.
Standards: HS-PS1-1, & 2.2: Cssa-Ela. Rst11-12.8
Narrative: Plate tectonic theory provides an explanation for the motion of continents, ocean basins, sea floor spreading, earthquakes as well as the creation of mountains / volcanoes, and supercontinents. Evidence from the fossil and rock record supports the existence of super continents such as Rodinia, Gondwana, and Pangaea. The formation of important mountain ranges in North America coincided with the creation of these supercontinents, which are central to the geological history of Wissahickon rocks. **Strategies:** Students will use fossil / rock evidence to recreate Pangaea and then explain how mid ocean divergent plate boundaries affected the breakup of Pangaea.

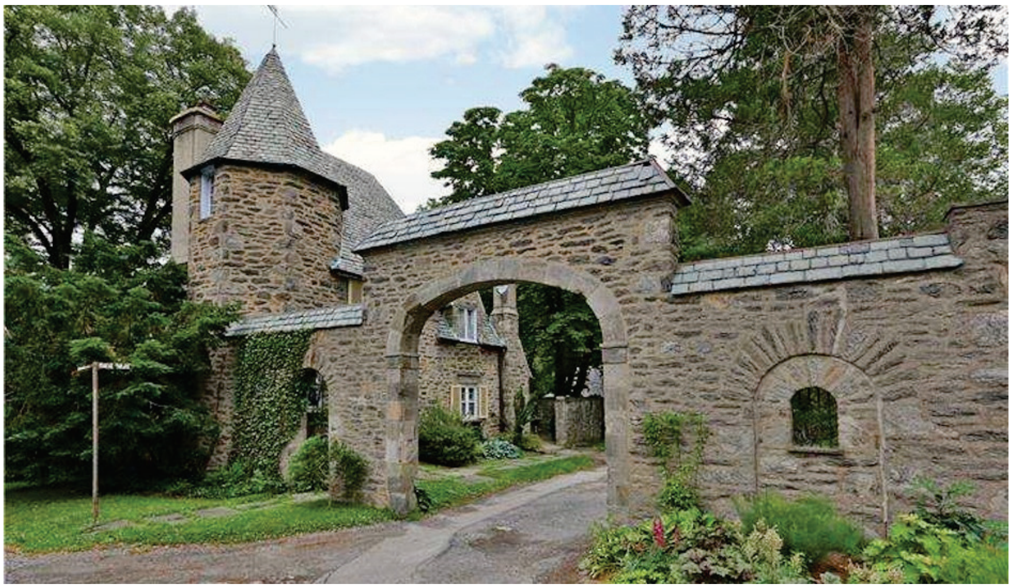
They will use coordinates of earthquakes / volcanoes to map the active regions of plate motion and explain why volcanoes / mountains, and earthquakes occur at plate boundaries. **Direct Instruction:** The lithosphere is divided into a series of tectonic plates (oceanic and continental crust). The interior of the earth is composed of three major sections: mantle, outer and inner core. Convection currents within the upper mantle (the asthenosphere) keep the plates in continual motion. The convergence of continental plates creates mountains, while the convergence of oceanic/ continental creates volcanoes. Divergent boundaries at mid ocean ridges cause seafloor spreading. **Classroom Activity**: Recreating Pangaea activity (with written explanation of rock and fossil evidence). Locating earth's volcanoes and earthquakes activity: Summary paragraph explaining how plate motion creates new oceanic crust, mountains, and volcanoes.
Materials: Pangaea activity handout, paper, scissors, etc., fossil / rock record data: coordinates of volcanoes / earthquakes, map projections (Mercator), a Globe.

Day Eleven: Wissahickon Geological History
Essential Questions: What are the processes / events that formed the Wissahickon Valley?
Objective: SWBAT: Summarize the geological history of Wissahickon Formation and the rocks found in the Wissahickon Valley.
Standards: HS-PS1-1, & 2.2: Cssa-Ela. Rst11-12.8
Narrative: This class combines the chemistry of Wissahickon rocks and the geologic record of the area. We will review our time lines and write a summary of the geological history of the rocks. **Strategies:** Class will use timelines from earlier class, paying attention to the periods of mountain building, rifting, and processes of sedimentation, and rocks formed during each time period. Students will summarize information as constructed responses. **Direct Instruction:** Teacher will review The Geological History of the Wissahickon from late Proterozoic to now. Focus will be on periods of mountain building and rifting. **Classroom Activity**: Summarize geological history of Wissahickon as a constructed response.
Materials: Geological Time lines.

Appendix

FIGURES and TABLES

Figure 1 Wissahickon Schist in Philadelphia Architecture



Source http://cdn.phillymag.com/wp-content/uploads/2014/08/00000.jpg

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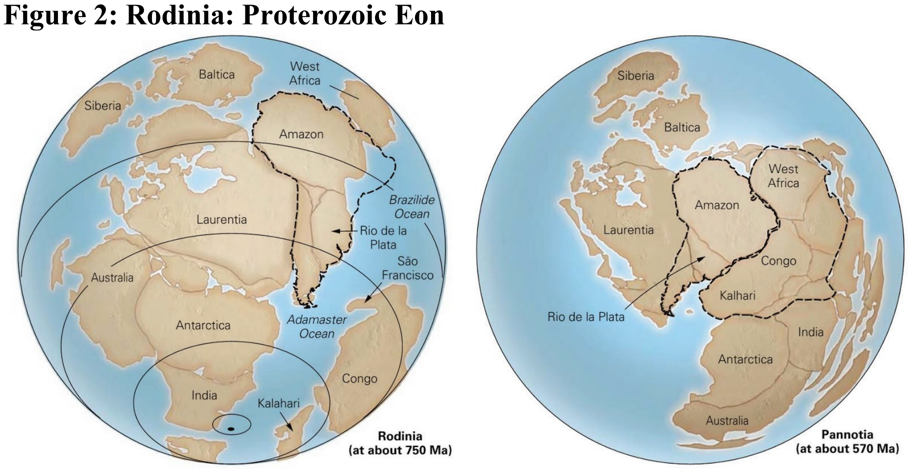
Figure 2: Rodinia: Proterozoic Eon



(a) Rodinia formed around 1 Ga and lasted until about 700 Ma. North America and Greenland together comprise Laurentia.

(b) According to one model, by 570 Ma Rodinia had broken apart; continents that once lay to the west of Laurentia ended up to the east of Africa. The resulting supercontinent, Pannotia, broke up soon after it formed.

Source: https://www.google.com/search?q=rodinia&source=lnms&tbm=isch&sa=X&ved=0ahUKEwj3wo6BocbNAhVIWT4KHYrUBMoQ_AUICCgB&biw=1008&bih=598#imgrc=Y59KM8qoe0eZQM%3A

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Figure 3: The Iapetus Ocean: Cambrian Period

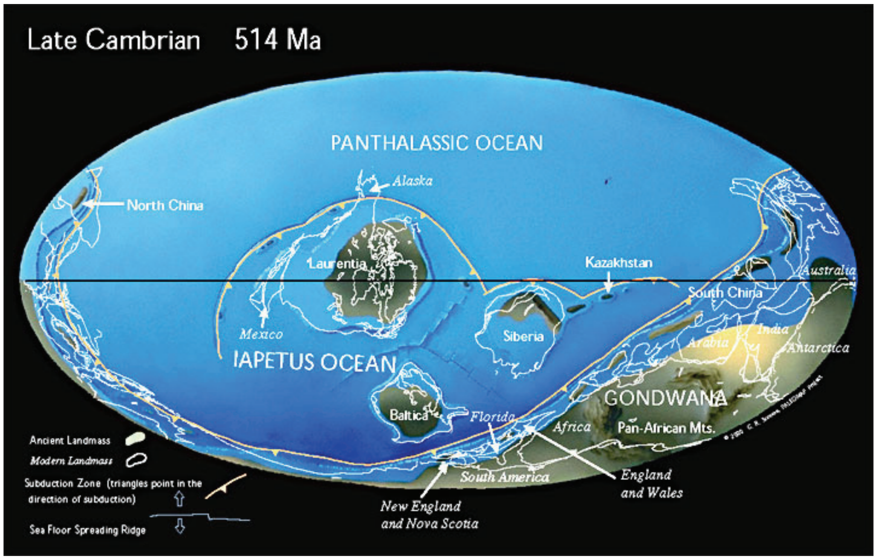

Plate tectonic maps and Continental drift animations by C. R. Scotese, PALEOMAP Project (www.scotese.com)

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Figure 4: Euramerica Forms:

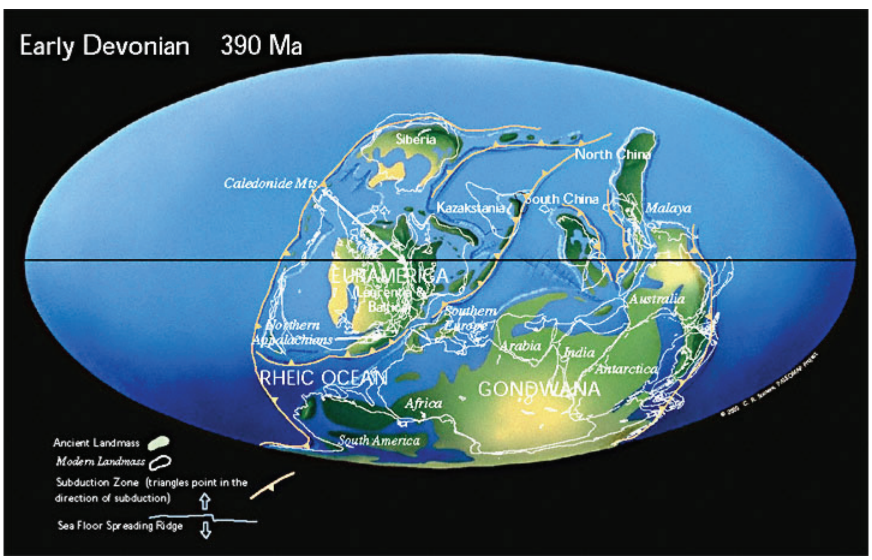

Plate tectonic maps and Continental drift animations by C. R. Scots, PALEOMAP Project (www.scotese.com)
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Figure 5: Pangaea Forms

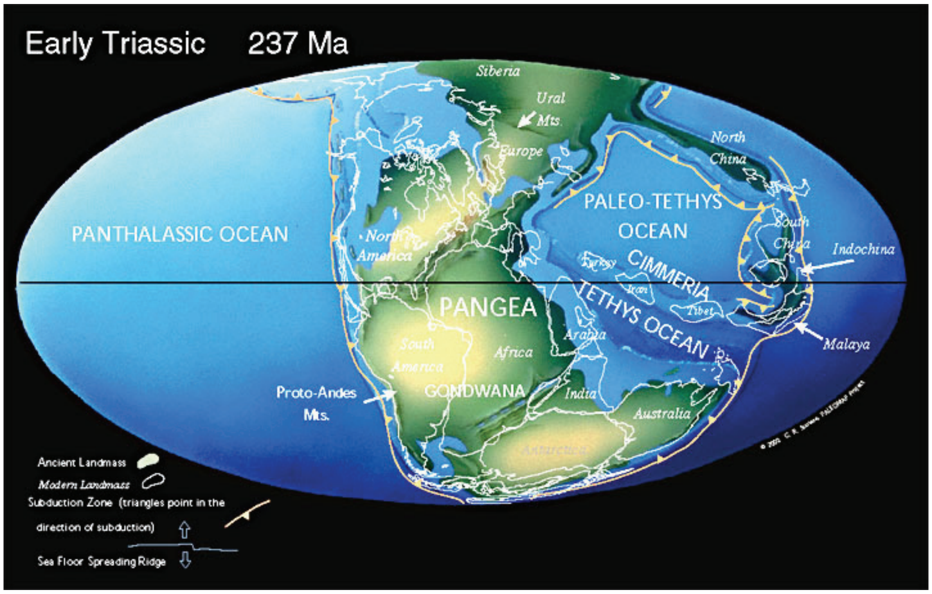

Plate tectonic maps and Continental drift animations by C. R. Scotese, PALEOMAP Project (www.scotese.com)
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Figure 6: Wissahickon Schist

Source: (Alcock, 2012)

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Table 1: Barrovian Metamorphism

DEVELOPMENT OF BARROVIAN METAMORPHIC ROCKS FROM A SHALE PARENT

	Sedimentary Processes	Greenschist Facies		Amphibolite Facies	Granulite Facies	Igneous Processes
COMPOSITION	Clay SiO2 Fe oxides Organic matter	Very small crystals of chlorite	Larger chlorite crystals. Fine grained quartz and feldspar	Chlorite gone. Qtz, feldspar, mica common. New Minerals include: garnet, staurolite, kyanite, andalusite, etc.	Quartz, feldspar mica dominate. Other minerals break down.	Rock melts to produce FELSIC magma.
TEXTURE	Sedimentary bedding	SLATEY CLEAVAGE Fine grained foliation leading to good, flat cleavage.	SLATEY CLEAVAGE Coarser grained foliation due to enlarging chlorite crystals	SCHISTOSITY Minerals completely intermixed, but with micas (biotite or muscovite) all aligned.	MINERAL BANDING Quartz and feldspar migrate into separate bands from micas.	MIGMATITE Partial (fractional) melting. Highly deformed rock with swirls of granite within banded gneiss.
DISTINGUISHING FEATURES	Dull sound when struck; it "thunks"	Rings like a bell. More dense than shale. More luster than shales, less than phyllite.	Has definite sheen in reflected light. Foliation begins to produce an undulating surface.	Minerals large enough to be easily identified. Index minerals important: biotite ⇒ garnet ⇒ staurolite ⇒ kyanite ⇒ sillimanite	Defining bands of light and dark colored minerals	

Source: http://csmres.jmu.edu/geollab/Fichter/MetaRx/Barrov.

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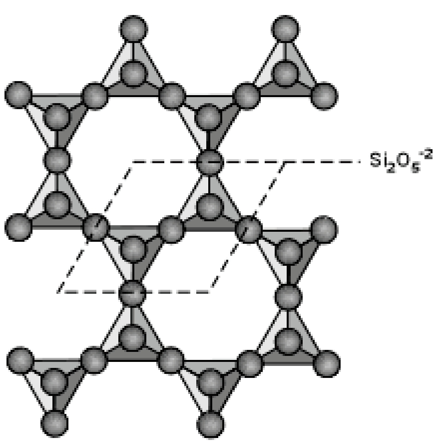
Figure 9: Phylosilicate Ring Structure



Source: (Nelson, 2013)

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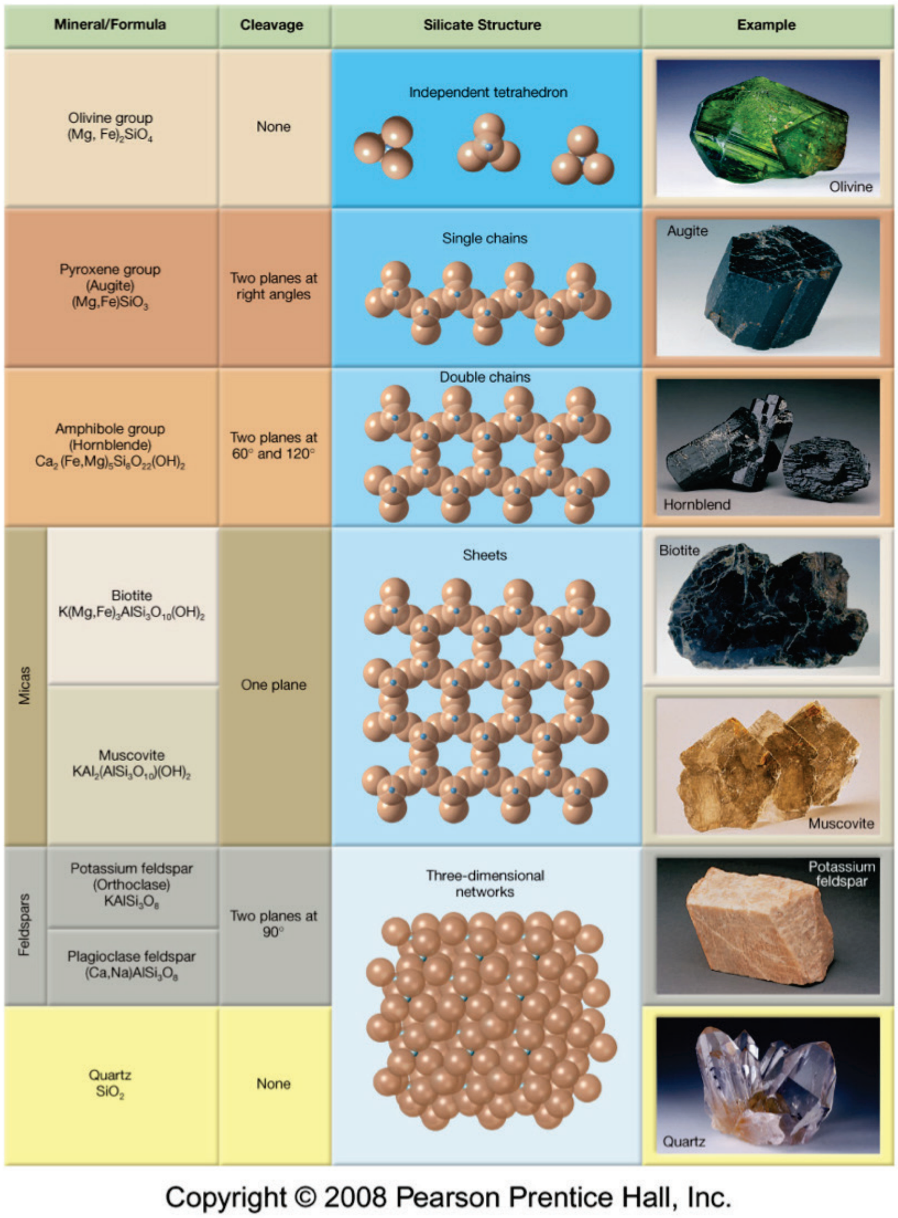
Figure 8 Silicate Structures



Source: (Tarbuck, 2006)

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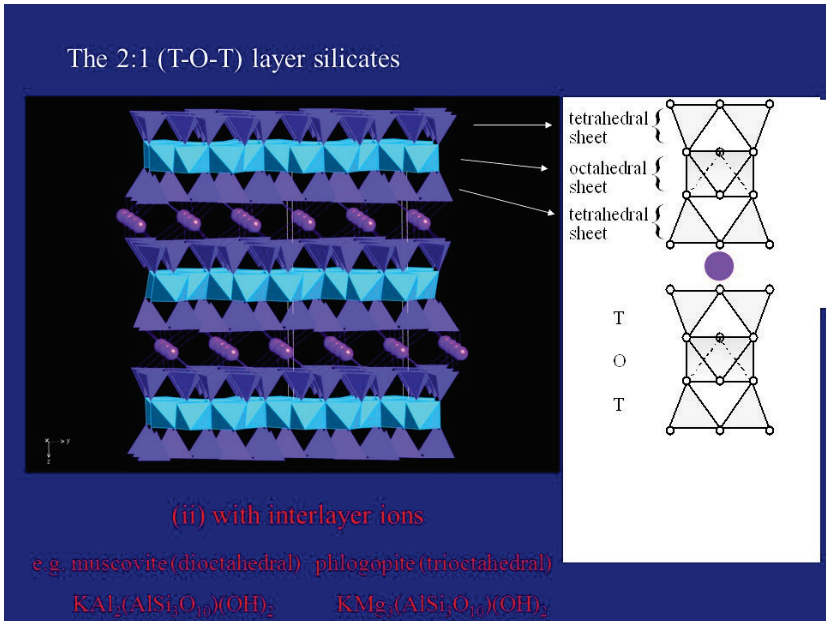
Figure 10: T-O & T-O-T Layers in Silicate Bonding



Source: http://images.slideplayer.com/25/7963085/slides/slide_13.jpg

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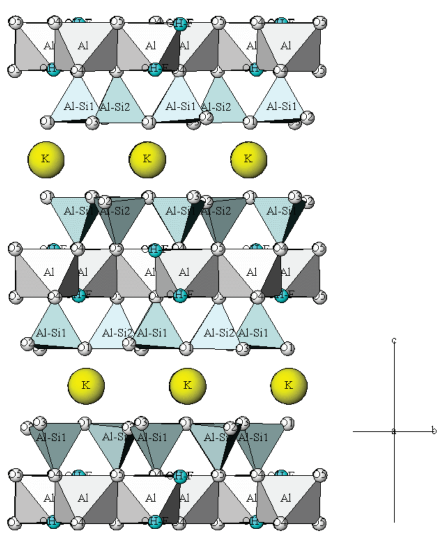
Figure 11: Bonding in Muscovite



Source: Crystal Structure Gallery, National Institute of Advanced Industrial Science and Technology (AIST) https://staff.aist.go.jp/nomura-k/english/itscgallery-e.htm

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Geological Time Line

GEOLOGIC TIME SCALE

AGE (millions of years)	ERA OR EON	PERIOD	ACTIVITY AFFECTING PENNSYLVANIA	MAIN ROCK TYPES OR DEPOSITS IN PENNSYLVANIA	SOME DOMINANT LIFE-FORMS IN PENNSYLVANIA
0-2.6	CENOZOIC ERA	QUATERNARY	Glaciation; periglacial erosion and deposition; formation of Lake Erie	Sand, silt, clay, gravel	Hominids (esp. man) and other mammals, grasses, flowering plants
2.6-66		TERTIARY	Weathering and erosion; creation of landscape south of glaciated areas	Sand, silt, gravel	Primates (first hominids) and grazing mammals, birds, flowering plants, grasses
66-145	MESOZOIC ERA	CRETACEOUS	Erosion and weathering	Clay, sand	Dinosaurs, reptiles, mammals, birds, rays, sharks, ammonites
145-201		JURASSIC	Diabase intrusions; opening of Atlantic Ocean	Diabase	Dinosaurs, reptiles, mammals, birds, ammonites, rudistid bivalves, conifers, cycads
201-252		TRIASSIC	Separation of Africa from North America; sedimentation in rift valley	Shale, sandstone, conglomerate, siltstone	Early dinosaurs, reptiles, early mammals and birds, conifers, cycads, seed plants
252-299	PALEOZOIC ERA	PERMIAN	**Alleghanian Orogeny:** Collision of Africa and North America creates Appalachian Mtns; thrust faulting, folding; erosion	Sandstone, shale	Conifers, fungi, insects and other arthropods, amphibians, reptiles
299-359		PENNSYLVANIAN AND MISSISSIPPIAN (Carboniferous)	Erosion of southeast highland; deltaic transitioning to alluvial deposition; development of alluvial plain	Sandstone, siltstone, shale, conglomerate, coal, limestone	Land plants, crinoids, foraminiferans, insects, bryozoans, brachiopods, amphibians, air-breathing snails, early reptiles
359-419		DEVONIAN	**Acadian Orogeny:** Collision of Avalonia, Europe, North America; formation of Catskill Delta	Sandstone, siltstone, shale, conglomerate, limestone	Armored and lobe-finned fish, tetrapods, brachiopods, reef corals, ammonoid cephalopods, insects, land plants
419-443		SILURIAN	Erosion of mountains; deposition of sand and mud	Sandstone, shale, quartzite, siltstone, limestone	Crinoids, brachiopods, corals, reef-building stromatoporoids, jawed and jawless fish
443-485		ORDOVICIAN	**Taconic Orogeny:** Thrusting of volcanic arc; development of Appalachian basin	Limestone, dolomite, shale, sandstone, siltstone, chert, schist, gneiss, phyllite	Trilobites, graptolites, mollusks, bryozoans, conodonts, echinoderms, jawless fish
485-541		CAMBRIAN	Transgression of the sea; carbonate deposition	Limestone, dolomite, quartzite, sandstone, shale, schist, gneiss	Trilobites, brachiopods, hyoliths, bizarre "Burgess Shale"-type life-forms
541-2,500	PROTEROZOIC EON	Geologic time older than Cambrian is commonly referred to as Precambrian	Accretion of microplates to form Laurentia	Gneiss, serpentinite, metabasalt	Blue-green algae, Ediacaran life-forms, jellyfish, worms
2,500-4,000	ARCHEAN EON		Bombardment by comets and asteroids; creation of continental crust	None identified in Pennsylvania	Bacteria
4,000-4,600	HADEAN EON		Formation of Earth and solar system	None identified in Pennsylvania	None identified

Source: (Barnes & Sevon, 2016)

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Mohs Hardness Scale

Source: http://diamondabrasives.eu/wp-content/uploads/2013/12/MohsHardnessScale-from-igs.indiana.edu_.jpg

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