Terrestrial and Lunar Geological Terminology

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Introduction

This section is largely a compilation of defining geological terms concepts. Broader topics, such as the ramifications for simulant design and *in situ* resource utilization, are included as necessary for context.

Mineral

Definition and overview

A *mineral* is a naturally occurring inorganic substance with characteristic chemical composition and internal order. The internal order is the arrangement of atoms that make up a mineral's crystal structure.

The summary of major lunar minerals and their properties is shown in Appendix 1. Good sources for understanding the mineralogy of the Moon are *The Lunar Sourcebook* (ed. by Heiken et al, 1991), *New Views of the Moon* (ed. by Jolliff, et al., 2006), and *Lunar Mineralogy* (Frondel, 1975). Standard references for mineralogy in the context of geology and physical chemistry are Deere et al. (1992) and Gaines et al. (1997).

The Moon is strongly depleted in volatile elements relative to the Earth. This is manifested by a complete lack of known H_2O- and OH^+-bearing minerals (e.g., clays and micas) and a paucity of Na-bearing minerals on the Moon. Conversely, there are few minerals on the Moon that do not occur on Earth, and those that are restricted to the Moon are generally related to terrestrial minerals; e.g., lunar armacolite is an extension of the terrestrial pseudobrookite mineral group (Frondel, 1975). However, the chemical compositions of lunar minerals may vary from their terrestrial counterparts. In addition to

the relative depletion of volatiles, the lunar environment has a significantly lower oxygen fugacity (fO_2) than that of the Earth. As a result, while most iron on earth occurs as Fe^{2+} or Fe^3, all iron on the moon occurs as Fe^{2+} or Fe^0 ("native" or metallic Fe). These differences and others are discussed under the section on mineral solid solutions, below.

Properties reflect internal structure

The chemical composition and atomic structure of a mineral result in its having a unique set of diagnostic properties, among these properties are color, luster, specific gravity, hardness, fracture and cleavage behavior, and melting temperature. As discussed below, minerals have a characteristic chemistry and structure, but in most minerals these are variable between fixed points, and that variation between results in some variation in diagnostic properties.

Color is self-explanatory, but it should be noted that in some minerals color varies substantially with small changes in mineral chemistry. *Luster* describes how a mineral's surface interacts with light: a mineral may be highly reflective and be termed metallic or sub-metallic, it may be vitreous or glassy, or dull and earthy. These two characteristics are essential to determining the spectral reflectance, absorptivity, and emissivity of a mineral.

Hardness is defined by resistance to scratching or indentation. Most geologists use Moh's Hardness Scale, a relative scale that ranks minerals from 1 (talc, which can be scratched by a fingernail) to 10 (diamond, which can scratch any other naturally occurring material). See Figure 1 for minerals and materials that characterize steps of Mohs' hardness. Absolute hardness scales based on force required for surface indentation are described by Knoop et al., (1939.
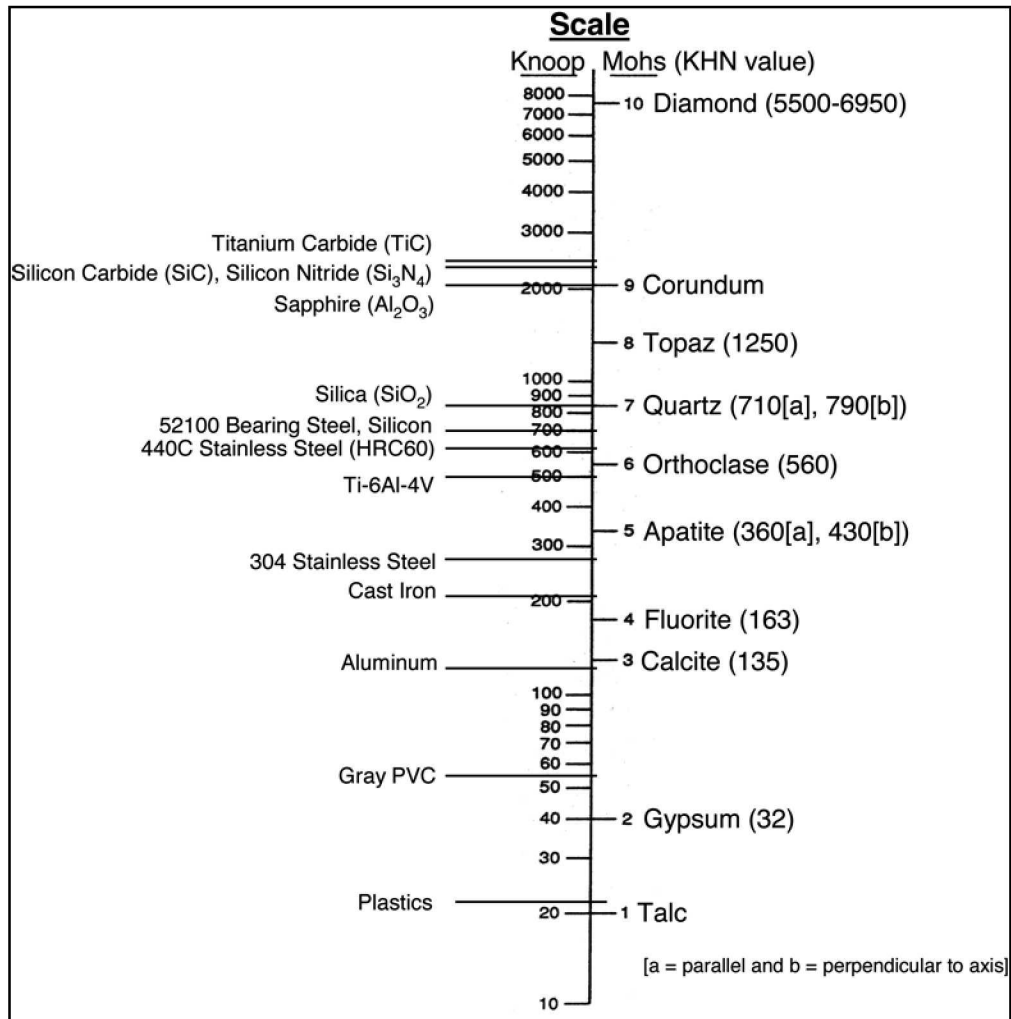
Figure 1. Moh's and Knoop's hardness scales.

Cleavage and *fracture* are related properties of particular importance to geotechnical behavior. Most minerals break along preferred orientations controlled by weaknesses in the crystal structure, which are in turn controlled by atomic bonding. *Cleavage* is characterized by the number of cleavage directions and the angle between them. A mineral with one direction of perfect cleavage splits into sheets, like mica. A mineral with three directions of perfect cleavage at 90° would break into cubes, like halite (NaCl or table salt). The common terrestrial mineral group of amphibole has two directions of cleavage that meet at 60° and 120°, while the pyroxenes, common on Earth and the Moon, have two directions that meet at 90°. *Fracture* is a characteristic that describes how a

material breaks when not controlled by cleavage. A mineral may have cleavage in some directions and fracture in others, or no cleavage and only fracture. Glass, having no crystal structure, has only fracture. The fracture characteristic of glass is *conchoidal fracture*, and can result in very sharp edges. The combination of a material's hardness and cleavage/fracture properties control its abrasiveness.

A mineral will have a characteristic melting temperature and melting behavior. The specific melting behavior of a mineral is dependent on the subtleties of its chemistry, as described below.

Solid Solution and its effects on mineral properties

Chemical composition in a mineral is characteristic, but not necessarily fixed. Many minerals, including the most common ones in lunar regolith, have compositions that vary between fixed points. This is called *solid solution* and it varies between *endmembers*.

Olivine

The mineral olivine is a common constituent in basaltic rocks on Earth and on the Moon and a minor constituent of the lunar highlands. Olivine chemistry provides an effective illustration of solid solution. Olivine has a composition between the Mg_2SiO_4 endmember, known as forsterite, and Fe_2SiO_4, known as fayalite. Its chemical formula is commonly written as $(Mg,Fe)_2SiO_4$. Magnesium and Fe are both 2^+ cations of similar ionic radius; thus, they behave similarly in geochemical systems and freely substitute for one another in olivine's crystal lattice (and in other minerals as well). It is common in mineralogy to refer to the composition of a mineral with solid solution by the fraction of one of the endmembers. For instance, pure Mg_2SiO_4 is 100% forsterite, or in common notation, Fo_{100}, and pure fayalite would be Fo_0. Though forsterite and fayalite have a similar hardness (see Appendix 1), their melting points differ by almost 700° C (Bowen and Schairer, 1935), and this is an important example of why solid solutions and mineral

chemistry may be crucial to ISRU applications. See Figure 2 for the olivine composition-T phase diagram.
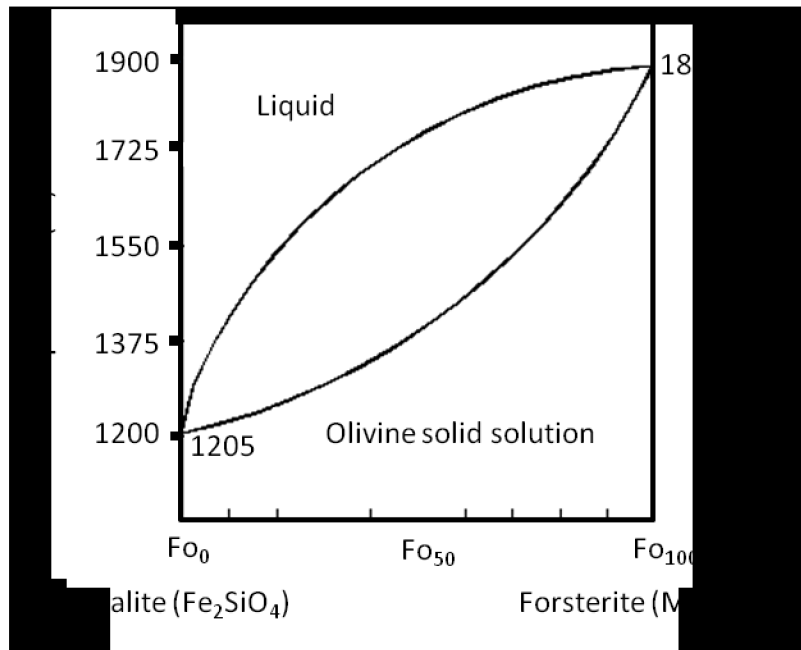
Figure 2. The olivine forsterite-fayalite composition-temperature phase diagram at 1 atmosphere, after Bowen and Schairer (1935). Pure Mg-olivine (forsterite) melts at 1890° C while pure Fe-olivine (fayalite) melts at 1205° C.

Plagioclase

A highly relevant solid solution is the mineral plagioclase feldspar – the most common mineral in the lunar highlands and in the Earth's crust. Plagioclase varies from the endmember albite, $NaAlSi_3O_8$, to the endmember anorthite, $CaAl_2Si_2O_8$. Because Na and Ca are differently charged, this requires a coupled substitution of $Na^{1+}Si^{4+} \leftrightarrow Ca^{2+}Al^{3+}$. Composition notation is from An_0 to An_{100}, but the user may see names attributed to somewhat arbitrary bins along the spectrum. The complete list of plagioclase feldspar minerals is: albite (An_{0-10}), oligoclase (An_{10-30}), andesine (An_{30-50}), labradorite (An_{50-70}), bytownite (An_{70-90}), and anorthite (An_{90-100}). The melting temperature ranges from 1118° to 1557° C from An_0 to An_{100} (Bowen, 1913) and the phase relations mimic the geometry of olivine, shown in Figure 2. Because the Moon is depleted in the volatile element Na relative to the Earth, most lunar highland plagioclase has a Ca-rich composition near An_{95}

(Heiken et al., 1991). This is significantly more calcic than almost any terrestrial source of plagioclase, which is problematic to simulant producers.

Pyroxene

Pyroxenes are the most abundant ferromagnesian silicate minerals on the Earth and the Moon. Pyroxene compositions fall largely into the subset of the ternary system $MgSiO_3$-$CaSiO_3$-$FeSiO_3$ below 50 mole% $CaSiO_3$. This truncated ternary field is bounded by the compositions $CaMgSi_2O_6$ (diopside)-$CaFeSi_2O_6$ (hedenbergite)-$MgSi_2O_6$ (enstatite)-$FeSi_2O_6$ (ferrosilite) and is known in mineralogical vernacular as the "pyroxene quadrilateral" (see Figure 3 for the pyroxene quadrilateral and the field of lunar pyroxene). Pyroxenes also contain nontrivial amounts of other cations, but most pyroxene phase equilibria can be described qualitatively and quantitatively by the quadrilateral system. For terrestrial pyroxenes, other cations present include Na^+, Li^+, Mn^{2+}, Fe^{3+}, Al^{3+}, Cr^{3+}, and Ti^{4+} (Deer et al., 1992); for lunar pyroxenes they are dominantly Cr^{3+}, Al^{3+}, and Ti^{4+}, though Cr^{2+} and Ti^{3+} occur in subordinate amounts (Papike et al., 1998). There is a region of Fe-rich composition in the quadrilateral system in which some lunar pyroxene but no terrestrial pyroxene occur (Papike, 1998).

Spinel and ilmenite

The spinel series is a complex solid solution of metal oxides that follows the formula XY_2O_4, where X and Y are 2+ cations (generally Mg^{2+} or Fe^{2+}) and Y is a 3+ cation (Al^{3+}, Cr^{3+}, or Fe^{3+}). If the spinel contains the 4+ cation Ti^{4+}, then the formula differs to, for instance, $Ti^{4+}Fe^{2+}_2O_4$ (ulvöspinel). The endmember species are shown in Appendix 1. Magnetite, Fe_3O_4, is the most common terrestrial spinel mineral, but because magnetite contains one Fe^{2+} and two Fe^{3+} atoms per formula unit, low fO_2 precludes its occurrence on the Moon. Some members of the spinel series, such as spinel *sensu stricto*, $MgAl_2O_4$, are quite abrasive.
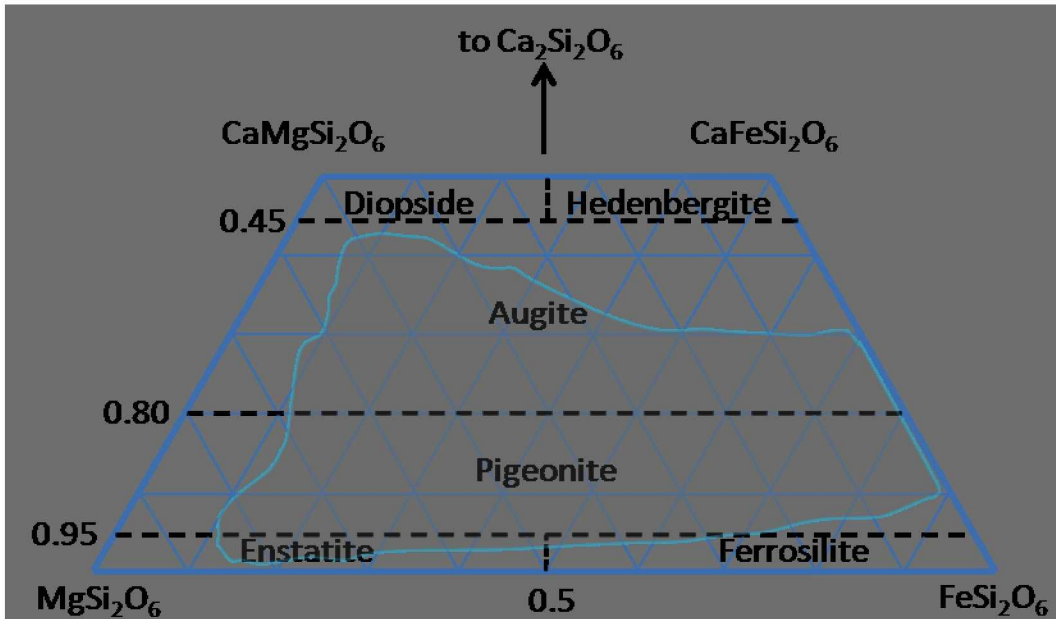
Figure 3. The pyroxene quadrilateral portion of the $Mg_2Si_2O_6$-$Ca_2Si_2O_6$-$Fe_2Si_2O_6$ system and the classification fields. The shaded region is the approximate limit of lunar pyroxenes compiled by Heiken et al. (1991).

Ilmenite, $FeTiO_3$, is a common mineral on the Moon, particularly in the maria. On Earth, ilmenite forms a solid solution with the Fe-oxide hematite (Fe_2O_3), of the form $Fe^{2+}TiO_3$-$Fe^{3+}_2O_3$. Minor amounts of Mg^{2+} and Mn^{2+} may substitute for Fe^{2+} as well. Almost all ilmenite from terrestrial feedstocks will contain some of the Fe^{3+}-bearing hematite component, while low fO_2 precludes its occurrence in lunar ilmenite. The presence of Fe^{3+} will have some effect on ISRU methodologies for production of O_2 by H-reduction or molten oxide electrolysis.

Summary of mineral chemistry ramifications

As a broad generalization, for most geomechanical/physical concerns the mineral assemblage of a material matters, while the specific chemistry of the minerals matters less, because hardness and cleavage/fracture do not vary much within solutions. The exception to this may be the spinels, where absolute hardness varies with chemistry.

As illustrated above, melting temperature can vary significantly within a solid solution. The color and luster may vary strongly as well, especially in minerals where the solution involves change in Mg/Fe. The ratio of Mg to Fe is a key determinant in the spectral reflectance of a mineral (Cahill and Lucey, 2007) and it is likely to bear on absorptivity and emissivity as well.

Glass

The term *glass* refers to a material that solidifies from a molten state without developing crystallinity. Glass is amorphous and lacks the internal structure that is characteristic of minerals. It is generally hard, brittle, and vitreous in appearance, though it may be opaque to transparent. It can have a wide range of chemical composition. In some senses, glass is more like a very viscous liquid than like a solid.

On the Moon, glass occurs by two mechanisms. One is by meteorite impact. The Moon experienced an early history of cataclysmic bombardment (e.g., Dalrymple and Ryder, 1996) but meteorite impacts continue on a diminished scale. The Moon experiences constant bombardment by micrometeorites (<1mm), which result in very localized melting, as well as less frequent larger impacts, which can create basin-scale melt sheets and may disperse melt great distances laterally. Another population of lunar glass is composed of volcanic glass. Almost of this material is basaltic (Mg- and Fe-rich), though the contents of other constituents like Ti vary considerably and result in differences in color. These processes result in the presence of a spectrum of glass compositions in the lunar regolith (e.g., Zeigler et al., 2006).

The composition of a glass, and how quickly it is quenched, will strongly affect its color, reflectance, and absorptivity. Because glass is not a crystalline solid, it cannot have a definable melting point, but the temperatures at which it becomes soft enough to work, to anneal, to sinter, and to flow are all strongly dependent on composition. For ISRU applications like oxygen production, glass with Fe contents that are unrealistically high for lunar regolith will yield unrealistically high O_2 returns.
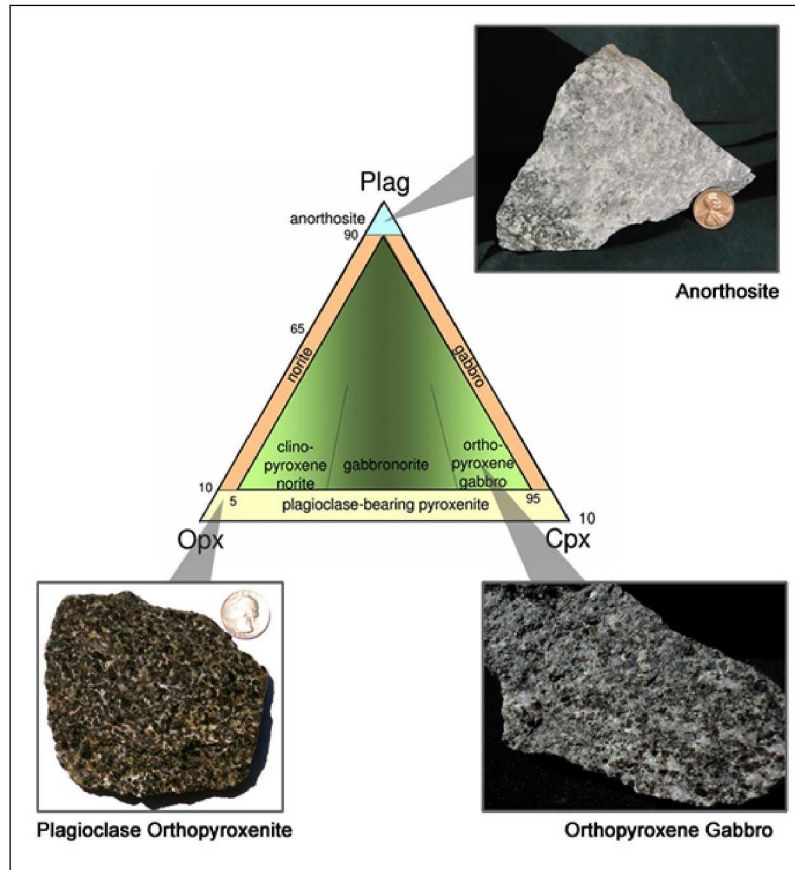
Rock

Definition and overview

A rock is a naturally occurring solid aggregate of consolidated minerals, with or without glass. A rock may contain fragments of other rocks. *Igneous* rocks are those that form from molten material (*magma*). Igneous rocks are divided into *plutonic* and *volcanic* rocks. Plutonic rocks form when magma is emplaced underground, cools slowly, and crystallizes minerals coarse enough to identify with the naked eye. Volcanic rocks are erupted onto the surface, cool relatively quickly, and are composed of fine-grained minerals and glass.

While a large portion of the lunar regolith is composed of free mineral grains and glass particles, there are many identifiable examples of original lunar plutonic and volcanic rocks. Many of these are partially melted or shocked.

IUGS (International Union of Geological Sciences) Definitions

Rocks are defined by the proportions of their constituent minerals, and the standard reference for rock classification is the International Union of Geological Sciences (IUGS) definitions found in Le Maitre et al. (2002). Lunar rocks that crystallized from magma mostly fall into the fields defined in Figure 4. It is worth noting that much is made of the lunar highlands crust being "anorthosite", though by the IUGS definition of anorthosite (a rock composed of >90% plagioclase by volume) few lunar rocks are true anorthosite (Warren, 1990). More highlands crustal rocks are norite, being composed of plagioclase and subordinate orthopyroxene, and the prefix "anorthositic" may be used to denote compositions approaching 90% plagioclase. The lunar geological literature has traditionally used various adapted rock classification schemes, often for sound reasons, but we attempt to hew to IUGS conventions.

Volcanic rocks cool quickly on the surface of the Earth or the Moon, and generally do not contain crystals large enough for classification. They are often named based on their chemistry, and Figure 5 shows such a classification diagram for volcanic rocks.

Figure 4. The orthopyroxene (Opx) - plagioclase (Plag) – clinopyroxene (Cpx) rock classification diagram with examples shown from the Stillwater complex, Montana. The diagram is adapted from Le Maitre et al., (2002).

Major likely terrestrial feedstock lithologies

The lunar maria are composed of regolith derived from lunar volcanic basalt. Basalt is one of these most common rock types on Earth, occurring both on the continents and composing the oceanic crust. The highlands regolith is derived largely from norites and anorthositic rocks. These are rare rocks on Earth, but can be found in some mafic layered intrusive complexes, such as the Stillwater complex in Montana or the giant Bushveld

complex in Africa. Other anorthosites occur throughout the world in the absence of pyroxene-rich rocks.

Some hurdles to overcome when considering feedstock materials are the following:

1. Are the rocks hydrothermally altered, metamorphosed, or weathered such that they contain hydrous or hydrated minerals? If so, will these disrupt their use as a simulant for the desired purposes?

2. Are the mineral chemistry and the whole rock chemistry appropriate to the desired use? Most plagioclase on Earth is much more sodic (Na-rich) than lunar highlands plagioclase. Most terrestrial basalt contains substantially more K and Na than lunar basalt.

3. Is the material available in large quantities and able to be economically extracted?

Impact-related rocks

Most of the rocks on the moon have experienced some shock from meteorite impact. These impacts have a range of thermal and shock effects: they may disrupt rock textures and partially fracture materials; they may partially melt the rock and leave glass along fracture and mineral surfaces; they may totally melt the rock and the liquid may crystallize, resulting in a new igneous rock.

This results in a range of *breccias* (a breccia is a rock of angular fragments of pre-existing rock, minerals, or glass, cemented in a matrix of glass or fine-grained material) of widely disparate mechanical strengths and coherence. Breccias are difficult to precisely define in a way that is meaningful to simulant developers and users, partly because so few data exist for geotechnical or geochemical characteristics of lunar breccias.
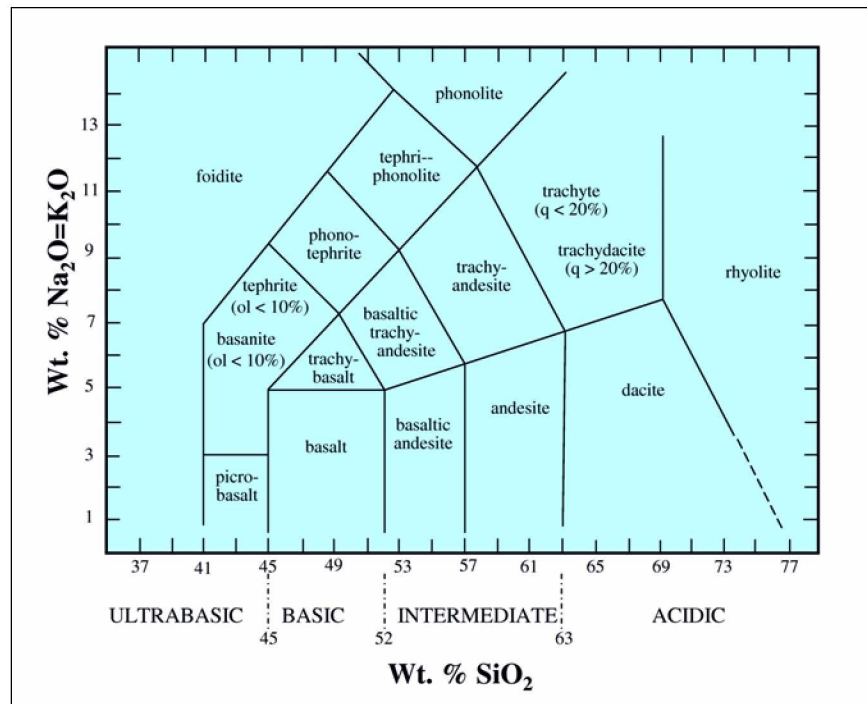
Figure 5. The total alkali (Na2O+K2O)-Silica (SiO2) diagram after Le Bas et al. (1986). This diagram is used with chemical analyses of volcanic rocks when they are too fine-grained to allow for classification by mineral abundances. Almost all lunar volcanic rocks plot in the basalt or picro-basalt fields.

Agglutinates

Agglutinates are products of micrometeorite impact at or very near the surface of the lunar regolith. They are composed of fragments of minerals, rock fragments, and previously existing glass in a matrix of impact-melt glass. They contain *vesicles* (small enclosed cavities in the glass analogous to frozen bubbles) formed by the volatilization and escape of elements like Na^+ and solar wind-implanted H^+. They also contain nano-phase Fe^0 (npFe) from the reduction of Fe^{2+} during melting and interaction with the volatilizing H^+.

Agglutinates are fragile and friable. They are abundant in the lunar regolith, and may locally compose 50% of the regolith by volume.

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Appendix 1: Some lunar and terrestrial minerals and their properties

Mineral	Mohs	[1]S.G.	[2]Mode: Cleavage	Mode: Fracture	Formula
Plagioclase					
Anorthite	~6.5	2.76	{001} perfect, {010} good	Conchoidal to uneven; brittle	$CaAl_2Si_2O_8$
Albite	~6.0	2.62	{001} perfect, {010} good	Conchoidal to uneven; brittle	$NaAlSi_3O_8$
Olivine	`				
Fayalite	6.5-7.0	4.39	{010} moderate, {100} weak	Conchoidal	Fe_2SiO_4
Forsterite	6.5-7.0	3.24	{100}, {010} indistinct to good; {001} poor to fair	Conchoidal	Mg_2SiO_4
Pyroxenes					
Enstatite	5.0-6.0	3.2	{210} good to perfect	Brittle	$Mg_2 Si_2O_6$
Ferrosilite	5.0-6.0	4	{210} good	Brittle	$Fe_2 Si_2O_6$
Diopside	5.5-6.5	3.3	{110} good to perfect,	Brittle	$CaMg Si_2O_6$
Hedenbergite	6	3.65	{110} good	Brittle	$CaFe Si_2O_6$
Spinel					
Spinel	7.5-8.0	3.56	No cleavage	Conchoidal	$MgAl_2O_4$
Hercynite	7.5-8	3.93	No cleavage	Uneven	$Fe^{2+}Al_2O_4$
Ulvospinel	5.5-6.0	4.7	No cleavage	Uneven	$TiFe^{2+}_2O_4$
Chromite	5.5	4.7	No cleavage	Uneven	$Fe^{+2+}Cr_2O_4$
Magnetite	5.5-6.0	5.2	No cleavage		$Fe^{3+}_2Fe^{2+}O_4$
Troilite	4	4.75	No cleavage	Uneven	$Fe^{2+}S$
Pyrrohtite					$Fe^{2+}_xS_{1-x}$
Whitlockite	5	3.12	No cleavage	Conchoidal	$Ca_9(Mg,Fe^{2+})(PO_4)_6(PO_3OH)$
Apatite					
Fluorapatite	5	3.19	No cleavage	Conchoidal	$Ca_5(PO_4)_3(F)$
Chlorapatite	5	3.19	No cleavage	Conchoidal	$Ca_5(PO_4)_3(Cl)$
Hydoxyapatite	5	3.19	No cleavage	Conchoidal	$Ca_5(PO_4)_3(OH)$
Ilmenite-Hematite					
Ilmenite	5.5	4.72	No cleavage	Conchoidal	$Fe^{2+}TiO_3$
Hematite	5.0-6.0	5.27	No cleavage		$Fe^{3+}_2O_3$
Native Iron	4.5	7.87	{001} Imperfect to fair	Hackly	Fe^0

[1]S.G. is specific gravity

[2] Bracketed numbers refer to Miller indices, which describe planes in crystal lattices.