Geology for Potters

by Linda Bloomfield

Clays and glazes are made of rocks and minerals from the earth. Minerals used by the ceramic industry are now widely available to potters and it is useful to know where they come from, their properties, as well as which materials can be substituted for others.

Defining the Terms

Rock: An aggregate of minerals e.g. granite.

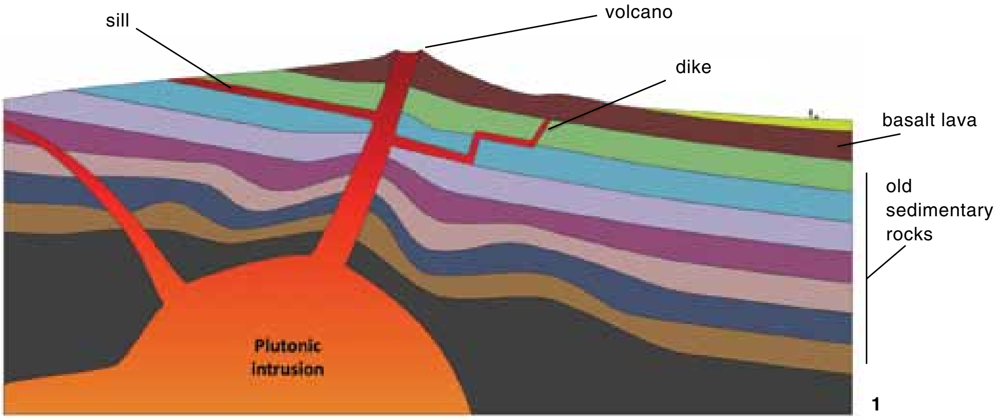
Mineral: An inorganic substance with an ordered atomic structure e.g. quartz.

Magma: Molten rock.

Igneous: Rocks formed from cooled magma.

Sedimentary: Rocks formed from deposited layers of sediment.

Metamorphic: Rocks formed from other rocks by pressure or heat.



1 Diagram of volcano, plutonic intrusion, sills, and dikes.

Rocks

Rocks can be classified into three types: igneous, metamorphic, and sedimentary. The igneous rocks most useful to potters are felsic (yielding feldspars and silica) which are found together with mica in rock aggregates such as granite. Mica is a lustrous, sheet silicate mineral, which forms thin, flat, hexagonal crystals. There are several types of mica, including silvery muscovite, dark biotite, and purple lepidolite. If the molten rock cools slowly deep beneath the earth's surface, the crystal size will be large and the granite coarse. This is known as plutonic or intrusive rock as it is often found in dikes intruding into other rocks. If the mineral crystals are very large (greater than 2 cm), the rock is called pegmatite and some types contain feldspars useful to potters. If magma cools quickly at the earth's surface, the crystals will be much smaller and the rock will have a finer grain size. This type of rock is known as volcanic or extrusive and includes light rhyolite and dark basalt, formed from cooled lava. Rocks that are erupted by volcanoes can cool very fast and include frothy pumice and glassy obsidian.

Metamorphic rocks that are useful to potters include slate, which is formed from shale, and marble, which is formed from limestone. More extreme pressures can give rise to gneiss and schist, which have banded, folded, or layered structures. Soapstone or steatite is a type of schist composed of talc, a magnesium silicate.

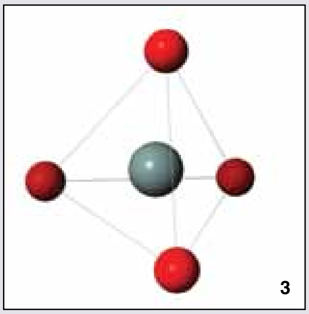
Over time, rocks are brought to the surface by earth movements and eroded, transported by glaciers, rivers, and the wind and deposited in lakes and estuaries as sediments. Sedimentary rocks include sandstone and limestone or chalk, which was built up from layers of fossil shells and plankton deposited in warm Cretaceous seas over millions of years (creta is chalk in Latin). Embedded in the chalk are nodules of flint, thought to be derived from ancient siliceous sponges. Most clays are also sedimentary deposits, composed of weathered granites and weathered shale.

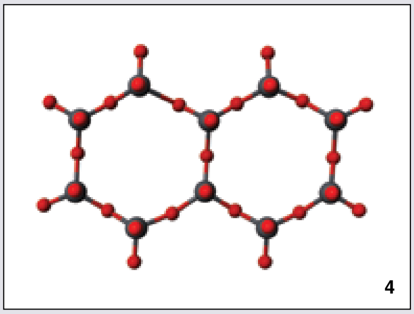
Light and Dark Silicates

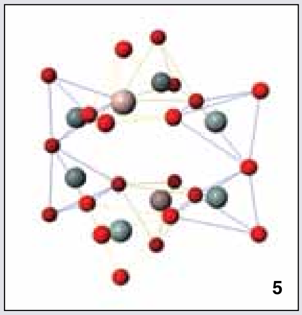
The most abundant elements in the Earth's crust are oxygen and silicon. Many rocks therefore contain silicate minerals, such as feldspar, which is an alumino-silicate (containing alumina and silica). These can be divided into two types, the light (felsic) and the dark (mafic) silicates (2). The light-colored silicates contain over 65% silica and are acidic. Intermediate rocks such as syenite and diorite can contain 55–65% silica. The dark-colored silicates contain only 45–55% silica and are therefore more alkaline. Silica is an acidic oxide even though it is not readily soluble in water. The light-colored silicates include quartz and feldspar, which are the main constituents of granite and are used by the ceramic industry in both clays and glazes. The dark-colored silicates contain iron and magnesium and include minerals such as olivine and pyroxene. These make up the darker

Silicates	Order	Mineral	Formula	Structure
Dark (Mafic)	1	Olivine	$FeMgSiO_4$	Single tetrahedron
	2	Pyroxene	$MgCaSi_2O_6$	Single chain
	3	Amphibole		Double chain
	4	Biotite mica		Sheet
Light (Felsic)	1	Calcium Feldspar	$CaAlSi_2O_8$	Framework
	2	Ca-Na plagioclase feldspar	$NaAlSi_3O_8$	Framework
	3	K orthoclase	$KAlSi_3O_8$	Framework
	4	Muscovite Mica		Sheet
	5	Quartz	SiO_2	Framework

2 Bowen's reaction series showing the order in which minerals solidify from magma. The amount of silica in each mineral increases from the dark to the light silicates.







3 Silica tetrahedron; gray =silicon atom, red=oxygen atom. **4** Quartz network structure, plan view; grey =silicon atom, red=oxygen atom. **5** Feldspar structure; grey=silicon atom, red =oxygen atom, brown =aluminium atom. *Courtesy of Elin Barrett.*

rocks such as fine-grained basalt and coarse-grained gabbro, which are sometimes used by potters, particularly those making glazes from locally sourced rocks.

As magma cools to become granite and basalt, the magnesium, iron, and calcium crystallize out first, forming dark green-colored olivine (a group of minerals ranging from Fe_2SiO_4 to Mg_2SiO_4) and pyroxene (minerals ranging from $FeCaSi_2O_6$ to $MgCaSi_2O_6$). These ferro-magnesian silicates are heavier and have higher melting points than the lighter silicates in the magma, although once melted they are more fluid.

The remaining liquid magma is high in sodium, potassium, and silica and this crystallizes as light-colored feldspar and quartz. This is lighter in weight, but more viscous, and often flows from large underground masses called plutons into cracks between other rocks, called sills (horizontal) and dikes (vertical) (1).

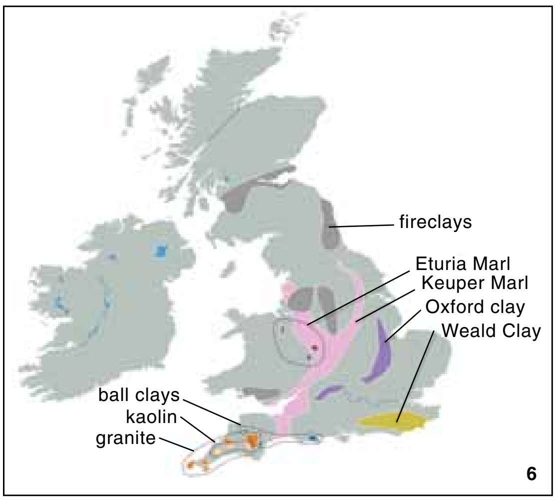
The most unstable minerals, which break down and weather most easily, are the ones with the highest crystallization temperature. Olivine is the least stable and quartz is the most stable silicate mineral and therefore the least weathered. The dark silicates break down to the smallest particles, found in many clays such as bentonite, whereas quartz is often found in large crystals. The structure of silica is based on a tetrahedron (a triangle-based pyramid), with a silica atom in the center and oxygen atoms at each of the four corners. In the dark silicates such as olivine, each isolated silica tetrahedron is bonded with magnesium and iron, rather than with other silicon atoms. In pyroxene, the silica tetrahedra are bonded together in chains, while in amphibole the chains join together to make double chains. In biotite and muscovite mica, the silica tetrahedra make up whole sheets. The underlying atomic structure is scaled up in the crystalline structure of mica, which forms pseudo-hexagonal plates visible to the eye. Mica breaks down to form clay, which has a similar sheet structure.

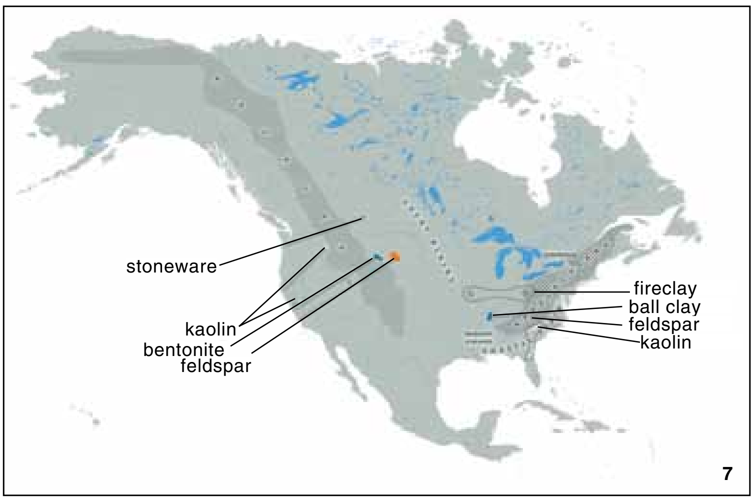
In feldspar and quartz, the silica tetrahedra are connected in three dimensions to form a framework structure, which is very stable. In feldspar, some of the silicon atoms are replaced by aluminium and spaces in the structure are filled by sodium or potassium atoms (3–5).

Geology Timescale (6–7)

Old Rocks: Geologists can date rocks by measuring the relative amounts of radioactive minerals present in the rocks. Some of the oldest rocks used in the ceramics industry are nepheline syenite from Ontario, Canada, and metamorphic talc and wollastonite from the Adirondack mountains in north-eastern New York state. Fossils found in sedimentary layers also help to date rock deposits. Similar trilobite fossils found in Scotland and North America showed that they were once joined together, 500 million years ago. Around that time, plate movements in the Earth's crust caused the uplift of a range of mountains stretching from North America, through Scotland to Norway. The tectonic plate covered by the ancient Iapetus ocean was subducted beneath the North American plate, the sea closed up and Scotland and England collided. The Caledonian mountains were at their highest around 400 million years ago in the Devonian period, when they weathered to produce large deposits of sandstone, known as the Old Red Sandstone as it often contains red iron oxide. Sandstone and metamorphosed quartzite are also found in the Appalachians and in the Midwest US. Sandstone is easier to break up for grinding than the large quartz crystals found in rock veins. Clays were also deposited during this period but over time they became covered by subsequent deposits and compressed into shale and slate.

Coal and Fireclay: During the Carboniferous period 350 million years ago, deposits of coal were formed from ancient swamps. Sedimentary clays from weathered basalt were also laid down in layers with the coal. This occurred in Staffordshire, England, where red Etruria Marl is found overlying coal seams, as well as in Missouri and Ohio in the US, where fireclays are mined. Geological maps show strikingly that the six pottery towns of Stoke-on-Trent in Staffordshire were built along the line where





6 Map of Britain and Ireland showing commercial clay and granite deposits. **7** Map of North America showing commercial clay and feldspar deposits. (Article focus is on the geology of Great Britain and North America, which were once joined together and share similar features.) *Courtesy of Henry Bloomfield.*

the red clay seam meets the surface. During the eighteenth century, potters also started to bring in flint from south-east England, ball clays from Dorset and kaolin from Cornwall but still used the locally available fireclay for saggars and coal for firing. They used chert, a silica rock, to make millstones to grind the calcined flint and bone ash used in the white clay bodies.

Similar clays were deposited in the Pennsylvania and Mississippi lowlands in the US. Carboniferous deposits of fireclay, coal, and red clay are found in Oak Hill, Ohio, where RedArt earthenware clay and GoldArt fireclay are mined by the Cedar Heights clay company. The fireclay in southern Ohio was rediscovered in the mid-19th century by a firebrick maker from Wales. It had also been used by Native Americans. The yellow clays of eastern Ohio were used from the 1840s onward by immigrant potters from Staffordshire. The main centers of the American pottery industry that developed around that time were in East Liverpool, Ohio, and Trenton, New Jersey.

Era	Million years ago	Major Epoch	Formation of various potters' materials
4	Recent	Holocene	
	1.6	Pleistocene	Ice age. Iron-rich clay Fremington/Albany slip
3	5.3	Pliocene	Boron-rich hot springs, California, US
	23	Miocene	Lithium in Atacama salt flats, Chile
	36.5	Oligocene	Ball clay, Devon UK
	53	Eocene	Ball clay Dorset UK/ Tennessee, Kentucky US; Kaolin Georgia, Florida, US
	65	Paleocene	The Great Extinction. Atlantic Ocean widens.
2	135	Cretaceous	Chalk, flint, clay, South East UK. Whitemud formation, Canada. Bentonite, Wyoming, US
	205	Jurassic	Ammonites/dinosaurs. Limestone, Oxford clay, UK
	250	Triassic	Keuper Marl, Midlands, UK
1	290	Permian	Cornwall stone, UK. Kaolin, UK. Pegmatite, US
	355	Carboniferous	Clay/coal layers. Sandstone. Limestone.
	410	Devonian	Old Red Sandstone
	438	Silurian	Caledonian/Appalachian mountain ranges uplifted
	510	Ordovician	Scotland still attached to North America
	570	Cambrian	Trilobites appear
0	2500	Precambrian	Talc, wollastonite, New York. Nepheline syenite, Ontario. Custer feldspar, South Dakota

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8 Geological time line of the formation of various potter's materials. Based on Richard Fortey's dates in his book, *The Hidden Landscape*, published in 1993.

Feldspar: In Cornwall, England, a large granite batholitic intrusion (magma dome) formed underground 300 million years ago. Hot gases caused the formation of minerals including tin and copper ores, which were mined from the Bronze Age until the twentieth century. More importantly for potters, the granite decomposed to form Cornwall Stone and pure white kaolin.

In North Carolina and South Dakota, granites and coarse-grained pegmatites were formed. These are important sources of sodium, potassium, and lithium feldspars. Potash feldspar is mined in the Black Hills in South Dakota, which are formed from very old, Precambrian granites and pegmatites. The hills were explored by George Armstrong Custer and gold was found in 1874. Custer feldspar has been mined there since 1928.

Bentonite: During the Cretaceous period 135 million years ago, volcanic ash rich in iron and magnesium was deposited and transformed into bentonite clays in the Benton Shale, Wyoming, not far from the Black Hills. The Great Plains of North America were covered by an inland sea during that time and bentonite deposits were formed around the edges of the Black Hills and in the Bighorn Basin to the west.

Further north, in Canada, a range of stoneware clays is mined near Ravenscrag in southern Saskatchewan by Plainsman Clays. The clays are part of the Whitemud formation, deposited when the Rockies were weathered and layers of clay were washed down onto the plains, which were still covered by the Cretaceous inland sea. On the east coast of the US in New Jersey, the South Amboy fireclay was deposited near Staten Island and later used by early American stoneware potters.

In south-east England, which was also covered by a warm sea, the chalk deposits were formed, containing layers of flint nodules along what was once the sea bed.

The great extinction occurred 65 million years ago and the dinosaurs on the land and ammonites in the sea died out. Their fossils can be found in the limestone deposited during the Jurassic period. At that time, the continents of North America and Europe began to drift apart.

Ball Clays: Many ball clay deposits were laid down between 35 and 50 million years ago when kaolin was washed into lakes and lagoons. This occurred in Devon and Dorset in England, as well as Kentucky and Tennessee in the US. The clays were often deposited in lenticular (lens shaped) sediments, together with sand and gravel. The sand is heavier and is usually found at the bottom of the deposit, while the carbon-rich organic matter is near the top. In Georgia and Florida, secondary kaolin deposits were washed down to the coastal plain. These deposits remained relatively white and pure, but contain more titanium than primary English china clay. There are also secondary kaolin deposits west of the Rocky Mountains in Helmer, Idaho, and Ione, California.

Glacial clays: The latest clays to be deposited, during the ice age, were iron-rich red earthenware clays including Fremington clay in Devon and Albany slip in New York, supplies of which have now been used up, although there are alternative red earthenware clays available.

Minerals useful to potters which formed relatively recently include borates in desert hot springs and lithium in salt flats.

Minerals

The study of the formation of rocks and minerals can give insight into how glazes form in the kiln, as stoneware glazes are made from the same minerals: feldspar, limestone and quartz. Glazes form crystals while molten in the same way as rocks, depending on a slow rate of cooling for a large crystal size.

Feldspar: ($KNaO{\cdot}Al_2O_3{\cdot}6SiO_2$) The first molecule in the formula is potassium-sodium oxide. The next is aluminium oxide or alumina. Finally, there are six molecules of silica. This is the theoretical formula for feldspar. Some types of feldspar, including Cornwall Stone and petalite, have a formula with eight molecules of silica to one of alumina. Feldspars make up more than 60% of the Earth's crust. There are several types of feldspar. As well as silica and alumina, feldspars used by potters usually contain both sodium and potassium. Particular alkali feldspars are usually named potash or soda feldspar, depending on which is the dominant alkali. Pure soda feldspar is known as albite (it is white) and has the formula $Na_2O{\cdot}Al_2O_3{\cdot}6SiO_2$, while pure potash feldspar is known as orthoclase, $K_2O{\cdot}Al_2O_3{\cdot}6SiO_2$ and can be white or pink. Most feldspars used by potters are a combination of these two alkali feldspars. Calcium feldspar is named anorthite and has the formula $CaO \cdot Al_2O_3 \cdot 2SiO_2$. It has a higher melting point and occurs in rocks associated with darker-colored silicates, so is less often used in ceramics. The general name used by geologists for mixed soda-calcia feldspar is plagioclase feldspar.

Various feldspars come from different mines (e.g. Custer feldspar from South Dakota) and when they run out or become uneconomical to mine, they cannot always be replaced, except by combining other materials to make the same chemical formula.

Cornwall Stone is a type of partially decomposed granite containing potash feldspar and is also high in silica. It is no longer mined, but potters' suppliers make a similar material by combining other feldspars. It is almost a glaze in itself when fired to stoneware temperatures and, together with kaolin, is also a component of porcelain clay bodies. Other materials such as volcanic ash, rhyolite and granite may be substituted for feldspars. A Cornwall stone substitute is Custer feldspar, NC-4 feldspar (or Minspar), plus EPK kaolin, silica, and wollastonite.

Feldspars are abundant minerals, mined as granites, pegmatites, and feldspar sands. They are found in many areas, including the US, Finland, and Norway. NC-4 Feldspar (now known as Minspar) is a soda feldspar from Spruce Pine, North Carolina. Custer feldspar is a potash feldspar from the Black Hills in South Dakota. In the US, feldspars are distinguished by brand names, however, in the UK, they are usually given the generic names potash and soda feldspar and are often sourced from Scandinavia.

Nepheline Syenite ($K_2O \cdot 3Na_2O \cdot 4Al_2O_3 \cdot 8SiO_2$): is a feldspathic rock high in sodium, but with more alumina and less silica than other feldspars. It is mined in Blue Mountain, Ontario, Canada, and North Cape, Norway.

Lithium: is found in the pegmatite minerals petalite, spodumene, lepidolite, and amblygonite. Petalite ($Li_2O \cdot Al_2O_3 \cdot 8SiO_2$) is similar to feldspar in composition, although it is higher in silica, like Cornwall Stone. Spodumene ($Li_2O \cdot Al_2O_3 \cdot 4SiO_2$) is a type of pyroxene, lower in silica than feldspar. Lepidolite ($LiFKF \cdot Al_2O_3 \cdot 3SiO_2$) is a type of mica, a glittery, platy mineral that is more difficult to grind than feldspar and also contains fluorine. Lithium carbonate can be extracted from these minerals but is expensive and is slightly soluble in water. It is cheaper to extract lithium from brine in salt flats such as those in Atacama, Chile.

Calcium: Limestone is calcium carbonate ($CaCO_3$), known to potters as whiting. Chalk is a very pure form of limestone, found in the white cliffs of south-east England. Others forms of limestone may contain some magnesium carbonate. An alternative calcium mineral is wollastonite, calcium silicate ($CaSiO_3$). Wollastonite is mined in north-eastern New York, Finland, and China. It is more expensive than whiting but is preferred in the ceramics industry as it produces no bubbles of carbon dioxide on firing. However, some studio potters' glazes, such as celadon, are enhanced by the presence of small bubbles, which give opacity and depth. Calcium is also found in bone ash, calcium phosphate $Ca_3(PO_4)_2$, and wood ash—particularly soft wood ashes, such as those from pine, beech or apple trees.

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9 Granite from south Devon, England: dark band and black crystals contain iron and magnesium; glittery crystals are muscovite mica; white and pink patches are feldspar; gray areas are quartz. This is a medium-grained type of granite known as granodiorite. *Photo: Henry Bloomfield.* **10** Matthew Blakely's *Dartmoor Granite Sphere*, 18 in. (46 cm) in height, clay made from kaolin and quartz derived from the same parent granite, glaze based on a macrocrystalline gray granite, wood fired, 2015. *Photo: Courtesy of the artist.*

Magnesium: Talc is hydrated magnesium silicate ($3Mg \cdot 4SiO_2 \cdot H_2O$), also known as steatite or soapstone, derived from magnesium-rich pyroxenes ($Mg_2Si_2O_6$) crushed and folded in mountain ranges such as the Adirondacks in north-east New York state. Dolomite is a mineral containing both calcium and magnesium carbonate ($CaCO_3 \cdot MgCO_3$) named after a range of mountains in the Italian Alps. Used in glazes in small amounts (5%), dolomite and talc help to prevent crazing as they have low thermal expansion. They are used in larger amounts (20%) to make satin matte glazes. Light magnesium carbonate is used to make crawling glazes. Cordierite is an alumino-silicate containing magnesium, used to make flameproof clay bodies.

Barium and Strontium: Barium is found in the mineral barite ($BaSO_4$), which was used by Josiah Wedgwood in his colored Jasperware clay body. It is non-toxic because it is insoluble, but it gives off sulphur dioxide on firing. Today barium found in glazes is in the form of barium carbonate, which is toxic. The mineral witherite is barium carbonate.

Strontium is mined as celestine (strontium sulphate) and converted into strontium carbonate for use in glazes (the mineral strontianite is strontium carbonate but it is less commonly mined.) It is used as a non-toxic substitute for barium carbonate but it has properties similar to calcium carbonate.

Zinc (zinc sulphide ZnS): The main ore of zinc is zinc-blende or sphalerite. Zinc oxide can be used as a flux in mid-range glazes. It is an essential component of zinc silicate crystalline glazes. It prevents crazing but reacts with chromium-based colors, turning them brown. Zinc oxide glazes should not be fired in reduction as the oxide is reduced to the metal zinc, which is volatile at 1742°F (950°C).

Boron (calcium borate $2CaO \cdot 3B_2O_3 \cdot 5H_2O$): Boron is found in colemanite and Gerstley borate substitutes such as Gillespie borate. Borates form in hot springs and are found in evaporated lake basins in California and Turkey. However, these materials are slightly soluble and can cause gelling problems in the glaze bucket. Frits containing boron are less soluble. Calcium borate frit or Ferro Frit 3134 is high in boron and is similar in composition to colemanite. Boric oxide is a powerful flux and a glass former and helps prevent crazing.

Silica: (SiO_2): is found mainly in quartz, flint, and sandstone. It is the main glass former in glaze, and also in vitrified stoneware and porcelain. Secondary sources of silica include feldspar, clay, wollastonite, talc, frits, zirconium silicate, and wood ash. Grass ash and hard wood ash contain more silica than soft wood ash.

Alumina (Al_2O_3): The main source of alumina is clay, usually in the form of kaolin, ball clay, or bentonite. It can also be found in its pure form in alumina hydrate and is present in feldspar and kyanite, a metamorphic rock composed of alumina and silica and used as grog in clay bodies. Clay is the common supplier of alumina in glazes as it helps to suspend the glaze particles in water and improves the dry strength of the glaze. Alumina makes the glaze stiff and viscous in the melt and also inhibits the growth of crystals in a glaze.