# THE GEOLOGY OF STONE

## 1.0 INTRODUCTION

**1.1** Earth is geologically classified as a "stony planet," as it is entirely stone (rock) of various mineral compositions and forms, excluding its water and atmosphere.

**1.2** Earth scientists prefer the term "rock,"[1] while the commercial stone industry, prefers the term "stone".[2] Both words are correct in their respective frame of reference, and for practical purposes, interchangeable. Every type of rock or stone is composed of one or more minerals. For those who work with dimension stone, it is important to know these minerals—there are about 25 common minerals—that make up the bulk of all dimension stone commonly used. These 25 minerals are easy to learn to recognize, and this basic knowledge in turn helps to identify the many varieties of natural stone.

**1.3** Identifying the minerals in a particular type of stone is important because the properties and behavior of stone are the sum total of the properties and behavior of the minerals found in the stone. Knowing something about the mode of formation or "genesis" of a stone further aids predicting the behavior of a stone. Thus, performance questions can be knowledgeably approached, such as how a particular stone might behave in a given application. Stone industry professionals need this information to reduce waste and avoid costly mistakes.

## 2.0 STONE CATEGORIES

**2.1** Three general rock or stone categories are recognized according to their mode of origin. This is a genetic classification, and it not only states how and under what general conditions a stone was formed, but also implies a general compositional range. The basic stone groups are:

**2.1.1 Igneous rock** is formed by solidification (cooling) or, in some cases, by solid-state transformation[3] of molten or semi-molten material in the Earth's upper mantle or crust into crystalline rock generally consisting of silicates (compounds with $SiO_4$) and some dark-colored accessory minerals such as iron oxides or other iron- and magnesium-bearing silicate minerals. Example: granite.

**2.1.2 Sedimentary rock** can be:

**2.1.2.1 Detrital sedimentary stone**, which is the naturally cemented accumulation of solid granular materials or particles derived from both mechanical and chemical weathering of any existing rock. Examples include limestone, shale, sandstone, and conglomerate.

**2.1.2.2 Chemical sedimentary stones**, the precipitates of chemicals like salt that are the dissolved weathering products of any existing rocks. Chemical weathering yields some soluble salts, and examples of the resulting stones include onyx ($CaCO_3$), limestone ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), alabaster ($CaSO_4$), some types of travertine ($CaCO_3 + SiO_2$) and common table salt (NaCl). Onyx is actually precipitated in

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[1] *The Glossary of Geology,* 4th edition, 1997, Robert L. Bates and Julia A. Jackson, eds., American Geological Institute (AGI), defines rock as "a mixture of one or more minerals."

[2] *The Glossary of Geology* (ibid) defines *stone* as: "A general term for rock that is used in construction, either crushed for use as aggregate or cut into shaped blocks as dimension stone."

[3] A *solid-state transformation* is an atomic or molecular-level process by which a compound changes from one crystalline solid to another new crystalline solid–without going through an intervening liquid and/or gaseous state. This process occurs under conditions of very high pressure, temperature, and chemistry through time at depths in the crust of several to tens of kilometers.

caverns and travertine is a precipitate deposited around freshwater springs in shallow marine (salty) water. Alabaster is usually a slightly metamorphosed anhydrite or calcium sulfate.

**2.1.2.3** Many other chemical precipitates are of no use as dimension stone due to solubility and softness, but may be much more valuable as chemical feedstock, table salt, or fertilizer.

**2.1.3 Metamorphic[4] rock** is formed from any pre-existing rock type in the Earth's crust under variable conditions of high pressures, high temperature, chemistry, and time. The process produces mechanically deformed stone and chemically alters the mineral assemblages of the parent stone. The new mineral suite may be a different or the same chemical composition as the parent, but as newly formed crystals. Examples of metamorphic stones include marble, slate, schist, and gneiss.

**2.1.3.1** Earth scientists have assigned hundreds of names for rocks in each of the genetic groups, and for minerals or stones resulting from different processes of formation and slightly different chemical makeup. The many technical names are confusing; the few names given in this chapter will suffice for most commercial purposes. When legal questions arise, it may be appropriate to consult a professional earth scientist about stone types and nomenclature of a particular stone.

## 3.0 STONE FORMATION

**3.1 Igneous Stone (Oceanic And Continental Stone).** The Earth's crust is composed of two general types of stone: oceanic and continental. Each has distinct characteristics, mineral and chemical compositions, colors, specific gravities, and behaviors. Most, but not all, commercial stone is quarried from continental rock. Earth's **lithosphere**, or rocky crust, is the cool and rigid outermost rock layer, which varies from about 3 to 25 miles thick.

**3.2** The underlying mantle is about 1,620 miles thick and can be is envisioned as two parts: a weak **upper mantle** of about 190 to 440 miles of rock, mostly uniform in composition and capable of flow, i.e., not quite molten. Below it, the **lower mantle** is a denser, "mushy" or partially molten material somewhat different in composition from the upper mantle.

**3.3** Deep in its center, Earth has a solid, iron-rich **inner core** about 760 miles thick, and a molten metallic **outer core** about 1,420 miles thick.[5] As the inner core is under tremendous pressure, it is hard to conceive what its "molten" physical state is really like.

**3.4** Ocean basins cover approximately 70% of Earth's surface and are underlaid by oceanic-type crust, while a thicker continental-type crust, being lighter in weight, floats on older, denser, oceanic crust. Continents comprise the remaining 30% of Earth's surface.

**3.5** The chart on the following page contrasts characteristics of the two major kinds of rock in the lithosphere (see next page):

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[4] *Metamorphic* is a word derived from Greek that literally means *to change in form.*

[5] Since deep Earth materials cannot be physically examined, the above information is known through geophysical studies of earthquakes and vibrations from atomic bomb tests.

| **Oceanic Stone** | **Continental Stone** |
|---|---|
| Dark in color | Light in color |
| Comp: High Iron (Fe), Magnesium (Mg), Calcium (Ca) | High silica ($SiO_2$, ≈70%), Potassium (K), Sodium (Na) and Aluminum (Al) |
| Low: $SiO_2$ (<50%), K, Na & Al | Low: Fe, Mg, Ca |
| Heavy: Specific gravity ≈2.9 | Not heavy: Specific Gravity ≈2.6+ |
| Melting temperatures: High (1000-1500° C.) | Low: ≈800°+ C. |
| Viscosity of Lava: Very runny – flows like water | Very stiff – like honey in winter |
| Kind of eruption: Quiet like Hawaii | Explosive like Mt. St. Helens |
| Scientific name of lava type: Basaltic | Granitic |
| Scientific code word: Mafic[6] | Felsic[7] |

**3.6** In each case, it is the elemental content of the major minerals that make the sharply different characteristics shown in the chart. The generalizations of composition in the chart hold for most cases. Although the differences in specific gravity or density of the two classifications of stone appear to vary little, that apparently small difference is enough for oceanic rock to float on denser layers underneath. Like blocks of wood in ponds, the world's continents are floating on heavier, darker crust below.

**3.7** Nature, however, is by no means quite so accommodating as to always exactly fit this twofold classification. The compositional differences of these stone classifications represent the end members of a continuous element spectrum of high Fe, Mg, Ca and low Si, K, Na, etc., to low Fe, Mg, Ca and high Si, K and Na.

**3.8 Andesite**, named after the Andes Mountains of South America, is a lava stone with an intermediate composition at about the middle of the element spectrum. It is gray and has a medium specific gravity. Andesite flows well or poorly depending on its silica content, and may contain all of the following elements in its variable composition: Si, Fe, Mg, Na, Ca, K and Al. It is known simply as an "intermediate" or "Andean-type" stone.

**3.9 Plate Tectonics.** According to the theory of plate tectonics, the lithosphere of the Earth is divided into large crustal plates that have continuously separated or collided with each other over millions of years, always moving and forming new and destroying old crustal material in the process. Almost all of the ocean floor is basaltic or volcanic rock created by plate movement called "sea-floor spreading," initiated from mid-oceanic ridges. These linear ridges or rifts are the spreading centers between undersea crustal plates that allow molten rock to emerge from the mantle through volcanic action. Conversely, when plates collide, the far edge of one oceanic floor plate is thrust under the edge of the adjacent plate in a process called *subduction*. Subducted material is reincorporated into the Earth's upper mantle.

**3.9.1** The life-span of oceanic floor is typically no more than 180 million years from formation at spreading centers to disappearance of subduction. This is a relatively short time compared with some continental stone that is 3.9 billion years old. Thus, the sea floor is similar to a conveyor belt moving from zero to 180 million years old, then disappearing. However, because of its comparatively young age, oceanic stone lacks the abundant variety of types, colors, and textures found in the much older continental stone.

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[6] *Mafic* is a word made up from the first letters of its characterizing components. In this case, *ma-* from *ma*gnesium plus *–fic* from *f*err*ic,* which means "of iron content."

[7] *Felsic* is derived from *fel*dspar and *si*lica, from the high quartz content.

**3.9.2** The lower crust and upper mantle of Earth are composed of rocks remarkably similar in composition, closely related to basaltic lava: dark-colored, heavy, with silicate minerals having high amounts of Fe, Mg, and Ca-rich silicates and lesser amounts of silica in the form of quartz ($SiO_2$). The natural process of crustal formation through nearly 4.5 billion years has chemically differentiated these dark, heavy stones into the lighter-colored and lighter specific gravity stones of the continents.

**3.9.3** Other stone formation processes that are a part of or affect plate tectonics include continental movement and collision, mountain formation, earthquakes, chemical weathering of stone, the freeze/thaw cycle, landslides, and climatic events, such as violent storms, torrential rain, and floods.

**3.9.4** These and other natural processes continuously operate to form new stone and to chemically differentiate existing stone materials through time, yielding a spectrum of colors and unique designs in an abundance that satisfies an increasingly demanding market.

**3.10 Igneous Stone.** Igneous stone is cooled and solidified from material melted by heat from decay of radioactive minerals in the Earth's crust (lithosphere), and by frictional heat caused by crustal movements. The release of these powerful forms of thermal energy can produce explosive volcanism like the type seen in mountain ranges such as the Cascades in the northwestern United States. Mount St. Helens in Washington is an example of this geologic process.

**3.10.1** Other volcanic areas known as "hot spots" are formed from molten rock emerging on the ocean's floor through stationary spots or plumes or vents in the underlying upper mantle and crust. The basaltic volcanic islands of Hawaii were born in this manner. Subsea volcanic activity is continually creating new oceanic floor and volcanic islands.

**3.10.2** However, not all igneous stone is volcanic. All genuine granites[8] are solidified slowly from a melt miles deep in the crust, well encapsulated and thus well insulated by surrounding solid rock. This is significant to the quality of granite dimension stone because slow cooling yields the larger crystals that give many commercial granites their distinctive textural character and beauty.

**3.11 Clastic Sedimentary Stone.** The formation of clastic sedimentary stone is relatively uncomplicated compared to the complex chemistry and natural processes associated with either igneous or metamorphic stone.

**3.12 Clasts** are fragments or grains of any existing stone, produced by one or more processes, such as freezing and thawing, earthquakes, and other events of weathering, both mechanical and chemical. Clasts are also called "detritus;" thus, clastic sedimentary stone is sometimes referred to as detrital sedimentary stone.

**3.13 Sizes of clasts** range from boulders to cobbles, pebbles, sand grains, silt, and clay-sized particles. They are moved by gravity, wind, and water, and are further abraded or rounded and dissolved in the process, and sorted and carried vast distances. The rivers of the world are the prime movers of sediment while sorting them by size, weight, and shape, grinding or abrading the particles to very fine sand, silt, and finally, clay-sized grains carried in suspension to the oceans and deposited on continental margins. As deposits thicken, compaction occurs and the natural process of chemical cementation takes place through time to produce clastic sedimentary stone.

**3.13.1** Chemical alteration is a continual process acting on stone, from the moment of solidification, exposure and weathering, to its transportation, deposition, compaction, burial, and cementation throughout the time

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[8] Some types of stone defined by ASTM International as "granite" are not true, geological granites.

that piece of stone exists. Chemical change during burial continues. Change continues after quarrying, fabrication, and installation on a structure, and faster if water is present. But if stone is kept dry, chemical action slows up to a minimal level.

**3.14 Clast Sizes.** Clasts are graded according to size, and the resulting stone after compaction and cementation is classified as follows:

**3.14.1** Particle Name[9]: **Boulders**
Size Range (in mm): >256
Rock Name: Boulder Conglomerate
Stone Abbreviation: Cgl.

**3.14.2** Particle Name: **Cobbles**
Size Range (in mm): 64 to 256
Rock Name: Cobble Conglomerate
Stone Abbreviation: Cgl.

**3.14.3** Particle Name: **Pebble**
Size Range (in mm): 2 to 64
Rock Name: Pebble Conglomerate
Stone Abbreviation: Cgl.

**3.14.4** Particle Name: **Sand**
Size Range (in mm): 1/16 to 2
Rock Name: Sandstone[10]
Stone Abbreviation: Ss.

**3.14.5** Particle Name: **Silt**
Size Range (in mm): 1/256 to 1/16
Rock Name: Siltstone
Stone Abbreviation: Slst.

**3.14.6** Particle Name: **Clay**
Size Range (in mm): <1/256
Rock Name: Mudstone and Shale
Stone Abbreviation: Sh.

**3.15 Sandstones And Conglomerates.** Sedimentary stones most important to the dimension stone industry are sandstones and some of the smaller-grained conglomerates. Siltstone, shale, and the very large-grained conglomerates are of less commercial importance except for landscaping and occasional artistic constructions. Siltstone, where well-cemented and readily available, was utilized as a fieldstone for buildings or other structural work in earlier centuries.

**3.16 Sand Grain Composition.** Sand grains are graded very fine, fine, medium, coarse, and very coarse. They may be further characterized as well-rounded, almost spherical, to very angular. Angular grains tend to interlock well, and when cemented, are desirable in sandstone, just as angular sand is desirable for the same reason in masonry. Sandstones buried over tens to thousands of feet become compacted, and the flow, often miniscule, of chemical-charged aqueous fluids proceed to cement the grains with one or more of cementing minerals. Chemical activity does not cease, but continues to cement or de-cement the stone, or change the stone by introduction and sometimes substitution of one mineral for another of both grains and cement.

**3.17 Cementing Minerals.** The common cementing minerals of clastic sedimentary stone in order of hardness and desirability are the following:

**3.17.1 Silica:** Either hydrous or crystalline, both types are hard and relatively insoluble.

**3.17.2 Carbonate:** Even though calcite is soluble in dilute acids like rain, it is a good cement, and much clastic sedimentary stone is cemented with calcite and/or a mixture of calcite and silica cements. Other carbonates

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[9] Particle names are simply names for a defined grain size. They do not suggest the mineralogical content unless a mineral name precedes the particle name as a modifer.

[10] Although sand-sized grains can be from any rock fragment and one or more of several minerals, sandstone is generally regarded as "quartz" sandstone. Quartz is among the longest-lasting minerals in the environment, resisting chemical degradation and abrasion.

may be less soluble, but these are rare as cements.

**3.17.3 Iron Oxides:** These are fairly common as clastic cements, but tend to be softer and bleed ugly stain. Although some excellent sandstones are red to red-brown from some iron cement and stained quartz grains, the better brownstones may have silica cements, making them truly excellent, highly colored stones.

**3.17.4 Clay Minerals:** These are generally considered a rather poor cementing medium. Even though clay cemented stone may appear well-cemented, the clay cement is soft, weak, easily crushed, and readily removed by water.

**3.17.5 Other mineral cements** may be found from time to time, but are rare.

**3.17.6** All of the cementing minerals mentioned in this section, plus some other rare mineral cements, can combine in various mixtures that will bond stone satisfactorily.

**3.18 Chemical Sedimentary Stone**. This class of sedimentary stone precipitates from chemically dense bodies of water such as the Great Salt Lake, the Dead Sea, and other closed marine basins lacking outlets. Salt-laden water flows in and evaporation constantly increases the salt content until precipitation takes place. Common building stones that are chemical precipitates include travertines ($CaCO_3$), onyx ($CaCO_3$), alabaster ($CaSO_4$), and cherts such as flint, jasper, and agate. Chert is a sedimentary deposit of hydrous silica ($SiO_2 \cdot nH_2O$). The popular dimension stones **travertine** and **onyx** are chemical precipitates of mostly limestone or calcium carbonate ($CaCO_3$) deposited around ground springs, in caves, or springs in bodies of saline water, although some travertine is actually fossiliferous limestone, which is not strictly a chemical sedimentary stone (see the Travertine chapter).

**3.18.1** Salt, anhydrite, and gypsum form in other marine settings such as the Red Sea, which has very wide tidal flats in a hot climate that promotes evaporation and precipitation. Even the Mediterranean Sea was a closed basin millions of years ago in which thick evaporates formed similar to those now found in the Dead Sea.

**3.19 Metamorphic stone.** Many of the most colorful, highly figured, and beautiful dimension stones are the result of metamorphic processes. The popularity of these spectacular stones has encouraged the exploration for the new types of stone that frequently appear in the market. Metamorphic processes are capable of producing stone in a color palette and textural complexity that rivals that of igneous and sedimentary processes.

**3.19.1** Metamorphic stone makes up a large part of all continents, is exposed on all continents, and is found deep beneath the relatively flat areas of continents thickly covered by sedimentary rocks, such as the U.S. midwest. It makes up the core areas of continents. For example, the ancient, complex metamorphics of the Canadian Shield in northern Canada comprise the core of the North American continent. The root areas of many mountain chains such as the Himalayas, Rockies, and Urals are the same type of strongly metamorphosed rock that underlies the central midwest from Ohio to Illinois.

**3.19.2** Metamorphic stones are among the most interesting of Earth's products, for they are the only direct evidence of major catastrophic events in the history of the Earth's crust. Some of this stone is up to 3.8 billion years old, and has changed in its long existence from igneous to sedimentary to metamorphic.

**3.19.3** Any deeply buried, existing stone–igneous, sedimentary or metamorphic–may be subjected to forces that cause profound mechanical, textural, and ultimately, chemical changes in the mineral content. Metamorphosed stone may or may not resemble its parent stone. Metamorphism is caused by regional-scale crustal movements and mountain-building forces, or by local crustal disturbance, at temperatures about 200ºC to near-melting, ≈700-800ºC, and pressures from around 450,000 pounds per square inch (psi) to several million psi in the presence of chemically charged aqueous fluids through time.

**3.19.4** Metamorphic rock produced from widely variable conditions yields three distinct grades of metamorphism, from low-grade through medium- to high-grade metamorphic rock, each characterized by specific stone colors, textures, and mineral content. Stone of all metamorphic grades can be found as beautiful dimension stone of many types, including slate, quartzite, marble, and serpentine.

## 4.0 THE ROCK CYLE

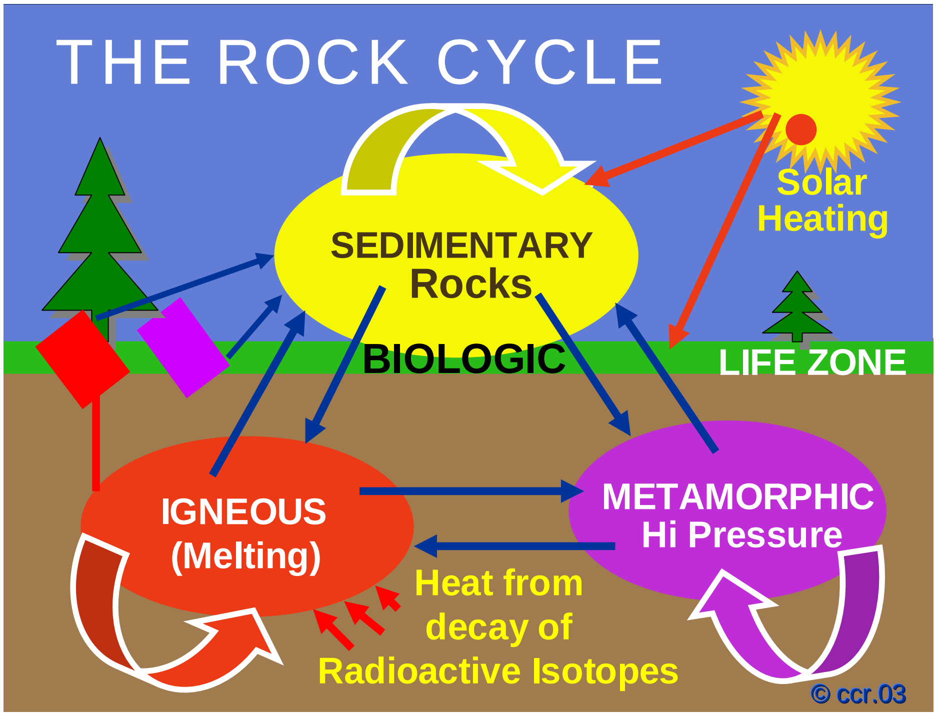
**4.1** Basic processes and relationships inherent in the geological concept known as "the rock cycle" help to understand the variety and complexity of stone.

**4.2** As shown in the rock cycle illustration on the following page, the curved arrows at each stone type indicate that a new igneous, metamorphic, or sedimentary stone can be developed from an existing stone by a repetition of melting and metamorphism, or by the weathering, transportation, deposition, compaction, and cementation processes.

**4.3** The straight arrows from one stone type to another show that any of the three basic types of stone can be produced from an existing stone of one of the other types.

**4.4** Two great energy sources drive the rock cycle: the sun, and the heat from the Earth's interior generated from the decay of radioactive materials. The sun heats the Earth's gaseous atmosphere, driving the weather patterns that cause weathering and erosion of any exposed or nearly exposed rock—the beginning of the sedimentary cycle. Biological activity on the Earth's surface, and to some depth beneath it, also interacts with the chemical processes affecting stone.

**4.5** The rock cycle has been going on continuously for much of the Earth's 4.5 billion years. Some zircon grains (zirconium silicate, $ZrSiO_4$) from an Australian sandstone have been through the rock cycle five times, covering more than 3.9 billion years. Continuous cycling through the multiple processes, mechanical and chemical, serves to chemically and mineralogically differentiate stone; thus, the rock cycle allows continental stone to develop into the wide range of colors and varieties of beautiful dimension stone that have been used by mankind throughout history.



The geological concept of the rock cycle illustrates that new igneous, metamorphic, or sedimentary stone can form from existing stone of another type through the repetition of natural processes.

## NOTES:

Each Material chapter has a section that further details geological information about that specific stone.