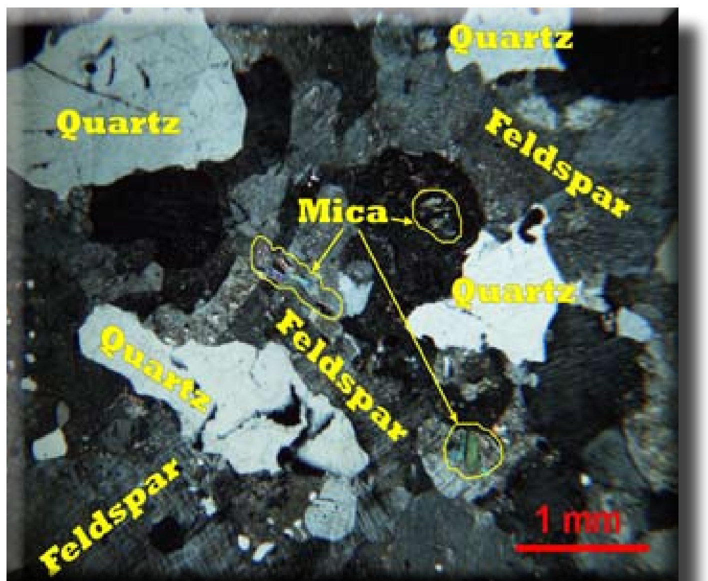
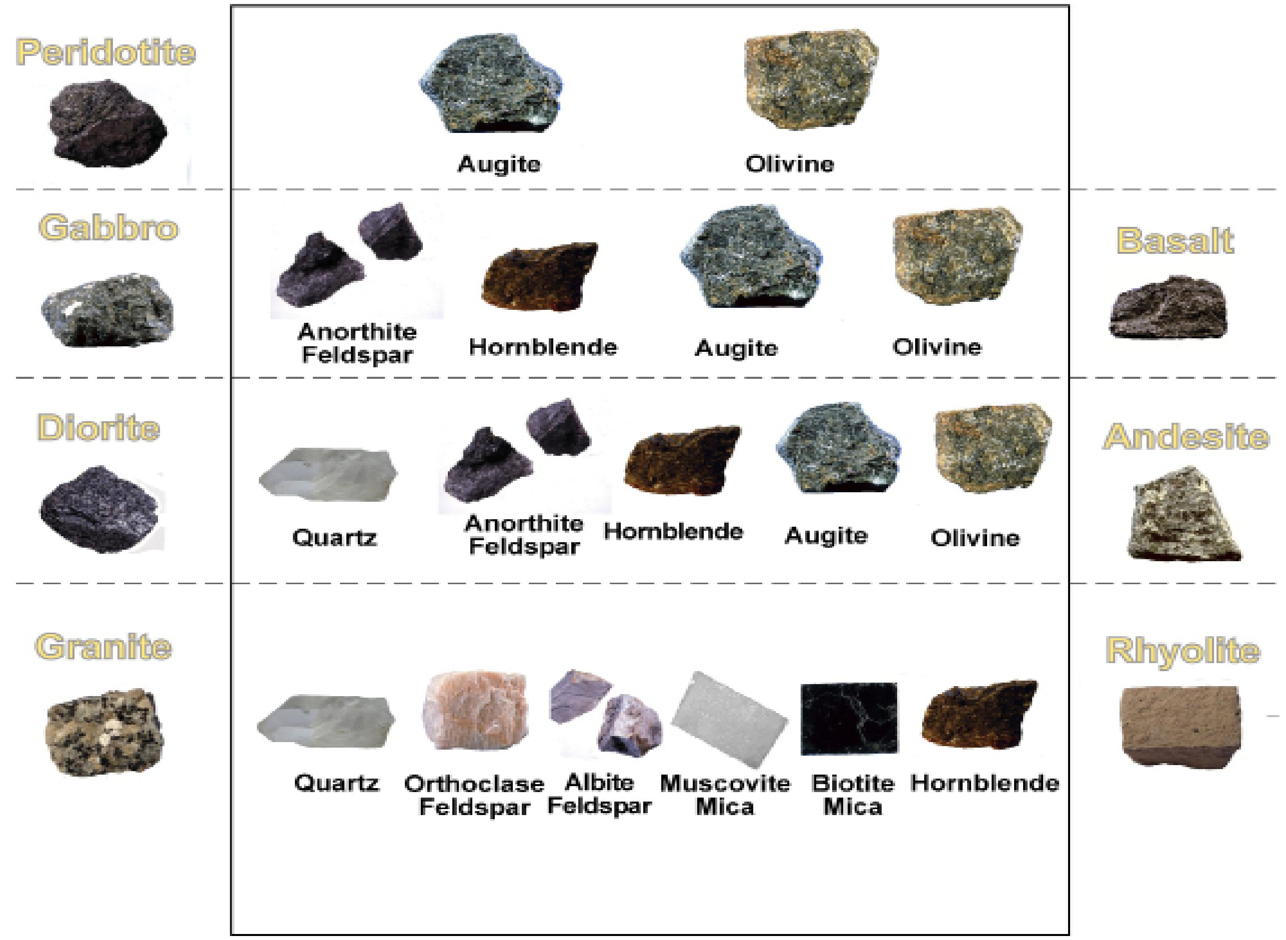
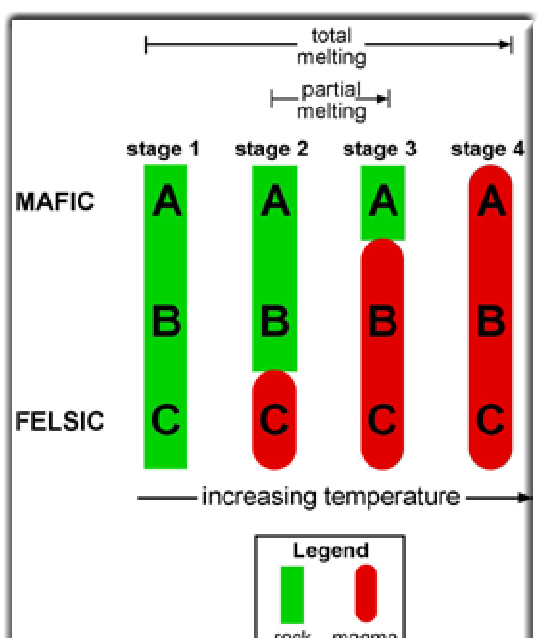
Conceptual Understanding Series for West Virginia Science Teachers

Igneous Rocks







Igneous Rocks		COLOR: Light Felsic	COLOR: Intermediate	COLOR: Dark Mafic
TEXTURE	coarse grained (Large Crystals)	Granite	Diorite	Gabbro
TEXTURE	fine grained (Small Crystals)	Rhyolite	Andesite	Basalt

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Foreword

Understanding igneous rocks and the minerals of which they are comprised are fundamental knowledge taught within the K-12 science curriculum. Unfortunately, most West Virginia K-12 science teachers possess, through no fault of their own, limited knowledge of such content. Rectifying this shortcoming is often not accomplished by enrolling in undergraduate geology courses because they routinely employ the traditional higher education process of “telling” not “doing.” In this text we try to veer away from the traditional approach by attempting to use a coaching-style teaching approach. Most of your reading will engage you in the step-by-step development of a critically important illustration that, while initially daunting, may ultimately simplify the way you teach igneous rocks while still addressing required curriculum standards. The readers’ task is to continually evaluate, reconsider, and reconstitute what is important for their own use.

The best way to begin any new topic is to explore prior knowledge. You have ten seconds to answer the following questions. Ready? Begin!

1. Write the names of three igneous rocks in the provided spaces.

Igneous rock #1 ________________ Igneous rock #2 ____________________ Igneous rock #3 ____________________

2. Are there any naturally occurring igneous rocks in West Virginia? Yes__________ No____________

Be honest. How many did you name? Granite? Maybe basalt? Did you get three within the time limit? Most do not! Did you use lava and/or magma? Wrong, they are not the name of specific rocks. Did you use marble? Nope, metamorphic! But, many of your students might use it. How did you respond to the second question? There actually are igneous rocks in West Virginia. Not a lot, but they do exist! The last page of the discussion addresses them and provides a reference for additional free information and photographs.

The novice would be best served by reading with an open mind, slowly, and more than once. Our attempt to simplify is not based on the notion, which I personally detest, of “dumbing down.” But, it does mean ignoring some material and extreme simplification of some very complex ideas. Therefore, take the text and illustrations at face value...avoid the temptation to apply self-proclaimed intuitive leaps of logic. More often than not they will lead to self-inflicted confusion and contradiction. Read with the notion of building “Now I understand moments”. In the end, maybe the second time through, you will be surprised at your level of pedagogical content knowledge and the number of “ah ha” moments.

I would like to thank Mike Hohn, Jim Britton, Jeanie Sutton, Barnes Nugent, Mary Sue Burns, and Deb Hemler for their suggestions, insights, and admonitions. Betty Schleger has, as usual, been the person most responsible for actually getting this project completed. Artwork, page layout, reviewing, and making suggestions that result in concrete forward movement all exist within her formidable skill set. I thank her for her continued patience.

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Conceptual Understanding Series for West Virginia Science Teachers

(or, How we Teach it)

Igneous Rocks

CONTENTS

Exploration

True or false: The Earth is a sphere of igneous rock.

If your first thought was “What is an igneous rock?” then this is the book for you.

In a simplified view, we live on an planet made up primarily of igneous rocks. Earth’s brittle oceanic crust is primarily composed of basalt while the brittle continental crust is mainly granite (Figure 1). Most of Earth’s upper mantle is dominated by a plastic igneous rock called peridotite. Have you ever heard of peridotite? Do you use it when describing Earth’s mantle? Do you use granite and basalt when discussing Earth’s crust?

Asking simple exploratory questions can be a powerful way for you to gauge students’ prior knowledge.

Read *Conceptual Understanding Series for West Virginia Science Teachers: Plate Tectonics* to learn about plastic rocks of Earth’s interior.

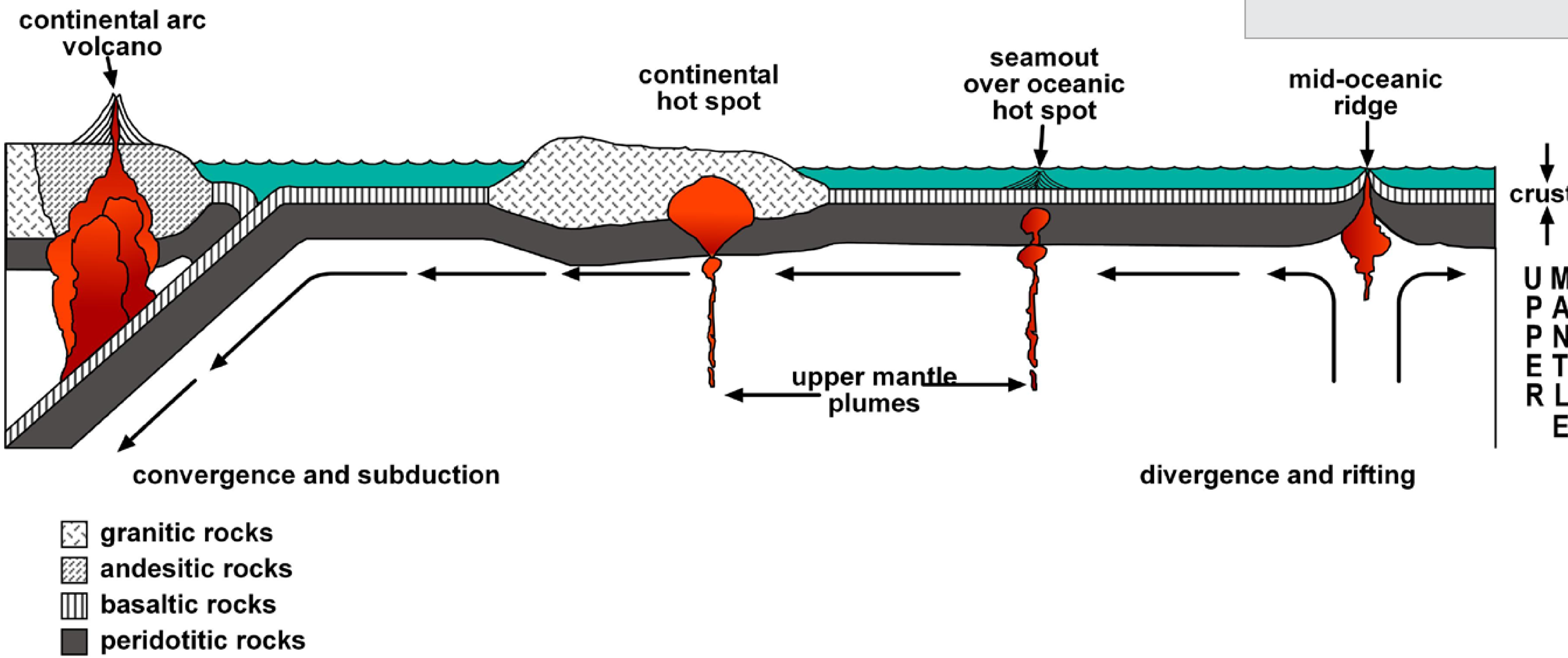


Figure 1

Introduction

Understanding igneous rocks, let alone teaching the subject to others, can be overwhelming to the point that the topic is only tangentially addressed. Our idea is to help the teacher construct a beginning level conceptual understanding that can be used to meet common content standards.

We will first address the common minerals associated with igneous rocks. This will lead us into discussions on magma, silicate minerals, and the construction of a useful illustration that may be used to both name an igneous rock and determine its mineral content. To simplify the discussion we are severely reducing the number of igneous rocks you need to know to an essential few. Other instructors may question this approach but it does allow us to focus on the basics.

Seven Igneous Rocks and Nine Minerals

Since a rock is a mixture of minerals our discussion of the igneous rocks peridotite, gabbro, basalt, diorite, andesite, granite, and rhyolite (Figure 2) means we must discuss the minerals of which these rocks are composed. Surprisingly, all seven are composed of various combinations of only nine minerals: olivine, augite, anorthite, albite, orthoclase, hornblende, quartz, biotite and muscovite. Thus all the rocks and minerals required to teach basic igneous processes, including volcanoes, are shown in Figure 2. Let's begin by examining the physical and chemical environments in which these materials form.

Figure 2. Seven rocks and the minerals of which they may be made. "May be made" is critical to comprehending igneous rocks. For example, a granite must contain some quartz, some feldspar, and some mica. In addition to these three, it may or may not contain hornblende or multiple kinds of feldspars and micas. Note the lack of scale in this and many other illustrations. In their original dimensions, most specimens are roughly 3 X 5 cm (1.2 X 2 inches) but will appear as different sizes to fit available space.

Magma

Igneous rocks and the minerals of which they are made form by the cooling, crystallization, and solidification of molten rock. Clarification of terms used to reference molten rock is our first priority. A common student simplification is to call all molten rock lava. Geologists, being scientists, are more particular and distinguish between molten rock above and molten rock below Earth's surface. As long as molten rock remains below the surface it is called magma. Once extruded onto Earth's surface it becomes lava. Even though magma and lava do not denote, nor imply, differences in mineral composition the geographic distinction plays an important role in the physical appearance of the rocks formed when they cool.

At this point we must also address the notion of the single "mother" magma from which all igneous rocks form. Actually, as shown in Figure 3, there are four distinct kinds of magma. A quick glance at photographs on the right side of Figure 3 clearly show each has a unique physical appearance. Our discussion will focus upon the more common basaltic, andesitic, and granitic magmas because they make most of the igneous rocks we see and because peridiotite magma is only very rarely seen on Earth's surface. As we will demonstrate later, each magma is temperature dependent and chemically distinct. This keystone concept means that as each cools it will produce a unique suite of solid minerals and rocks. Utilized correctly this idea can help the novice begin to appreciate the diverse nature, occurrence, and physical appearance of igneous rocks. By the way, did you connect Figure 3 magma names with several rock names in Figure 2. Indeed, magmas are named for a prominent igneous rocks produced by the cooling of that magma.

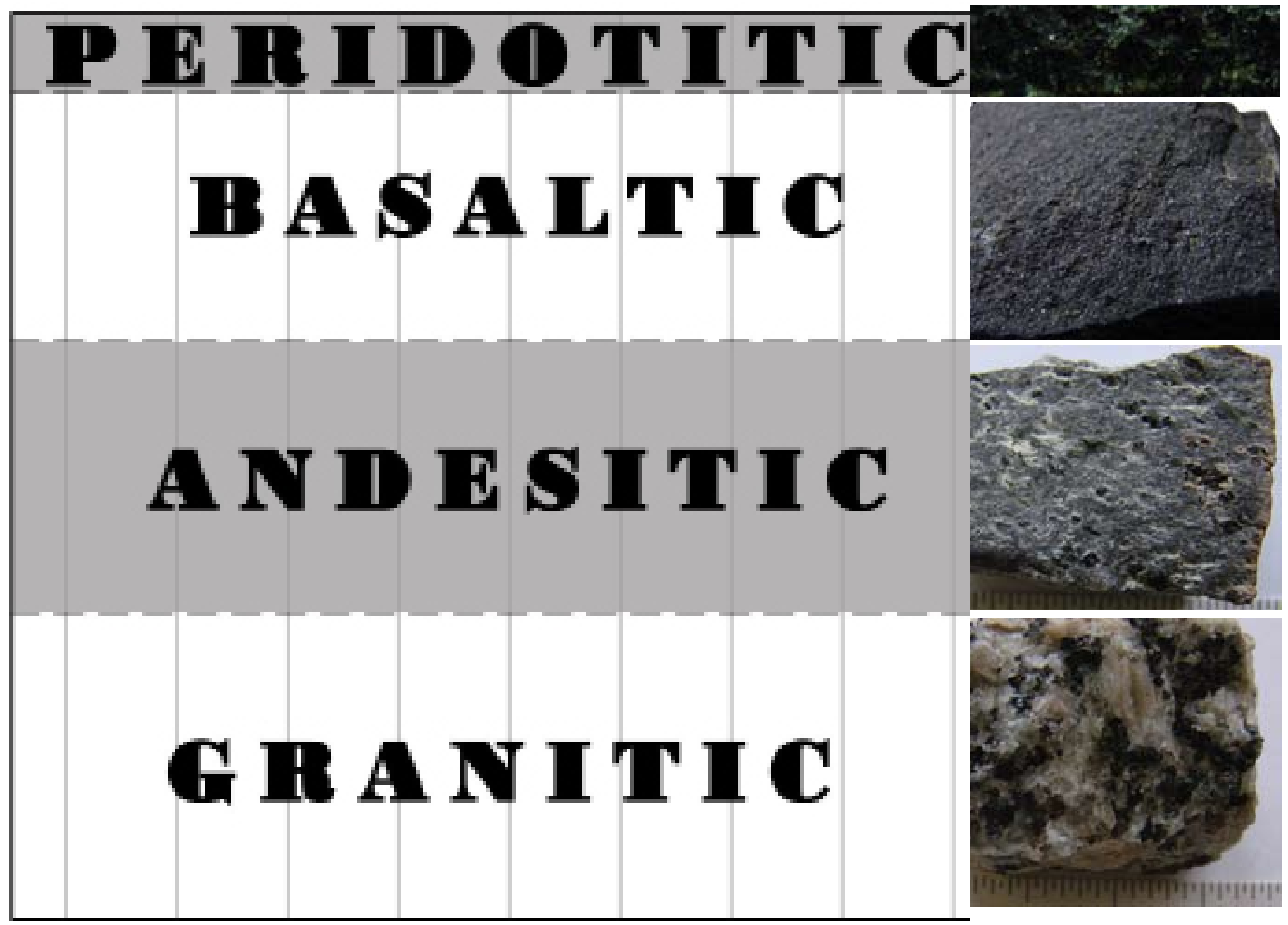


Figure 3

Students also have acquired, from popular media, the idea that all molten rock, especially lava, flows like water. This is not the case. A fluid's ability to flow is defined by its viscosity. By definition, viscosity is resistance to flow. Thus, a low viscosity fluid will flow very readily. Students seem to remember this best by the application of some simple word play: low-flow. Water is a good example of a low viscosity fluid. For our introductory purposes we need only concern ourselves with the concept of relative viscosity. Visually demonstrating viscosity is simple. Pour olive oil, pancake syrup, and molasses onto a flat surface. Students should concede that olive oil flows much more readily than the molasses while the pancake syrup ranks between them. We will revisit this analogy several times to explore magma and lava.

Magma = molten rock below ground.
Lava = molten rock above ground.

Peridiotite magma resides as a plastic rock within Earth's upper mantle, melts due to heating caused by natural radioactive decay and extreme burial depth, and is rarely seen at the surface.

Have you ever really considered the idea that liquids become solid by freezing. In the case of water, ice crystals form, grow, and interlock? Rocks form much the same way. When magma freezes mineral crystals form, grow, and lock together. The chemistry of the magma determines what minerals, and hence, what rocks, may be formed. Depending upon grade level, you could continue with the freezing analogy because it is perfectly correct. However, we think it is better for you to internalize the idea of crystallization since minerals are really chemically constructed crystals.

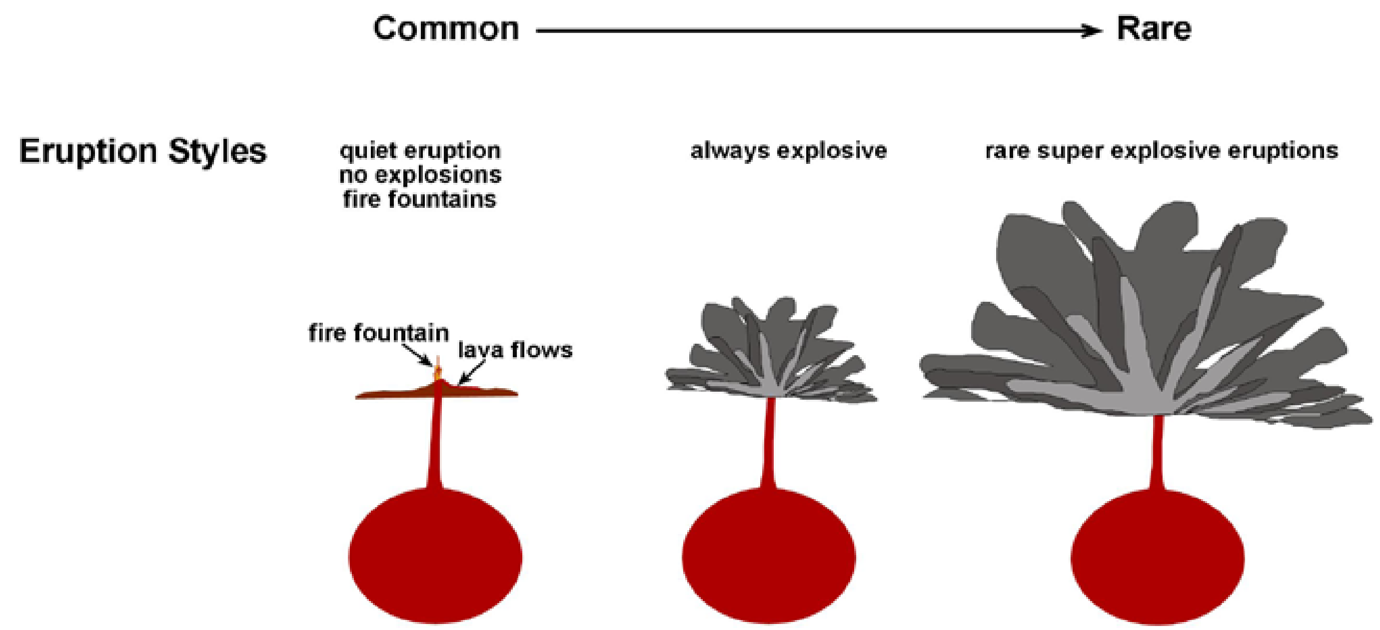
Peridotitic magma erupting to the surface is responsible for the formation an igneous rock called kimberlite, the source of diamonds.

Because magmas are heterogeneous chemical mixtures, crystallization may produce more than one kind of mineral.

Viscosity is resistance to flow. A good viscosity mnemonic device is "low-flow".

Explaining viscosity requires more effort than simply observing it. We have already stated that there is no such thing as a single parent magma. Different magma types implies variety. Although there are many ways in which they vary, the best place for us to begin is with silica content. Note the variations in silica content in Figure 4. Observations have shown that high silica content make molten rock more viscous. More than likely this is related to presence of more chemical bond producing longer chains of linked atoms.

Remembering the "low-flow" clue, and using Figure 4 silica data, will a granitic magma flow more readily than a basaltic magma? Which would be most likely to find ways to reach the surface? Refer to side bar to check your ideas.



Magma Type	Basaltic	Andesitic	Granitic
Geology	divergent plate margins and oceanic hot spots	subduction zones	continental hot spots
% Silica	45%	55-65%	75-85%
Viscosity	Low	Medium	Very High
Analogy	Olive Oil	Pancake Syrup	Cold Molasses

Figure 4

Viscosity and Dissolved Gases

At depth below Earth's surface, all magmas contain dissolved gases. How these gases escape from the molten rock is a direct function of the molten rock's viscosity. This simple relationship explains the explosive potential of volcanic eruptions (Figure 4). For example, as a low viscosity basaltic magma rises toward the surface most of its dissolved gases are quickly released from solution when magma becomes lava. On the other hand, high viscosity, granitic magmas greatly restrict the movement and dissipation of dissolved gas. With its trapped gas, the granitic magma/lava can be a potential supervolcano waiting to explode.

To help students observe the action of dissolved gas fill a clear beaker, flask, or jar with olive oil. Fill two similar containers with pancake syrup and cold molasses. Make sure your students note the fact that because each fluid flows into the jar at a different rate they are clearly dealing with fluids of differing viscosities. After sealing each jar, ask them to construct predictive statements to describe what will occur when each jar is shaken. Prompt them to think about the presence and movement of air bubbles in each fluid. Ask three students to vigorously shake a designated container for a minute. This action will thoroughly incorporate air into each fluid in the form of bubbles. At your call, quit shaking and set the jars down. Using a stop watch, time how long it takes for most of the bubbles to rise to the surface of each fluid. Do the results fit the students' predictions?

Silica is SiO_2.

Basaltic magma flows more readily than granitic magma. Its low viscosity not only allows it to easily use existing pathways to more quickly reach the surface but it also prevents it from plugging up the pathways.

An example of how Figure 4 can be used with students is shown in the following questions:

A. Hawaii sits over an active oceanic hot spot. Hawaii is composed of _________magma

Answer: basaltic

B. Yellowstone National Park sits on top of a violently explosive supervolcano. The magma beneath the park is probably ___________.

Answer: granitic

Explosive potential of an eruption is controlled by the amount of dissolved gas trapped within the magma and the magma's viscosity.

Exploration Activity: Students can develop hypotheses explaining the relationship between the rate at which the bubbles rise and vent versus fluid

Clearly, the bubbles rise to the surface most rapidly in the lower viscosity olive oil. Challenge students by asking them to explain the mechanics of how this occurs. In other words, what physical event, or events, transpired? Some will correctly state that the bubbles, being less dense than the surrounding fluid, are more buoyant, and must therefore rise. True. But, what controls ascent speed? In other words, what must the fluid do in order for the bubbles to rise through it? Clearly, the fluid must flow out of the way to allow each bubble to form. The fluid must also temporarily move out of the way, allowing the less buoyant bubble to rise. Afterwards, the fluid must close in behind the rising bubble to occupy the now empty space. This simple experiment shows that a lower viscosity fluid will allow gas to dissipate more readily than a higher viscosity fluid. You can reinforce these ideas by comparing what happens when blowing air through a straw fully immersed in a glass of water and a mike shake.

Magma is a fluid and, as such, must react in the same way. First, the magma must flow out of the way to allow any dissolved gas to come out of solution and form a bubble. Second, the magma must then flow out of the way to allow the bubble to expand to the point where it has sufficient buoyancy to rise. Finally, the magma must provide a pathway (move out of the way) so that the bubble can reach the surface and return to the atmosphere. Much like our olive oil, a low viscosity magma easily releases it dissolved gas as it flows toward Earth surface. How do we apply such understanding?

Figure 5

An effective classroom demonstration of the explosive power of the sudden release of dissolved gases can be accomplished using variously shaken pop-top cans of a warm carbonated soft drink.

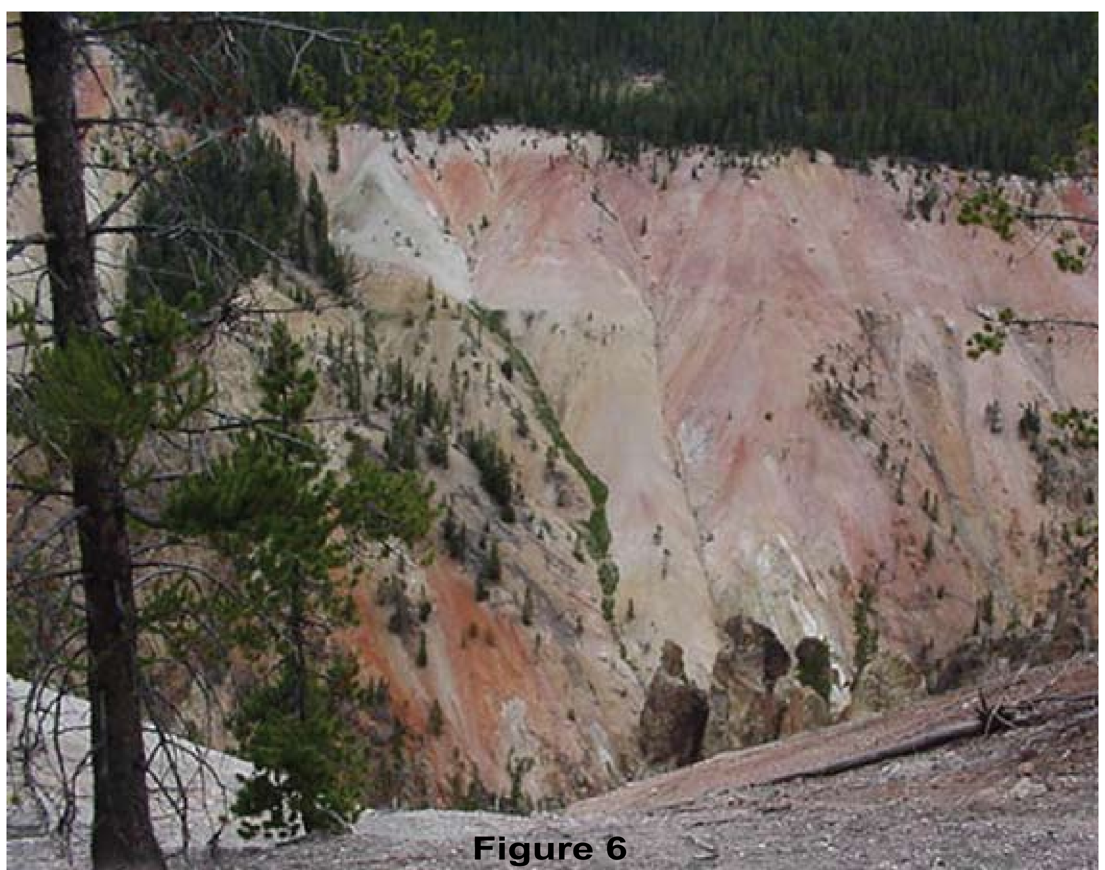


Figure 6

Low viscosity, low silica content, and rapid gas release while the magma is rising, produce generally non-explosive surface eruptions of low viscosity basaltic magma/lava. Oceanic hot spots and divergent plate boundaries provide avenues for the transmission of basaltic magma. Once on the surface the molten rock cools to become the igneous rock called basalt. Molten basalt's ability to flow explains why more than 70% of Earth's surface (ocean basins) is composed of basalt. Internet media can be employed to show that the basaltic magma of Hawaii flows very readily (Figure 5) and is generally non-explosive.

The extreme opposite of a basaltic magma is the highly viscous granitic magma. It contains more silica and has difficulty dissipating dissolved gases. Its lack of mobility means that most granitic magmas cool and solidify beneath the surface forming bodies of deeply buried granite. In those rare cases where granitic magma reaches the surface the sudden release of the dissolved gases produces Earth's most violent and destructive volcanic eruptions. Yellowstone National Park is an active supervolcano dominated by the igneous rock rhyolite, the more fine grained twin of granite (Figure 6).

Granitic magmas do flow, just very sluggishly and, due to its explosiveness, granitic lavas (rhyolite) is a rarity. Most often the material is distributed by the explosive blast, not be flowing. Much of the rhyolite found in Yellowstone National Park is fallout from a series of volcanic explosions of granitic magma.

The viscosity, silica content, and gas content of andesitic magma are intermediate between those of basaltic and granitic magmas. The intensity of the explosive eruptions of andesitic magmas are dependant upon the amount of gas still in solution when the magma becomes a lava. The andesitic-rich magma within Mount St. Helens (Figure 7) contained enough dissolved gas to cause a powerful explosion when the side of the mountain slid away and provided the trapped gas with a quick escape route. Andesitic eruptions are associated with subduction zones which produce andesitic-rich, linear ranges of volcanoes located near continental margins. The Andes Mountains of South America are andesitic volcanoes. In the theory of plate tectonics, geologists have come to understand that the presence of such volcanoes is evidence for the existence of an underlying subduction zone

Figure 7

Nine Important Rock-Forming Silicates Minerals

Let's now take a closer look at the nine minerals that combine to make our seven igneous rocks. We can begin by scrutinizing, not memorizing, the minerals' chemical formulae in Figure 8. Notice any common elements?

Olivine	$(Fe,Mg)_2SiO_4$
Augite	$(Ca,Na)(Mg,Fe,Al)(Si,Al)_2O_6$
Hornblende	$Ca_2Na(Mg,Fe^{2+})_4(Al,Fe^{3+},Ti)_3Si_8O(O,OH)_2$
Biotite	$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$
Anorthite	$CaAl_2Si_2O_8$
Albite	$NaAlSiO_8$
Orthoclase	$KAlSiO_8$
Muscovite	$KAl_2(AlSiO_{10})(OH)_2$
Quartz	SiO_2

Figure 8. *Do not memorize. Look at the bigger picture by comparing and contrasting elemental makeup.*

Can you define
a mineral? How about a familt of minerals? Use the internet. Careful: It may not be as clear cut as you think!

Muscovite and biotite belong to a group of minerals called micas.

Anorthite, albite, and orthoclase represent a group of the most abundant of all the major rock-forming silicate minerals, the feldspars. Feldspars are further subdivided into orthoclase and plagioclase. Dark colored Ca-rich anorthite is one end member of the plagioclase series with the light colored Na-rich albite serving as the other end member.

Hopefully you said silicon and oxygen. These two elements make up the silicate anion $(SiO_4)^{-4}$ which is the foundation for each mineral's crystalline structure. An understanding of these minerals and the ability to use their chemical characteristics as guide posts is crucial to building a practical and useful knowledge base.

Return to the mineral list in Figure 8. Can you chemically subdivide the nine minerals into two distinct categories? We have already established that each contains silicon and oxygen so no help there. How about the other elements? Calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K) are found in eight of the minerals but not in quartz. That could be one possible classification scheme but it is not the one we are looking for. Any other ideas? The answer we are looking for is related to the distribution of iron (Fe) and magnesium (Mg). Olivine, augite, hornblende, and biotite contain both iron and magnesium. Anorthite, albite, orthoclase, muscovite, and quartz contain no iron or magnesium.

The presence or absence of iron and magnesium is the basis of a geologic dichotomous classification scheme. This is one of those rare cases where common sense prevailed so that the rock-forming silicate minerals containing iron and magnesium are called ferromagnesian silicates while those that do not contain iron and magnesium are called the non-ferromagnesian silicates (Figure 9).

This is all well and good if you have the chemical data available. But, is there any practical application of this knowldege? In other words, are there any diagnostic physical differences between the ferromagnesium and nonferromagnesium minerals that can be used to help identify them? Note Figures 10A and 10B. What is the prominent visual difference between these two minerals? Simple: one is dark and the other light in color. Any idea which is the ferromagnesium mineral?

The color difference is associated with the darkening nature of iron. Thus, ferromagnesian minerals are generally darker in color because they all contain the element iron. By dark we mean a range from dark green to black. On the other hand, non-ferromagnesian minerals, which do not contain iron, are commonly white, peach, pink, rose, or clear. Figure 10A is the iron-bearing ferromagnesian mineral hornblende while Figure 10B is the nonferromagnesium mineral quartz.

How can your students use such knowledge? Give them a specimen of a dark colored igneous rock, like basalt. Can they construct the idea that its dark color must be related to the minerals of which it is made. Furthermore, can they deduce that this implies that basalt must contain at least one of the dark rock-forming silicate ferromagnesium minerals listed in Figure 9. So far, so good. However, by now your students may be asking where did the minerals themselves come from? To answer this question we must return to our discussion of magma and what happens when magma changes from its liquid phase to its solid phase. In other words, what happens when magma crystallizes into a solid?

Silicate Minerals

Ferromagnesian (dark)	Olivine	$(Fe,Mg)_2SiO_4$
	Augite	$(Ca,Na)(Mg,Fe,Al)(Si,Al)_2O_6$
	Hornblende	$Ca_2Na(Mg,Fe^{2+})_4(Al,Fe^{3+},Ti)_3Si_8O(O,OH)_2$
	Biotite	$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$
Non-Ferromagnesian (light)	Anorthite	$CaAl_2Si_2O_8$
	Albite	$NaAlSiO_8$
	Orthoclase	$KAlSiO_8$
	Muscovite	$KAl_2(AlSiO_{10})(OH)_2$
	Quartz	SiO_2

Figure 9

Dichotomous classification of rock-forming silicate minerals:
1. ferromagnesium
2. non-ferromagnesium

“Ferro” comes from the Latin ferrum which means iron.

Figure 10A.

Figure 10B.

Phase Change and Mineral Crystallization

Phase change is the physical transformation of matter between solid, liquid, or gaseous states. Ice changes phase when it thaws into liquid water. Water changes phase when it freezes into ice. Magmas/lava undergo a phase change when they “freeze” into solid mineral crystals and rocks. Whether we are talking about water or magma, the change from liquid to solid phase is merely the material’s response to energy being removed from the system. Conversely, a change from solid to liquid phase is accomplished by adding energy to the system. In our case, the energy manifests itself as heat from the Earth itself. Phase change can be discussed using the terms freezing and melting because these refer to a physical property dictated by the mineral’s chemical composition. The change from magma to solid rock is no different than the freezing of water into ice at $0^{O}C$ ($32^{O}F$). The obvious difference is that the high temperatures at which molten magma freezes are less intuitive for learners to process. Other factors, such as mineral crystal structure do influence phase change. However, as part of our attempt to simplify the discussion we are going to focus our attention solely on the relationship between chemical composition and mineral growth.

We will begin with a simple relationship: Minerals with a fixed chemical composition must have a fixed freezing and melting point. Consider water. Its chemical composition is the well known H_2O. Water’s fixed chemistry means it will always freeze (change phase from liquid to solid) at one specific temperature, the familiar $0^{O}C$ ($32^{O}F$) at standard atmospheric pressure. At what temperature does ice change phase (melt) to become water? This would also be the well known temperature of $0^{O}C$ ($32^{O}F$)! Thus, water and ice clearly, and easily, illustrate that the melting and freezing point temperature of matter with a fixed chemical composition occurs at a single fixed temperature.

Expanding upon this idea, what do you think happens to the freezing and melting temperatures of a mineral with a variable chemical composition? To demonstrate, let’s examine the formulae for our four ferromagnesian silicate minerals:

1. Olivine $(Fe,Mg)_2SiO_4$
2. Augite $(Ca,Na)(Mg,Fe,Al)(Si,Al)_2O_6$
3. Hornblende $Ca_2Na(Mg,Fe^{2+})_4(Al,Fe^{3+},Ti)_3Si_8O_{22}(O,OH)_2$
4. Biotite $K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$

Note that each formula has places where more than one element is contained in parentheses. Parenthetical notation is used by chemists to indicate chemical variability. For example, olivine’s $(Fe,Mg)SiO_4$ formula suggests it can vary from $FeSiO_4$ (100% iron with 0% magnesium) to $MgSiO_4$ (100% magnesium with 0% iron) with any percentage combination of iron and magnesium between these two extremes. Given such potential chemical variability should olivine have a fixed melting/freezing point? Since this physical property is dictated by which elements are present and how much of each is present, the potential variable chemical nature of olivine means that it can, and must, form from a cooling magma over a range of temperatures.

Just like ice, mineral crystallization requires molten rock to release or lose energy in the form of heat. In other words, minerals form as the magma cools by releasing energy into the surrounding environment. For any liquid, including magma, the temperature marking the liquid to solid phase transition is its freezing point. When a magma reaches its freezing point it begins to solidify when elements combine chemically to make mineral crystals. Geologists use the conceptual terms of solidification or crystallization instead of freezing to give a present a more accurate image of the process.

The concept of chemical variability is important in understanding the complex world of igneous rocks. The freezing/melting points of individual minerals within a group of minerals, such as micas and feldspars, produces individual, but related, minerals with defifnite chemical compostions.

Crystallization Temperatures of the Nine Major Rock-Forming Silicate Minerals.

It has long been known that the major rock-forming silicate minerals do not form from a single magma but rather from three different magma types, namely, basaltic, andesitic, and granitic. It was also known that some of these minerals posses a variable chemical formulae. Putting all of this information together did not occur until the 1900s when Norman L. Bowen (1887-1956) set out to determine the temperature at which the major rock-forming minerals crystallized from their respective magmas. Figure 11 is a very simplified version of Bowen's most important diagram. The dark green names represent our four ferromagnesium minerals and the tan are our five non-ferromagnesium minerals.

For our introductory investigation, understanding just the basic premise of Bowen's work is useful in that it allows us to determine which minerals cool from which magmas, at what temperature(s) this occurs, which rocks are formed, and what might happen if these rocks are remelted at a later date. The best way to accomplish this is to actively engage Figure 11.

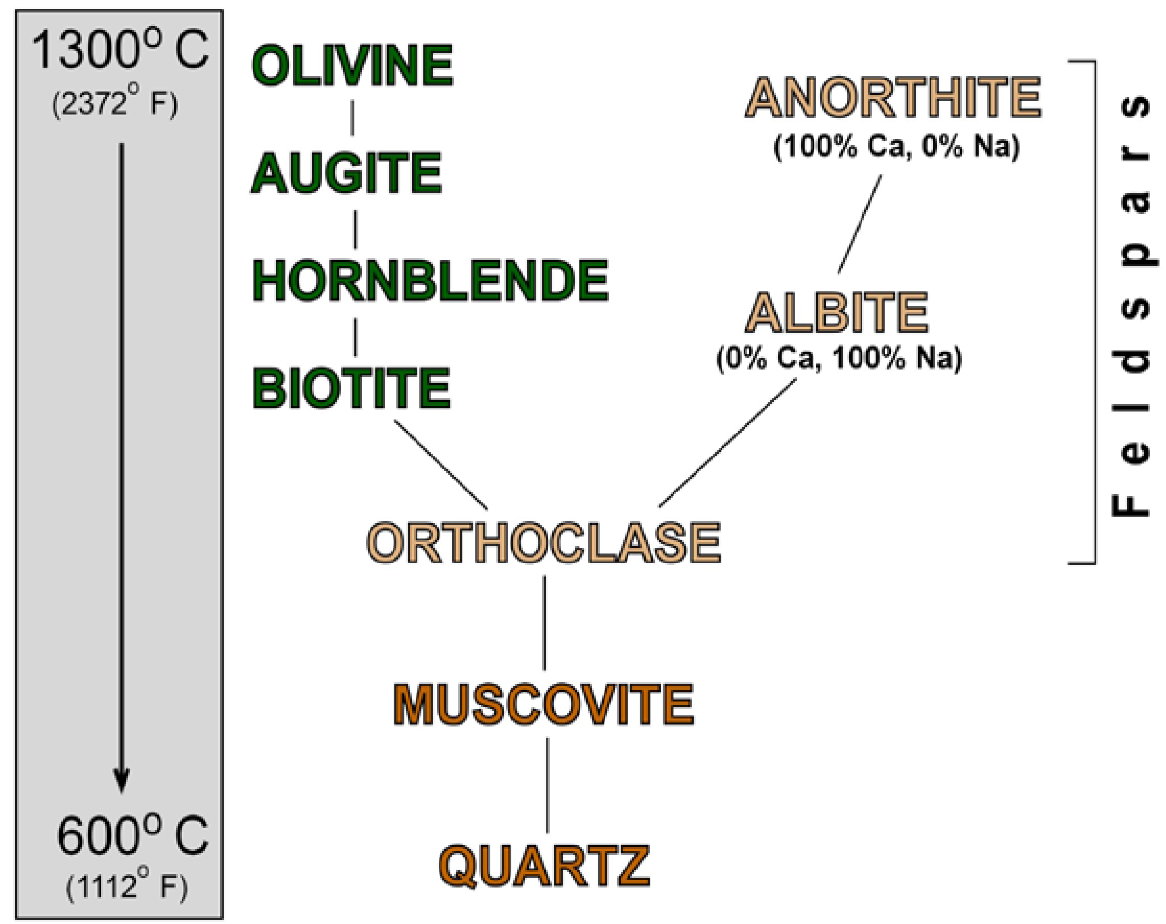


Figure 11

An interesting way to start a conversation is to ask at what temperature quartz forms. Quartz is a commonly known mineral and most students consider it to be very hard and durable. Unfortunately this leads to the intuitive deduction that it must form at very high temperatures.

On the following pages you will see several variations of Bowen's origin illustration. Do not read more into them than we present. This biggest mistake made by the beginner is constructing inappropriate ideas driven by over analysis and assumption.

To begin, completely cover Figure 11 with a piece of paper. Now, slowly (SLOWLY!) move the paper downward just far enough to reveal the identity of the first silicate mineral. Which one is it? Hopefully you said olivine. Now, with the paper still in place, note the temperature along the left side of the illustration. Do olivine crystals form at a high temperature or low temperature? Hopefully you recognize that this classification is nothing more than a relative determination defined by a high of 1300°C and a low of 600°C. Nevertheless, do olivine mineral crystals form when the magma is relatively hot or cool? If your paper is properly placed, you should see olivine forms at about 1300°C (2372°F). Repeat the activity one more time until the mineral quartz is revealed. Hopefully you found that its crystallization temperature is much lower, about 600°C (1112°F). Did you expect this? Or, did you assume that all minerals formed at about the same temperature?

Bowen was the first to demonstrate that the process of silicate mineral crystallization could be quantified. However, for all its value, the chart which bears his name is far from perfect. In fact, it can be downright misleading. While Figure 11 clearly demonstrates a relationship between cooling temperature and mineral crystallization, it also strongly suggests a single temperature for each event. Didn't we just determine that minerals with variable chemical formulae will not crystallize at a single temperature? The problem can be fixed by simply writing the mineral's name at a slant so it is associated with a range of temperatures (Figure 12).

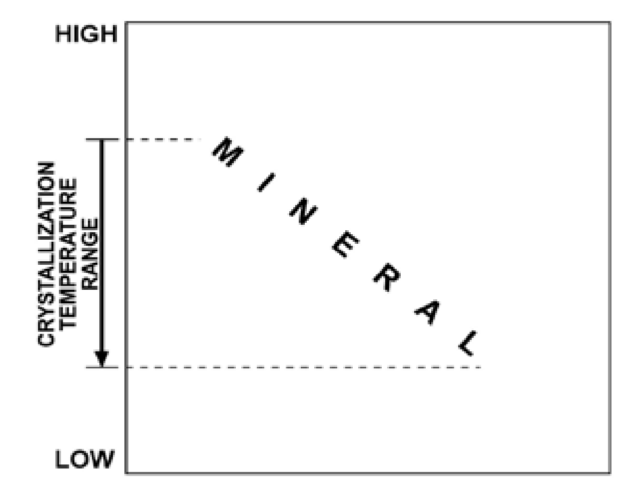


Figure 12

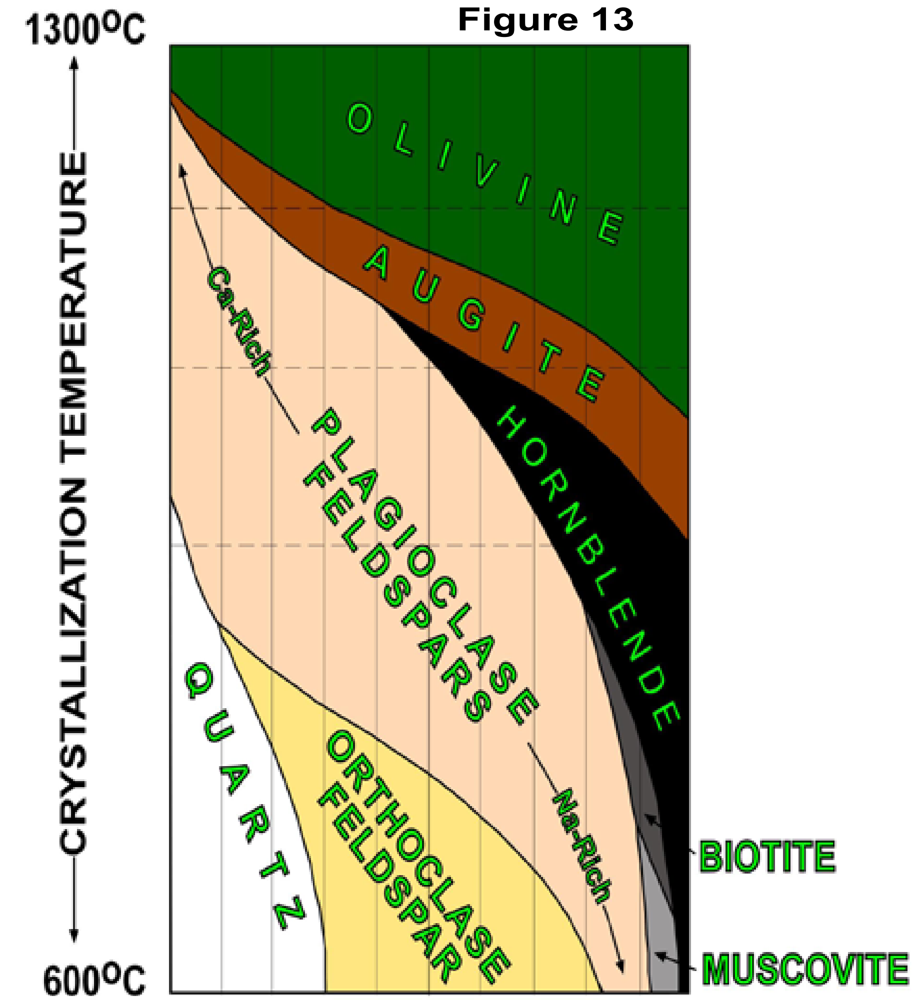
Note that we have applied this “slanting” technique to Figure 13. Clearly each mineral now forms over a range of temperatures. We can see how this changes our understanding by doing another cover and reveal activity.

What is happening to the temperature as more and more of olivine is revealed? It is decreasing, is it not? At some point, the last of the olivine area appears, signifying that, at this temperature, olivine crystallization ceases. Not only is the temperature range of olivine formation a requirement of olivine’s variable chemical composition it also means that a host of different olivine-type minerals, each with a slightly different chemical composition based on the amount of Fe and Mg present, have the opportunity to crystallize if the magma continues to cool.

Did you notice the appearance of the augite and the anorthite as more and more of the olivine is revealed? Can you suggest what this implies? The simultaneous appearance of all three minerals means that, within a particular range of temperatures, olivine, augite, and anorthite may crystallize simultaneously. The conceptual skill learned in this short exercise will be put to use shortly.

Figure 14 is another way to visualize what was occurring as you did the cover and reveal on Figure 13. In Figure 14A our molten magma is represented by the pink color. As the magma begins to cools, the first signs of mineral crystals (gray, white, black, etc.) begin to appear, as shown in Figure 14B. Continued growth of these crystals consume more and more of the magma (Figure 14C and D) until none remains (Figure 14E, pink all gone). At this point mineral formation must cease because all of the the source material, the magma, has used (Figure 14E). Since no more mineral can be added, the rock will eventually cool to the ambient temperature of the surrounding environment. Importantly, the rate at which the rock cools plays a critical role in its physical appearance and name.

Figure 13



But wait...what about the fixed chemistry of quartz and orthoclase? Why do quartz and orthoclase slope to indicate crystallization over a range of temperatures? First off, both minerals actually do form over a range of temperatures. Do we know why? No. Bowen, acknowledged the problem by writing that the “...process is really too complex to be presented in such a simple form. Nevertheless, the simplicity, while somewhat misleading, may prove of service...” Bowen’s statement reflects the true nature of science.

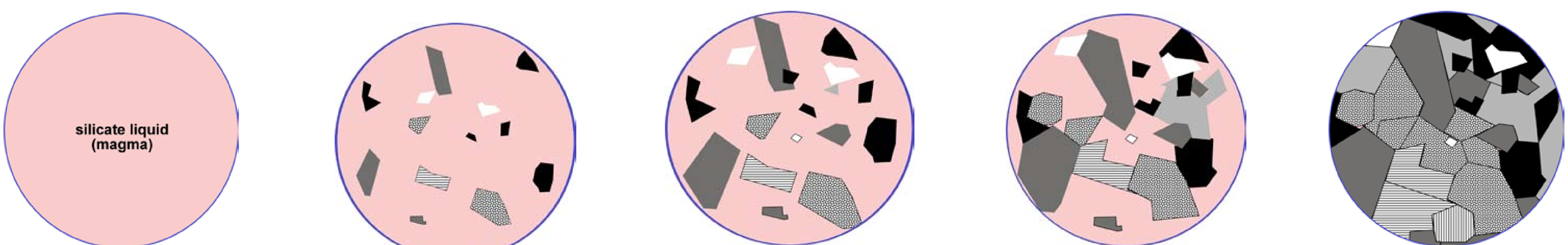


Figure 14A Figure 14B Figure 14C Figure 14D Figure 14E

Cooling Rate and Igneous Rock Texture

Our discussion on the dark colored ferromagnesiam minerals versus light colored non-ferromagnesiam minerals has already established that the physical appearance of an igneous rock is a function of the minerals of which it is made. However, geologists have observed that a slower cooling rate provides more time for crystal growth which translates into larger minerals crystals. This simple fact provides a powerful tool for suggesting the appropriate origin of any igneous rock. But, before proceeding, can you suggest what factor(s) influence cooling rate? Hint: apply the idea of insulation to compare and contrast the cooling rate of magma versus lava.

Magma, occurring beneath Earth's surface, cools relatively slowly when compared to lava due to the insulating properties of the surrounding rock into which it has intruded. Since the slower cooling rate provides more time for individual mineral crystal growth a rock produced from a slow-cooling magma will posses individual mineral crystals large enough to be seen by the unaided eye. In some cases, the cooling may be slow enough to produce museum specimens measured in centimeters and meters. These are known as coarse-grained textured igneous rocks. Granite (Figure 15, note penny for scale) is an example of a coarse-grained igneous rock.

In contrast, lava will cool much more rapidly because it lacks any surrounding insulating rock. In fact, lava that reaches water (ice or ocean) or that is blown directly into the atmosphere, cools almost instantaneously. No matter its environment lava cools so relatively fast that individual mineral grains have a very limited growth period. Hence, they are very small in size. Some are so small that magnification is required to view them. Rhyolite (Figure 16) is an example of a fine-grained igneous rock produced from a cooling granitic lava. Basalt and andesite are also considered to have a fine-grained texture. Given several specimens, or even photographs of igneous rocks, students should be able to suggest plausible cooling rates and environments using observed textural information.

Another way to appreciate textural differences is to view under a microscope. Figure 17a is a basalt and Figure 17b is a granite. Both images have been enlarged to make the 1mm scales equal size. The size of the minerals in the granite are clearly much larger than those in the basalt.

The rock surrounding an intruded magma is called country rock.

An igneous rock with a coarse-grained textured probably formed from a cooling magma.

An igneous rock that has a fine-grained texture most likely formed from a cooling lava.

Figure 15

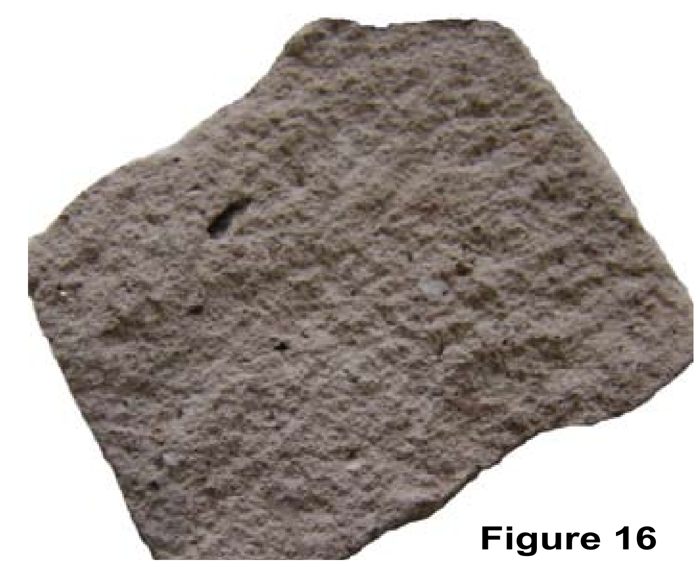


Figure 16

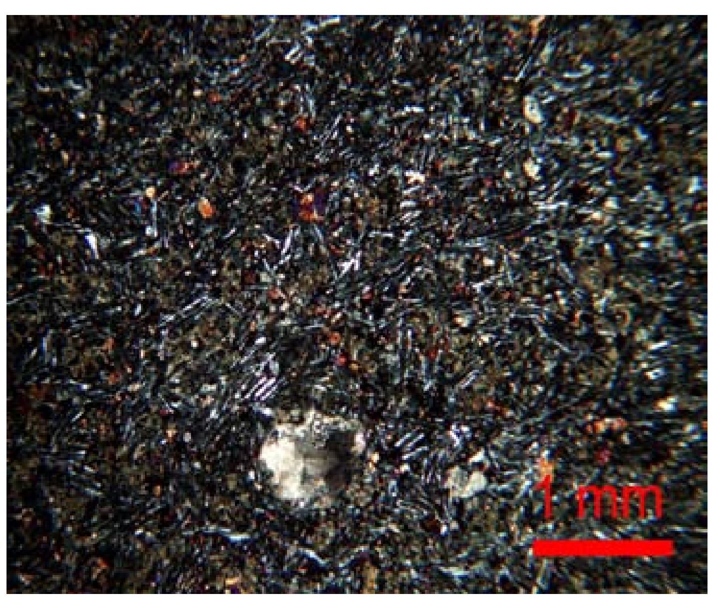


Figure 17a

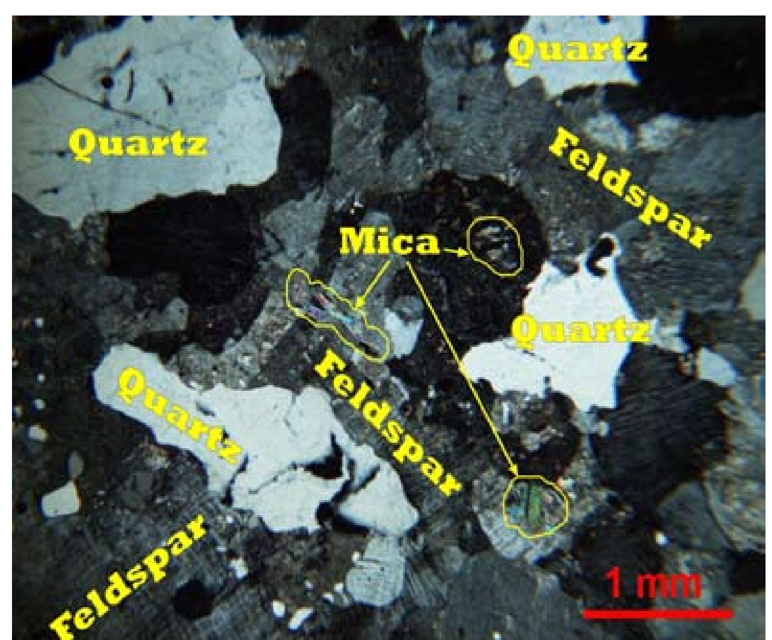


Figure 17b

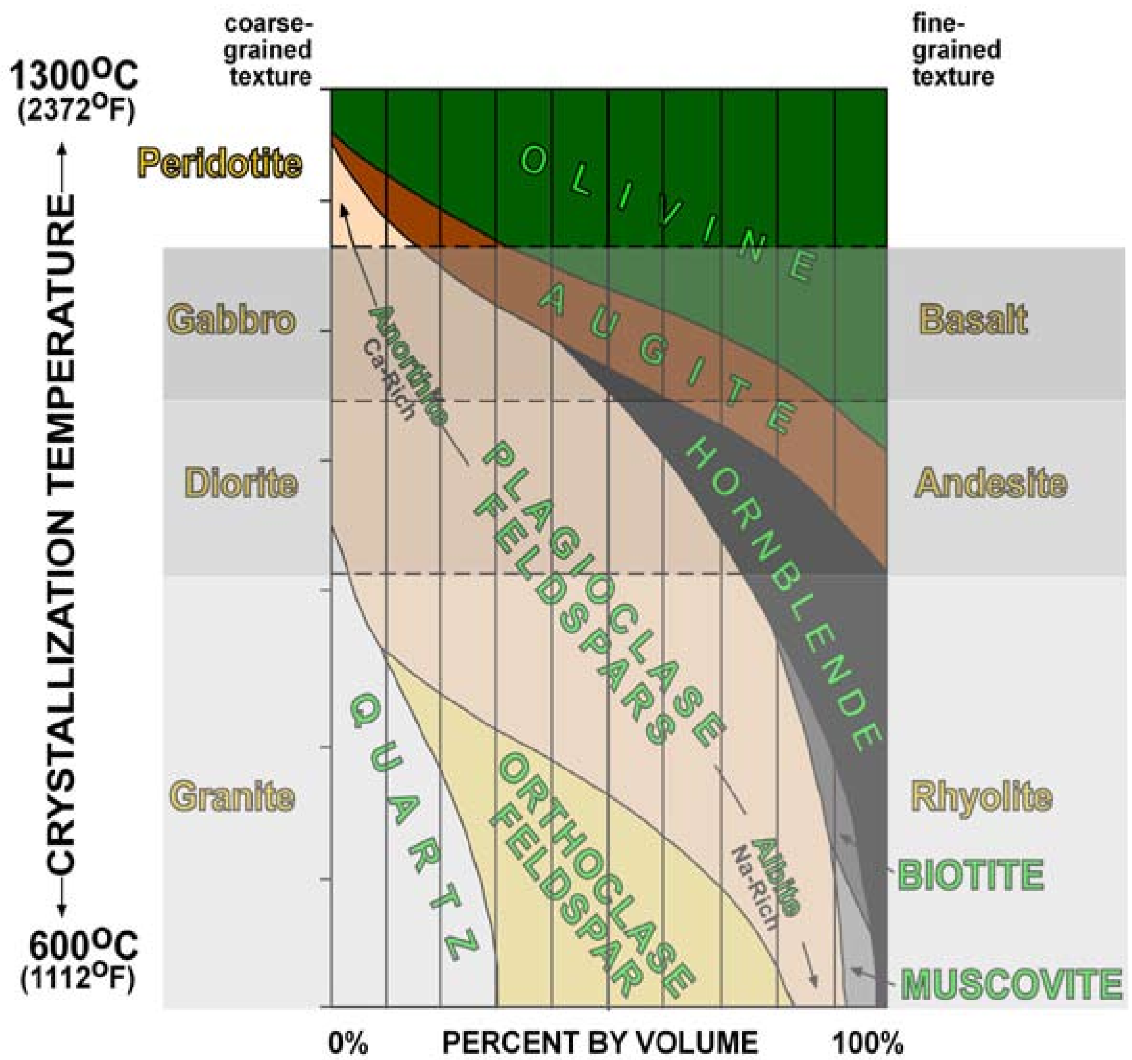


Figure 18

The information presented on the previous pages provides us with a lot of options for exploration and application. We will use Figure 18 to do that. As we have already stated, our discussion is focused on three of the four magma types originally shown in Figure 3. In Figure 18 basaltic magma is represented by the dark gray highlighted zone, andesitic magma by the medium gray highlighting, and granitic by the light gray highlighting. The segregation illustrates the mineralogical associations and temperature ranges uniquely associated with basaltic, andesitic, and granitic magmas.

Question: Does your interpretation of Figure 18 lead you to conclude that a basaltic magma could cool down enough to produce an andesite rock or even far enough to form the minerals biotite or muscovite? If you are, please stop because it can't happen. Why? Remember that there is no "mother magma" from which all of the minerals listed in the chart will precipitate as it cools. We stated this way back on page 3. While there is admittedly some small degree of overlap at the interface between individual magmas they are quite dissimilar in both the types of minerals and rocks that can form as they cool. For example, while the chart shows that a small amount of quartz may precipitate from an andesitic magma, no quartz can be expected to precipitate from a basaltic magma. On the other hand quartz is a major component of granite.

Look at the granitic highlighted zone. Clearly, the minerals formed by a cooling granitic magma crystallize at relatively lower temperatures. Also note that granite and rhyolite contain the same minerals in the same percentages. The only distinction between the two rocks is their texture. Applying this same logic to the other two zones provides some insight into the major difference between diorite and andesite and gabbro and basalt.

Let's take our application of Figure 18 one step further. We have already noted that granite is a coarse-grained igneous rock. By definition granite must contain quartz, feldspar, and mica. Look it up! Notice we did not say how much of each must be present and what other minerals could be present, but Figure 18 shows us the possibilities. Now, take a bigger picture look at the grantic magma zone by employing the lower axis data. Can you see that a granite formed at 600° C contains quartz, orthoclase, albite, muscovite and hornblende while a granite that cooled at 850°C contains quartz, plagioclase feldspar, biotite, and hornblende? Plus, one may cool faster the the other and hence have a different texture. What's the outcome of these differences? A bewildering array of rocks that can all bear the name granite!

Figure 18 is most definitely the wrong place take attempt leaps of logic. As we already mentioned, this has been a problem with calling it "Bowens Reaction Series." For our level of learning, it is not a series and there are no reactions. Read more in the paragraph to the left.

Consider a similar figure drawn for rock and minerals that form in the basaltic magma zone. Once again we have two compositionally related rocks of different textures. Which cooled from a lava? Using only the textural information provided across the top of Figure 18 you should be able to state with confidence that the fine-grained basalt is the product of a rapidly cooling lava. Which means that the coarse-grained gabbro most likely originated from slowly cooling magma body located at some depth below Earth's surface. This same textural concept can be applied to explain the differences between diorite and andesite and granite and rhyolite.

Mafic versus Felsic

So far we have discussed the roles of texture and mineral composition in igneous rocks. One last feature that can be helpful in describing igneous rocks is related to our very early mineral discussion: What is the diagnostic, and dichotomous, physical difference between ferromagnesian and non-ferromagnesian minerals? Color! The presence of elemental iron is the reason for the generally darker colored ferromagnesian minerals and the rocks which they make. Because they lack iron the non-ferromagnesian minerals are commonly white, peach, pink, rose, or clear.

Being verbally lazy, scientists develop their own slang. Geologists have done this by "mafic" or "felsic". For our most simple of purposes, mafic implies a dark igneous ferromagnesian rock while felsic implies a light colored non-ferromagnesian one. These two words can be used to convey both the chemical and physical nature of an igneous rock. They can also be used to help identify and name the rock.

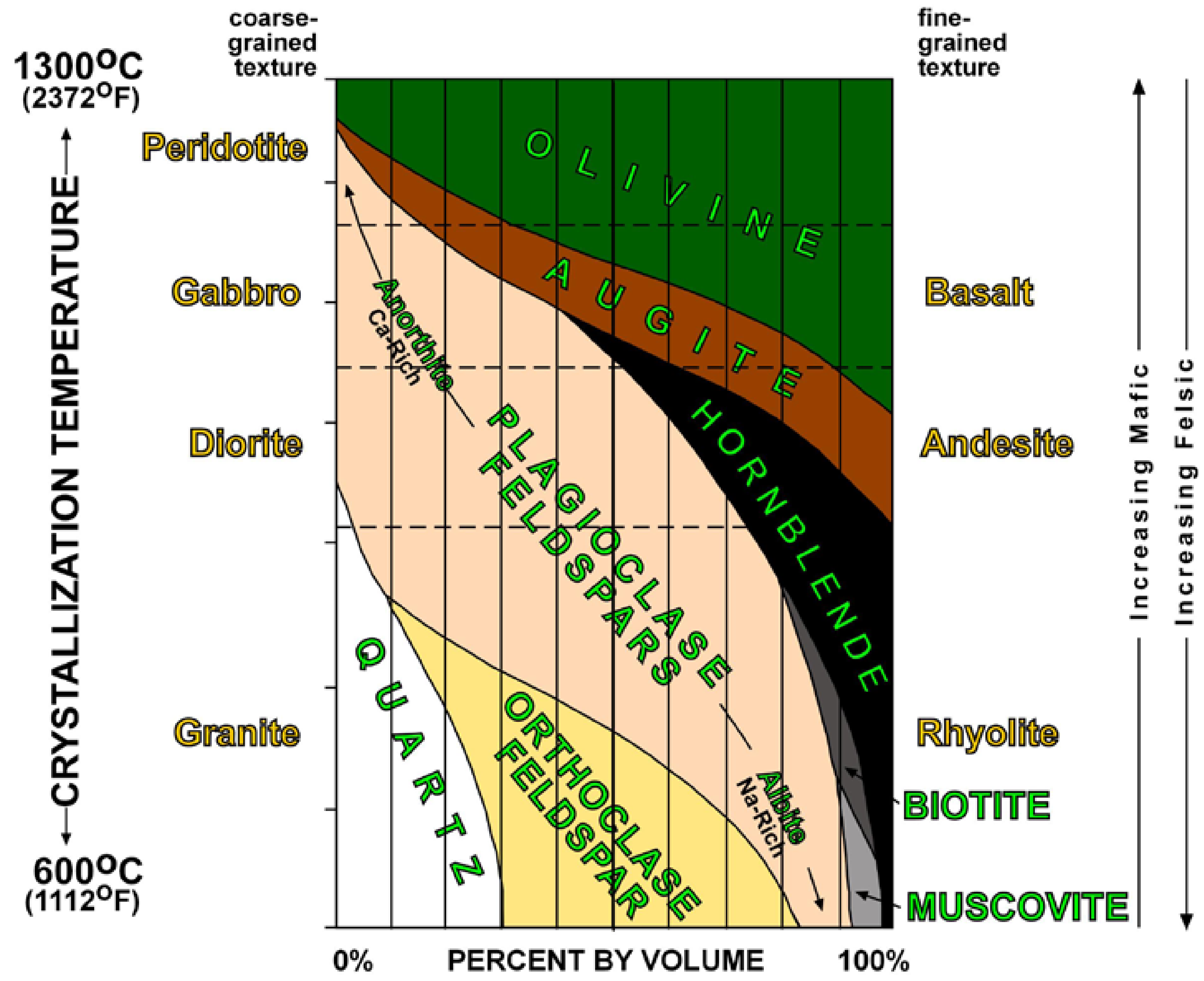


Figure 19

Do a cover and reveal procedure using Figure 19. This time note the directionally opposite mafic and felsic arrows on the right side. In which direction do rocks become more felsic? Asked another way, in which direction do they become lighter in color? Basalt and gabbro are a mixture of olivine, augite, and anorthite with the possibility of a small amount of hornblende. You already know that these two rocks have a similar mineral composition but differ in texture due to cooling rate. These two rocks, while still considered mafic, are not as mafic as peridotite. Another way to state this is to say that basalt and gabbro are more felsic than peridotite. Following this trend, which rocks on Figure 19 are slightly more felsic than gabbro and basalt? Did you say diorite and andesite? Correct. Because diorite and andesite are more felsic than basalt and gabbro you should anticipate them to look slightly lighter in color, which they are. Uncovered last, at the bottom of the chart, are the most felsic rocks: granite and rhyolite. Notice that the more felsic rocks and minerals occur at lower and lower temperatures as as you moved down the chart.

Remember the granite counter tops? Here's another explanation.

Review Notes:

1. The ferromagnesian minerals are Olivine, Augite, Hornblende, and Biotite.

2. The non-ferromagnesian minerals are Anorthite, Albite, Orthoclase, Muscovite, Quartz.

Your first inclination is to roll your eyes at still more terminology. However, "ma" refers to the presence of magnesium and the "fic" is a reference to iron. In the lighter colored non-ferromagnesian minerals and rocks, "fel" refers to felspar while the "si" denotes silica.

Concept Extension and Application

This is a good point for a brief break to explore some educational applications that might help students link content with processes that reflect the nature of science. Consider, for example, presenting igneous rocks using a learning cycle model that accentuates discovery and learner-constructed knowledge. Exploration can be as simple as comparing and contrasting provided samples to gauge if students can self-initialize collective color and textural differences or by providing a sample and asking if it is the product of a cooling lava or a magma? If these ideas are not revealed during exploration they must be adequately covered during the content development stage. Additional development can be accomplished in any number of ways, including lecture.

Application of learned knowledge is the most difficult process for a teacher to develop and implement due to time constraints. If possible, tell you students the name of an igneous rock, maybe gabbro. Do not provide them with any pictures or samples. Can they use Figure 19 to determine the generic mineral content of gabbro? How about its texture? Is it felsic or mafic and what does that imply about its overall color? Now distribute samples, or photographs, of several rocks and ask them to identify the gabbro.

Graphing and mathematical skills may also be employed. One approach is to pick a rock name. This time let's use our old friend granite. Draw a horizontal line across the illustration at the location of the word granite. Simple graphing interpretation skills used in conjunction with the bottom axis scale can be used by students to determine the percentage of each mineral found within granite. A more rigorous approach would be measuring, in millimeters, the portion of the horizontal line that crosses each of the intersected mineral fields. Add individual line segments to determine the overall length of the horizontal line. Divide the length of each individual line segment by the overall line length. Multiply by 100. The answers, within an error of ±1-2%, will be the percent of each mineral making up the rock. As an example, placement of the horizontal line at the word granite will show that that version of granite is made of 25% quartz, 37% orthoclase feldspar, 26% albite feldspar, 6% hornblende, and 4% biotite. Did you notice that the line you drew from granite intersected rhyolite? Remember, they have the same composition but differ only in texture. You, or your students, just demonstrated that!

Another application of the color and texture concepts is to have students use Figure 23 to help them identify a few of the more commonly seen igneous rocks. For example, what is the name of the rock in Figure 20. Begin with color. Is it light (felsic) or dark (mafic)? The correct answer is dark (mafic). Now look at its texture. Is it fine-grained or coarse-grained? The rock in Figure 20 is fine-grained because it is made of small mineral crystals due to its rapid cooling rate. We now know that Figure 20 is a fine-textured, mafic rock. What is the name of such a rock according to Figure 23? Basalt!

Let's repeat the exercise using the rock shown in Figure 22. Is it light (felsic) or dark (mafic)? Actually both! Large or small crystals? Bigger than those in Figure 20 but smaller than those in Figure 21. Could we call this texture intermediate? Congratulations if you said Figure 22 is diorite. Many geology students remember diorite by its distinctive salt and pepper appearance.

Igneous Rocks		COLOR		
		Light Felsic	Intermediate	Dark Mafic
TEXTURE	coarse grained (Large Crystals)	Granite	Diorite	Gabbro
	fine grained (Small Crystals)	Rhyolite	Andesite	Basalt

Figure 23

Figure 20

Figure 21

Figure 22

Melting Mechanisms

We have already stated that melting and freezing point are nothing more than terms used to indicate the direction of phase change and that phase change represents the addition or subtraction of energy from the system. The movement from liquid-to-solid phase (freezing), used in conjunction with Bowen's work provides us with a framework to better understand what happens when a fluid magma cools into a solid rock. But, where does the magma come from? Excluding products of its earliest geologic history, Earth constantly produces new magma by melting existing rocks at tectonically active locales such as subduction zones, divergent rift zones, hot spots, etc. This process can happen by three different mechanisms:

1. Direct heating involves the addition of sufficient heat energy to cause the chemical bonds within the crystal lattice of the rock's minerals to break. We can state that the melting point temperature is a measure of the amount of heat necessary to cause the bond disruption.

2. Pressure release involves the effect of pressure on melting/freezing points because the melting/freezing point of most solids can be increased by increasing the pressure under which the solid exists. In other words, increased pressure favors the more dense solid phase. If a solid is under pressure and at a sufficiently high temperature, a decrease in pressure will favor the less dense liquid phase, resulting in the melting of the solid rock if the amount of heat present after the pressure release is great enough to disrupt chemical bonds.

3. The third way to melt solid rock is to change it from a dry to a wet state by the introduction of water. In static systems where the rock temperature is just below that needed to begin melting, the introduction of a sufficient amount of water may supply the additional energy required to break the chemical bonds and initiate the transition from solid to liquid phase.

In most cases, the liquid phase is the higher energy state so change from the solid to liquid phase requires the addition of energy to the system.

Melting is a solid to liquid phase change that occurs when sufficient energy is present to break the chemical bonds that hold the solid together.

Water can be used to discuss the pressure drop concept. As pressure increases, the melting point and boiling point of water increases. At lower pressures the melting and boiling point decreases. This is why water boils at less than 100^{o}C at high elevations.

A rock is a mixture not a chemical compound. Melting a rock is really more about breaking the chemical bonds within the mineral crystals that constitute the rock.

Partial Melting

In a mixture of components, regardless of the melting mechanism, melting will be sequential, starting with the lowest melting-point components first and ending with the highest melting-point components. Melting that leaves higher-melting point phases unmelted is referred to as partial melting. In the case of our silicate minerals, the more felsic minerals (such as those that make up granite) will melt at lower temperatures than the more mafic minerals (such as those that make up peridotite). It might be pointed out that this simplistic picture can be complicated by reactions that may go on between liquid phases and the remaining solid phases during the melting process. For our introductory purposes, we need not consider such complications.

Partial melting can create two new products from a single source rock. These would be a fluid magma and a new igneous rock. Consider Stage 1 in Figure 24. The green represents the stable solid state of a hypothetical igneous rock composed of minerals A, B, and C. As indicated, mineral A is mafic and mineral C is felsic. Mineral B is of some intermediate composition. Using the idea of partial melting, what would happen if energy (heat) was introduced as the rock was dragged downward in a subduction zone? Hint: Think about increasing temperature and pressure with depth and which of the minerals (felsic, intermediate, or mafic) would melt first.

With increasing heat, the relative low melting point of the felsic mineral C would allow it to begin melting while the rest of the rock remained solid. If heating stopped at this point, the two new products would be a new, intermediate-to-mafic solid igneous rock composed of minerals A and B and a felsic magma composed of mineral C (Figure 24, Stage 2).

Can you explain Stage 3? Begin by addressing the increasing temperature noted along the bottom. You already know that the Stage 2 temperature will melt the felsic mineral C. In Stage 3 the heat is high enough to melt intermediate mineral B. Without an further addition of heat, the products produced at this point would be felsic-to-intermediate magma composed of minerals B and C and a mafic rock (actually a large mineral accumulation) of mineral A. Have you noticed a trend yet? In all cases, partial melting produces a magma that is more felsic than its source rock. But, what happens if we totally melt the source rock? This occurs in Stage 4 and the end product is a magma with the same mineral composition as the source rock.

When applied to the real world of igneous rocks, partial melting of a basalt can produce an andesitic magma while the partial melting of andesite can produce a grantic magma. What new magma is formed by the partial melting of the rock called granite? Since there is nothing more felsic left to produce, the partial melting of a granite must produce a grantic magma.

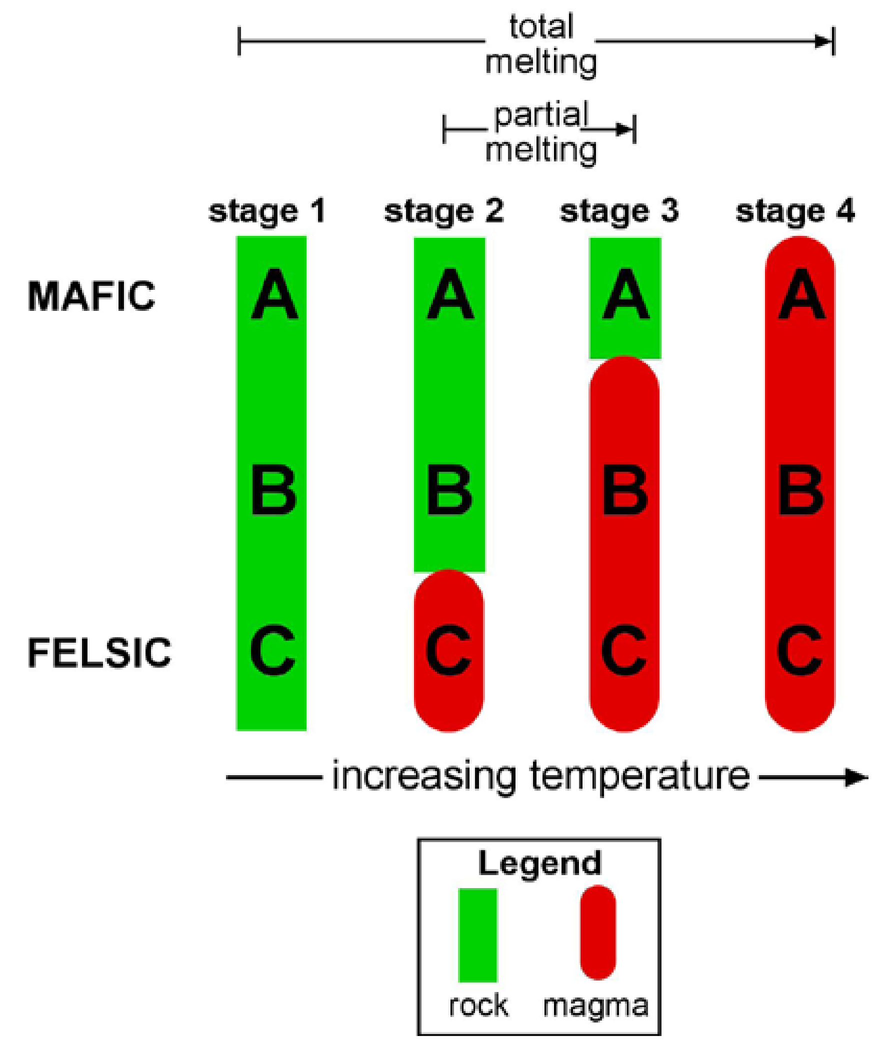


Figure 24

Extrusive igneous rocks form when lava cools on Earth's surface. Rhylolite is the extrusive form of granite. Obsidian is an extrusive igneous rock formed when by the rapid cooling of ejected magma at it falls back to Earth through the atmosphere.

Location and Abundance of Magmas and Lavas

Basaltic magmas are commonly produced at divergent plate margins associated with rift zones, rift valleys, linear oceans, and mid-ocean ridges. They are also found at mid-ocean hot spots (Figure 25). All of these locations provide conduits for the movement of basaltic magma generated when high temperatures and low pressures partial melt the underlying peridotite. For the most part, peridotite partial melting produces the relatively more felsic magma called basalt common in places like Hawaii. Many pages ago we discussed magma viscosity. Basaltic magmas were the least viscous while granitic magmas were the most viscous. We also explored how viscosity controls the ease with which the magma rises to the surface (to become lava) and the explosiveness of the eruption that may ensue. These ideas should permit you to understand that (A) it is easier for the low viscosity basaltic magma to rise to the surface and (B) why the most common type of observable lava is basalt. In fact, if we include the ocean floors, basalt covers 70% of Earth's surface.

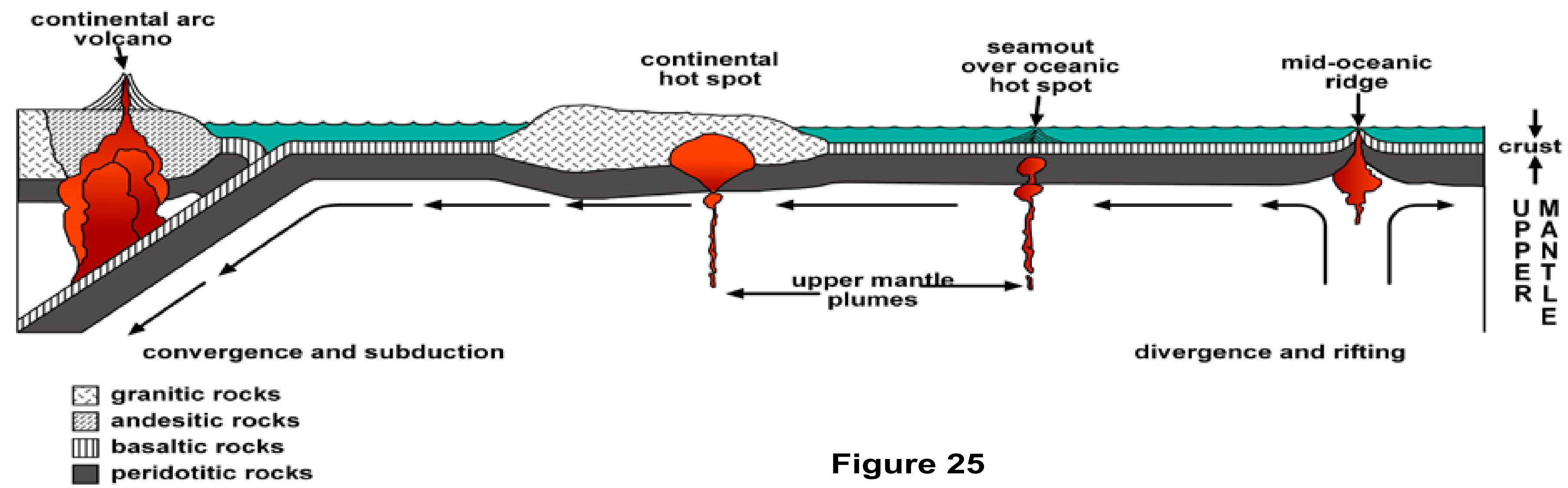


Figure 25

Although less common, andesitic magmas are produced in subduction zones associated with oceanic plate subduction beneath a continental plate (Figure 25). Examples are The Cascades of Washington and Oregon and the Andes of South America. Partial melting of preexisting basaltic rocks occurs but not for the obvious reasons. Pressure drop mechanisms do not occur because pressures within these compression zones are beyond comprehension. While some argue that the movement of rocks on opposite sides of the subduction zone could generate enough frictional heat to allow direct heating its effect is probably minimal. Most geologists consider the introduction of water to be the catalyst for subduction zone melting. While some of the descending basaltic oceanic plate will experience total melting, forming new basaltic magma, most of the basalt actually experiences only partial melting. It you remember that partial melting must produce magma that is more felsic than the parent rock, you can now explain the origin of most andesitic magmas.

Of the three magma types, the origin of the granitic magma is the most difficult to explain. Some geologists believe granitic magma can only be produced by the total melting of pre-existing granite. This explanation easily explains continental hot spot magmas but fails to explain the existence of rocks formed from granitic magmas in other locations. The big problem is that partial melting of existing rocks, other than granite, will not produce a granitic magma. Why? Not enough silica! Silica is known to be a major constituent of granitic rocks and elemental silicon is more plentiful nearer the crust because it is less dense than elements such as iron and magneisum. However, scientists have recently come to think that the weathered continental sediments may provide the required silica. It is well known that the basalt-rich ocean floors are covered by thick blankets of silica-rich sediments derived from weathered sandstones, deserts, etc. washed or blown in from continents. Even a weathered granite can produce silica-rich sediment under the right conditions. Once on the ocean floor these quartz-rich sediments can be carried on the subducting oceanic plate to a depth where their addition turns a partially melted andesite into a granitic magma.

The rock we call basalt can be produced by the partial melting of peridotite in active tectonic zones.

During the partial melting of an igneous rock, the more felsic components melt to form a magma that is just more felsic that the original rock.

Reminder: Granite and rhyolite are compositional the same. They are differentiated because of different grain size related to cooling rate. Granite cools underground (intrusive) as a magma while ryholite cools above ground (extrusive) as a lava. The same situation applies to grabbro/ basalt and diroite/ andesite.

Compare, Contrast, Connect

Figure 26 is a reintroduction of Figure 2. Figure 27 is the culmination of the developmental project spanning many pages of our discussion. Both figures were used as scaffolding upon which we help you construct you a conceptual understanding of the potential relationships between nine minerals and seven rocks. The rock names in Figure 26 and 27 are arranged, beginning at the top, from mafic to more felsic. Depending on your grade level you could conceptually simplify this to mean from dark to light. Or, as a chemistry instructor, you could also correctly demonstrate that both figures represent the a classification based upon the presence or absence of elemental iron within each of the multiple minerals found in each rock. As a final exercise, take some time to visually compare and contrast Figures 26 and 27. Can you begin to see they are just different ways of illustrating the same ideas? Having trouble? Use a pencil to draw lines connecting the mineral names in Figure 26. Note how your lines begin to show a pattern similar to the seen in Figure 27?

Figure 26

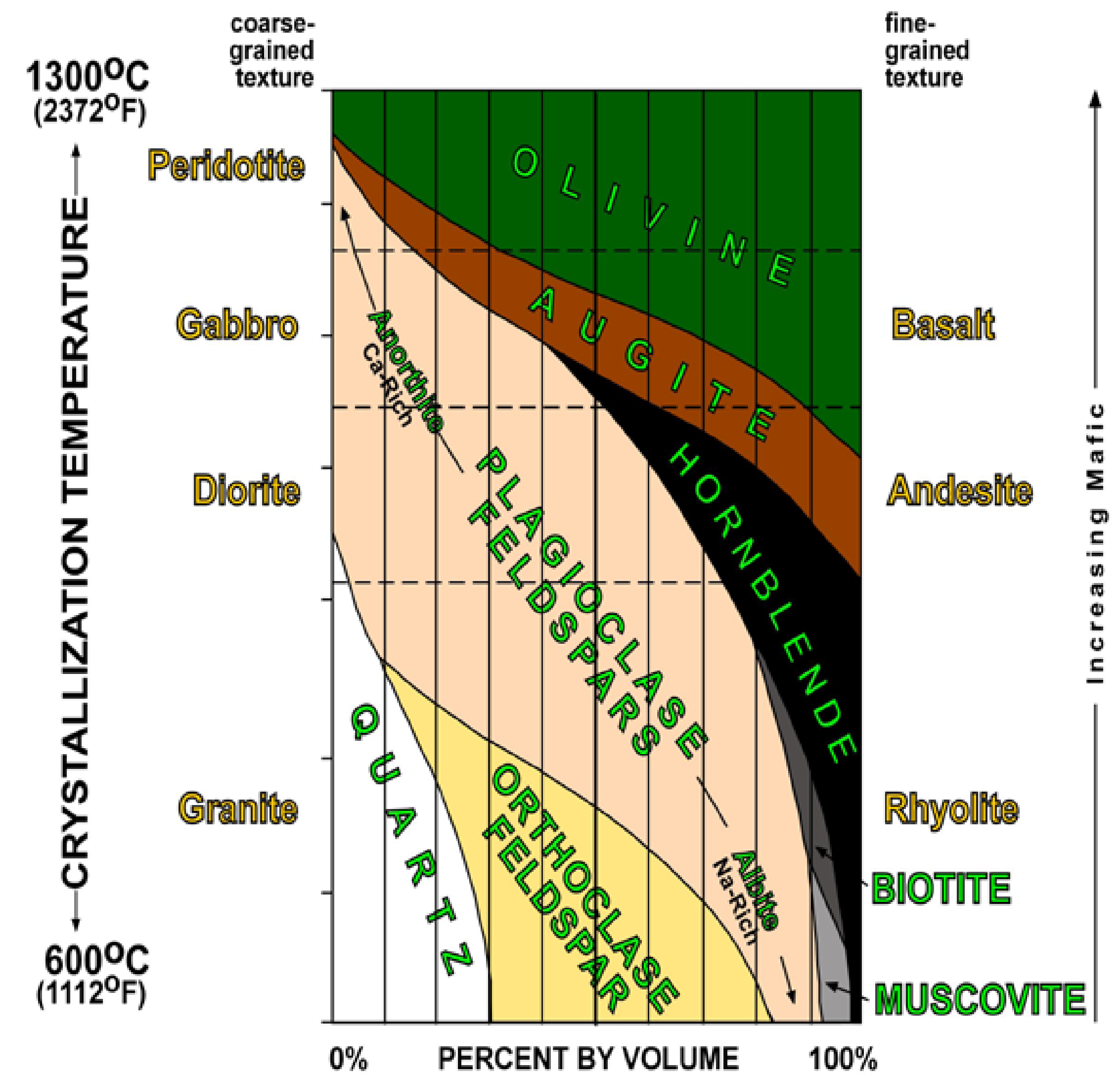


Figure 27

West Virginia Igneous Rocks

Yes, there are igneous rocks in West Virginia! They cover very little territory and are hard to find but saying West Virginia has no igneous rocks is wrong.

The brownish layer in Figure 28 is a 50,000,000 year old basalt. Directly underlying it is the 380,000,000 year old Millboro Shale. How did igneous basalt wind up adjacent to and in contact with a sedimentary rock nearly seven times older?

West Virginia's igneous rocks are confined to igneous bodies called sills and dikes. Viscous basalt can be forced into existing rock fractures, such as joints and bedding planes, as it rises to the surface. Upon cooling a planar body of igneous rock forms among sedimentary rocks. If the magma, as shown in Figure 29 is confined between parallel layers of sedimentary rock, upon cooling it is called a sill. On the other hand, if the magma was forced into vertical fractures and joints so that it cuts across the sedimentary rock layers it produces a dike. Using the concept of relative age dating, dikes and sills must be younger than the rocks they cut through. For West Virginia, the most interesting aspect of these bodies (Figure 30 and 31) is that they demonstrate molten rock was actively in motion in Pendleton County not all that long ago. More on West Virginia's igneous rocks may be found by exploring:

http://www.wvgs.edu/www/statemap/statemap.htm

Figure 28 (left). Eocene (?) basalt sill overlying steeply dipping strata of the Devonian Millboro Shale, south of Sugar Grove, West Virginia. The sill is the approximately 1 meter thick brownish looking layer. The fine-grained nature of the sill material suggests shallow emplacement and rapid cooling.

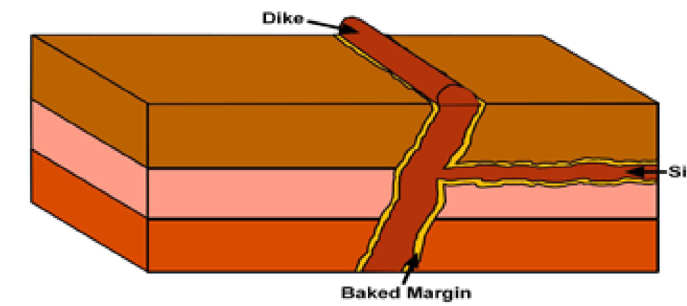


Figure 29 (above). Dikes and sills can partially melt adjacent sedimentary rock forming a baked margin (yellow) where metamorphic rocks may be found.

Figure 30 (below). Eocene basalt dike about 5 feet tall and 3 feet wide just over WV-VA line near Pendleton County.

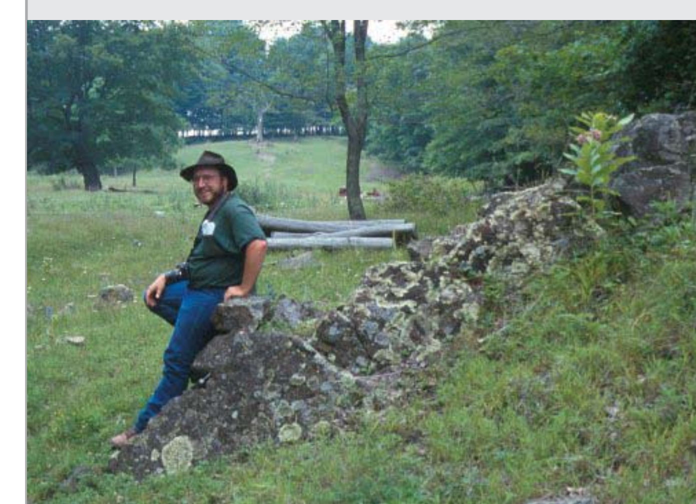


Figure 31 (right). The white rock in the foreground is an igneous dike exposed in Brushy Fork Creek. The dike is composed almost exclusively of albite feldspar with minor amounts of magnetite. The view is looking downward at the top of the 25 foot wide dike. Cooling fractures in the dike give the appearance of "pseudo-sedimentary" structures and the fine-grained nature of the rock makes it easily mistaken for a fine-grained sandstone. Grayish and partially rounded sandstone cobbles are visible in the background near the grassy area.