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1. Introduction

Classification and nomenclature of igneous rocks are based on several parameters as recommended by International Union of Geological Sciences (IUGS) Subcommission on the Systematic of Igneous Rocks (Streckeisen, 1973, 1976, Le Bas and Streckeisen, 1991, Le Maitre, 1989, 2002) with a prime objective to keep the uniformity in nomenclature, simple and easy to use. *Rocks should be named according to what they are and not according to what they might have been.* Primarily classification should be based on *mineral content* or *mode*. If not possible to determine the mode because of glassy nature of rocks, then chemical classification (Total Alkali Silica i.e. TAS) can be used. Details of IUGC recommended parameters used for classification and glossary of terms for igneous rocks are given in Le Maitre et al. (2002).

Petrography is the observational science of describing and classifying the rocks heavily based on megascopic (on the outcrop and hand specimen) and microscopic (under the petrographic microscope) features. The most common descriptions of an igneous rock are structure, texture including grain size and shape, colour index, mineral assemblage, paragenetic sequence (order of crystallization), accessory minerals, alteration (secondary processes) and name of the rock following IUGS recommendations. A straight line sequential description of rocks may become needlessly repetitive, thus often some comment on features of petrogenetic significance and any other unusual features should be recorded. Details of terminology commonly used to describe textures of igneous rocks and their genetic significance are well documented and described by Wager and Brown (1968), Cox et al. (1979), Shelley (1992), Philpotts (2003), and Hibbard (1995).

2. Experimental phase relationships of diverse crystallizing magma compositions: a conceptual basis of IUGS classification scheme

In most geological environment silica content of magma commonly varies from 45 wt.% to 70 wt. % representing a wide range of subalkaline to alkaline, mafic to felsic igneous rocks originated in the mantle and crust, and finally emplaced as intrusive or extrusive magmatic bodies. Magma is composed of complex chemical molecules that link together shaping specific structure to the melt. Slow crystallization allows more organization ($S \rightarrow 0$) of these chemical components into crystalline silicate solids whereas rapid cooling or quenching of lava solidified as glass. Many common igneous rocks have eutectic compositions. Some systems, for examples, Nepheline-Silica binary system divided by a albite thermal maximum and Diopside-Nepheline-Silica ternary system with a temperature maxima between the eutectics are not only capable of explaining incompatibility of silica and nepheline minerals in an igneous rock but also form a strong basis for the classification of silica-oversaturated and silica-undersaturated igneous rocks in the IUGS recommended Q-A-P-F space (already discussed in the modules 2 & 3 of this series of e-pathshala). Natural thermal barrier between them follows Alkamade's theorem, which states that the direction of falling temperature on any boundary curve is always in the direction away from the intersection of boundary curve with the line joining the two phases that coexist in the boundary curve (Philpotts, 1994). On the other hand, the basaltic Di-Ne-Ol-Qtz tetrahedron (Yoder and Tilley, 1962) can be divided into three compositional volumes (quartz tholeiite, olivine tholeiite and alkali-olivine basalts) by the *plane of saturation* (Pl-Di-Hy) and *critical plane of undersaturation* (Pl-Di-Ol).

3. Classification of Igneous Rocks

Igneous rocks are commonly divided mainly based on texture, colour, and composition (Fig 1).

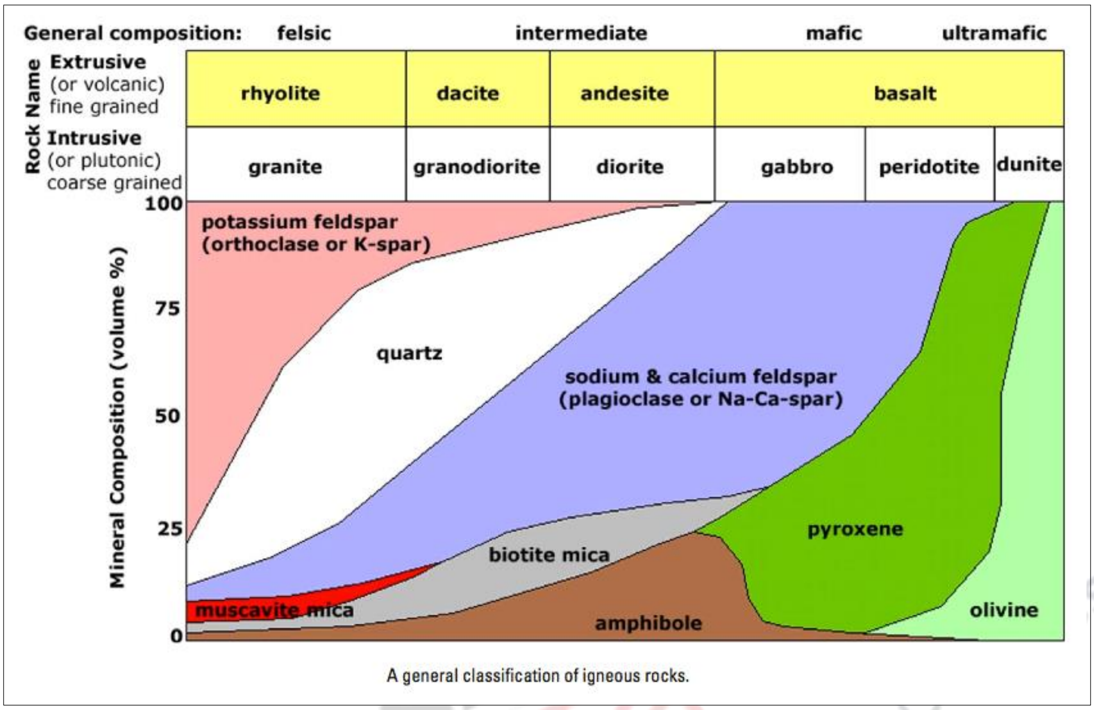


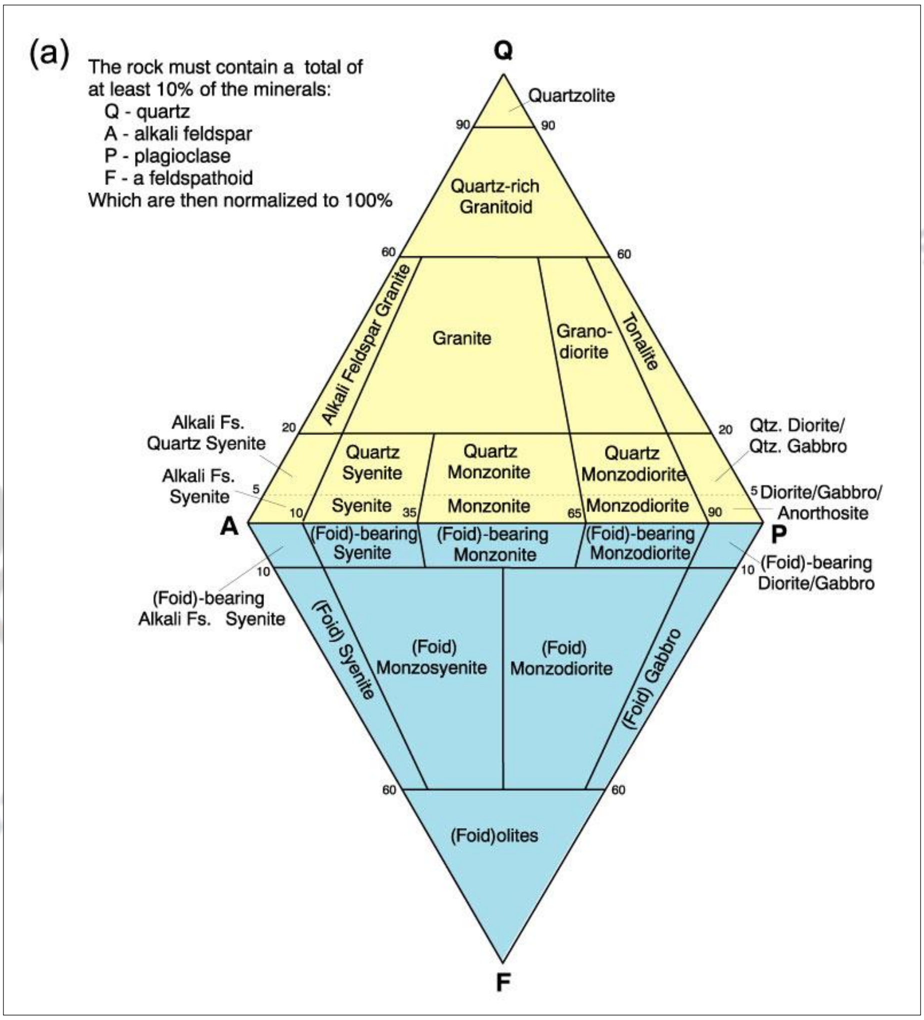
Fig. 1 Types of igneous rocks based on texture, colour, and composition (Ehlers and Blatt, 1999).

3.1 Texture

The textural developments of igneous rocks are highly dependent on the mode of emplacement and degree of cooling of magma. Plutonic or intrusive rocks result when magma cools and crystallizes slowly within the Earth's crust and a very common example of this type is granite. The volcanic or extrusive rocks result from magma reaching the surface either as lava or fragmental ejecta, forming the rocks such as pumice or basalt. There are numerous intermediate igneous rocks.

3.1.1 Phaneritic Texture

Phaneritic igneous rocks are comprised of large crystals that are clearly visible with necked eye or without adding a hand lens or binocular microscope. The entire rock is made up of large crystals, which are generally 1/2 mm to several centimetres in size, and there is no fine matrix material. This texture forms by slow cooling of magma in the plutonic environment. The prefix micro- should be used to indicate that a plutonic rock is finer-grained than usual, rather than giving the rock a special name. The only exceptions are dolerite and diabase (=micro gabbro) which are long established terms, and are still being used. IUGS recommends the classification of phaneratic rocks based on modal volume % of minerals present in granitoids (Fig. 2a) and gabbroids (Fig. 2b).



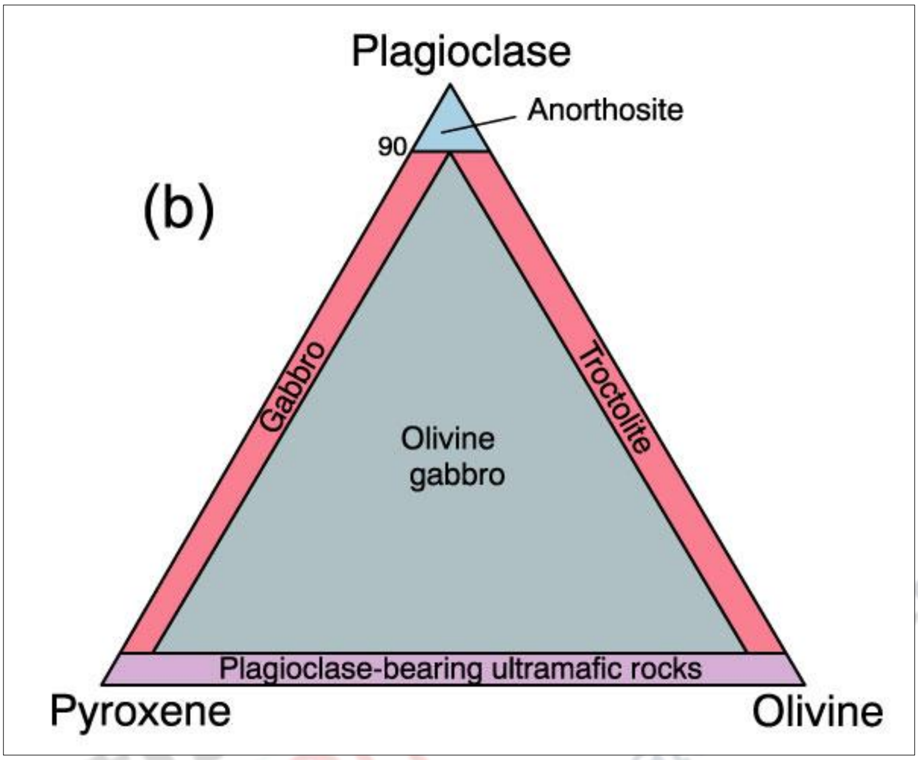


Fig. 2 IUGS recommended classification scheme of phaneritic rocks such as granitoids with more than 10% quartz + feldspar + feldspathoids (a), and gabbroids (b).

The ultramafic rocks can be classified on the basis of proportions of olivine, orthopyroxene and clinopyroxene (Fig. 3).

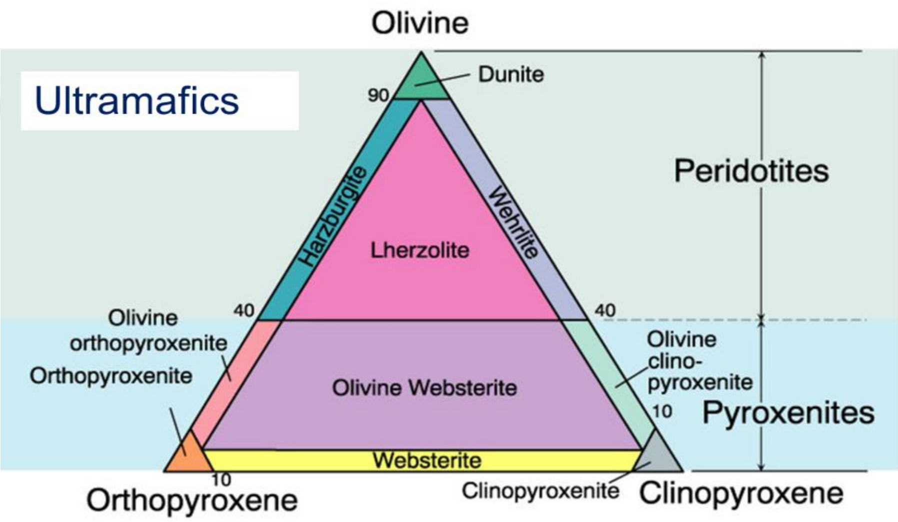


Fig. 3 Modal classification scheme of ultramafic rocks (after Streckeisen, 1973).

The melilite-bearing rock classification is used for rocks with >l0% modal melilite. Triangular classification plots are presented here for plutonic (melilitolite) and volcanic (melilitite) rocks (Fig 4). For the classification of kalsilite-bearing rocks, kimberlites and lamproites the readers are referred to consult LeMaitre (2002), Woolley et al. (1996).

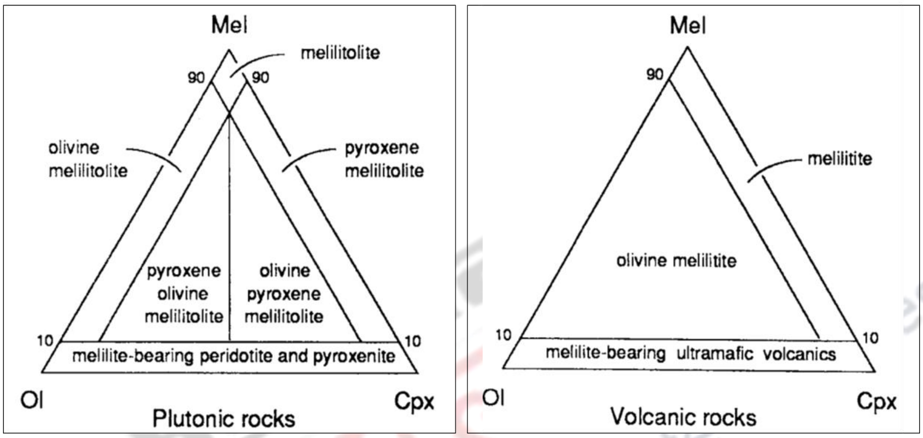


Fig. 4 Classification of the plutonic (melilitolite) and volcanic (melilite) rocks with modal melilite >10% (after LeMaitre, 1989).

3.1.2 Aphanitic Texture

Aphanitic igneous rock consists of small crystals that cannot be seen by necked eye or without adding hand lens. The entire rock is made up of small tiny crystals, which are generally less than 1/2 mm in size. This texture commonly results from rapid cooling in volcanic, subvolcanic or hypabyssal (shallow subsurface) environments. However, there are some examples of rapid cooling in plutonic environments too forming the fine grained igneous rocks. The volcanic QAPF classification (M<90%) should be used only if the mineral mode of rock can be determined (Fig. 5).

The term meta- should be used to indicate that an igneous rock has been metamorphosed e.g. meta-andesite, meta-basalt etc. but still igneous texture is preserved and original rock type can be deduced.

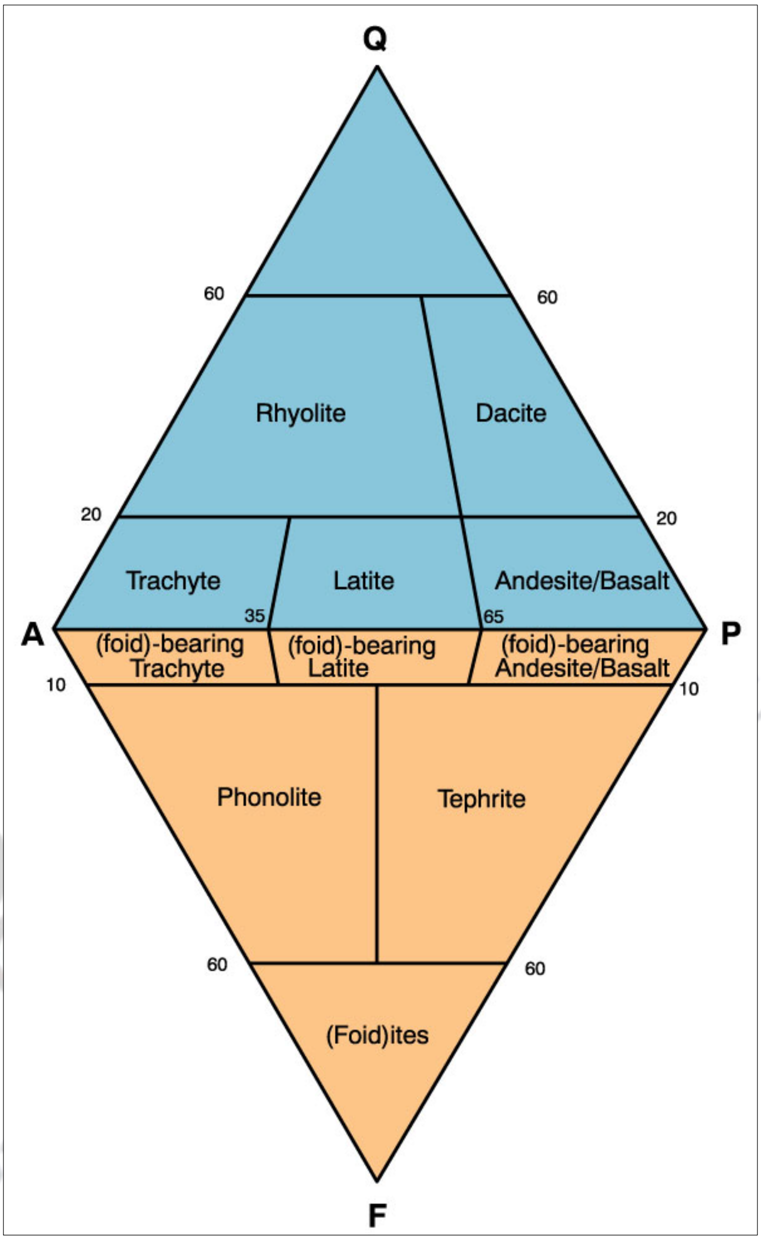


Fig. 5 Mineral based (Q= Quartz, A= Alkali-feldspar, P= Plagioclase, F= feldspathoid) IUGS recommended classification and nomenclature of volcanic igneous rocks of volcanic rocks (LeMaitre, 2002).

3.1.3 Porphyritic Texture

Porphyritic igneous rocks are composed of at least two mineral phases having a conspicuous (large) difference in grain size. The larger grains are termed *phenocrysts* and the finer grains either *matrix or groundmass*. Porphyritic rocks are thought to have undergone two stages of cooling;

one at depth where the larger phenocrysts formed and a second at or near the surface where the matrix grains crystallized. Based on visible minerals (usually phenocrysts) the porphyritic rock can be assigned the name based on QAPF based field (Fig. 5) or TAS (total alkali silica) classification (Fig. 7) preceded by the prefix *pheno-*. For example, a rock containing phenocrysts of sodic plagioclase in a cryptocrystalline matrix may be provisionally called *pheno-andesite*.

3.1.4 Glassy Texture

Glassy igneous rocks are non-crystalline meaning the rock contains no mineral grains. Glass results from cooling that is so fast that minerals do not have a chance to even nucleate and crystallize. This may happen when magma or lava comes into quick contact with much cooler materials near the Earth's surface. Pure volcanic glass is known as obsidian. If the volcanic rock contains 0-20 %, 20-50%, and 50-80% glass the prefix *glass-bearing*, *glass-rich*, and *glassy* terms should be used respectively.

3.1.5 Vesicular Texture

This term refers to vesicles (cavities) within the igneous rock. Vesicles are the result of gas expansion (bubbles), which often occurs during volcanic eruptions. Pumice and scoria are common types of vesicular rocks.

3.1.6 Fragmental (Pyroclastic) Texture

Pyroclastic are rocks blown out into the atmosphere during violent volcanic eruptions. These rocks are collectively termed fragmental (lithic fragments) because it is comprised of numerous grains or fragments that have been welded together by the heat of volcanic eruption. There will be often feel of grainy like sandpaper or a sedimentary rock over the rock surface and one can also spot shards of glass embedded in the rock. Based on the proportions of the grain size of rock fragments (block and bomb, lapilli and ash contents) the *pyroclastic rocks* can be classified and named individually (Fig. 6).

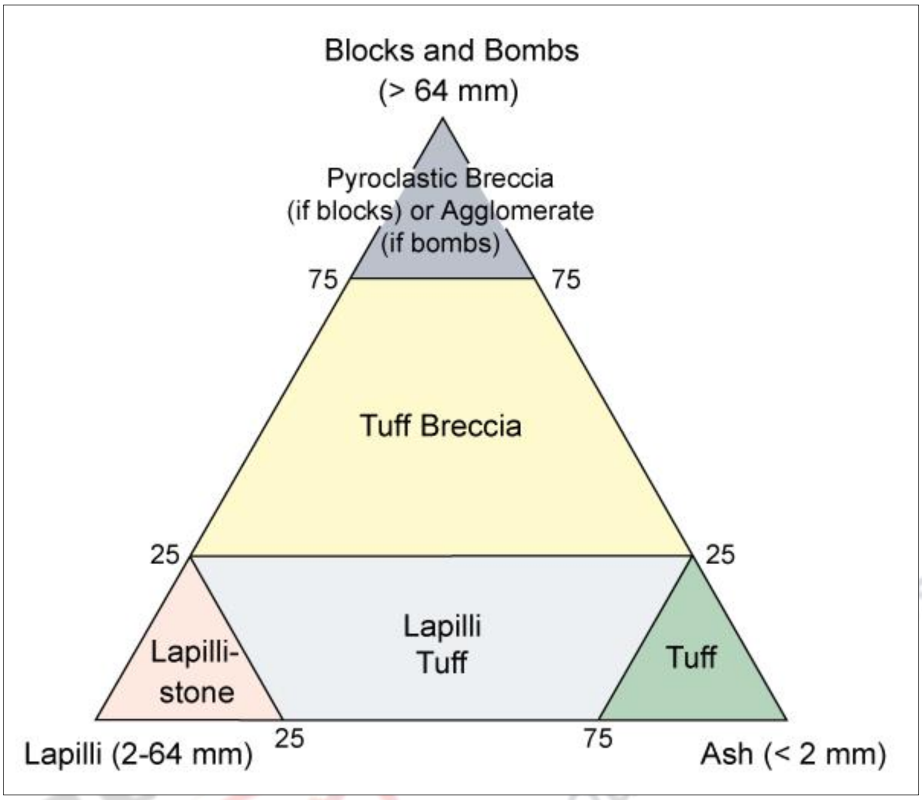


Fig. 6 Classification of the pyroclastic rocks (after Fisher, 1966, and adopted by IUGS as described in LeMaitre, 2002).

3.2 Colour

An igneous rock with majorly of dark coloured minerals forms the mafic to ultramafic igneous rocks. More fractionation magmas or crustally-derived magmas during cooling are commonly enriched in light coloured felsic minerals. Proportion of mafic to felsic minerals in igneous rocks depends upon the on saturation of these components in the magma. Based on this colour difference the rocks can be either mafic or felsic as shown in the in Figure 1. As we move from right to left we can encounter mafic to ultramafic igneous rocks.

3.2.1 Colour Index (M)

The colour index M' is defined as 100 minus colourless (mostly felsic) minerals including the muscovite, apatite, primary carbonate etc. for the purpose of colour index. If the M' varies in the range of 0-10, 10-

35, 35-65, 65-90, and 90-100 the terms hololeucocratic, leucocratic, mesocratic, melanocratic, and holomelanocratic should be used to describe the rocks respectively, not to describe the minerals.

3.3 Composition

Igneous rocks can also be classified based on whole rock chemical analysis. Conventionally this was mainly based on silica content as highlighted in Figure 1. When silica is above 75% main minerals that form are feldspars and quartz while with reduction of silica more mafic minerals form. This is a general conceptual basis of compositional differences encountered in an igneous rock series with changing proportions of felsic to mafic minerals. However, the IUGC recommends use of more precise chemical classification scheme only for the igneous rocks whose mineral modes cannot be determined i.e. mostly for the volcanic rocks, and a chemical analysis of rock is available.

3.3.1 Total Alkali Silica (TAS) Classification

The most popular chemical classification scheme is total alkali silica (TAS) diagram (Fig. 7). The fresh rock analysis with $H_2O^+ < 2\%$ and CO_2 <0.5% should be taken into account, and each analysis should be re-calculated on 100% H_2O and CO_2 free basis. The TAS classification is purely descriptive and that no genetic significance is implied. However, a critical line of silica-saturation can be drawn on TAS diagram which divides the igneous rock series of silica-saturation (tholeiitic or subalkaline) and silica–undersaturation (alkaline and peralkaline). If the analysis falls in certain fields, additional normative calculations such as CIPW norm should be performed for determining the correct root name. The FeO and Fe_2O_3 should be left as determined or should be left on user to justify the method of partitioning of FeO and Fe_2O_3 from determined total iron.

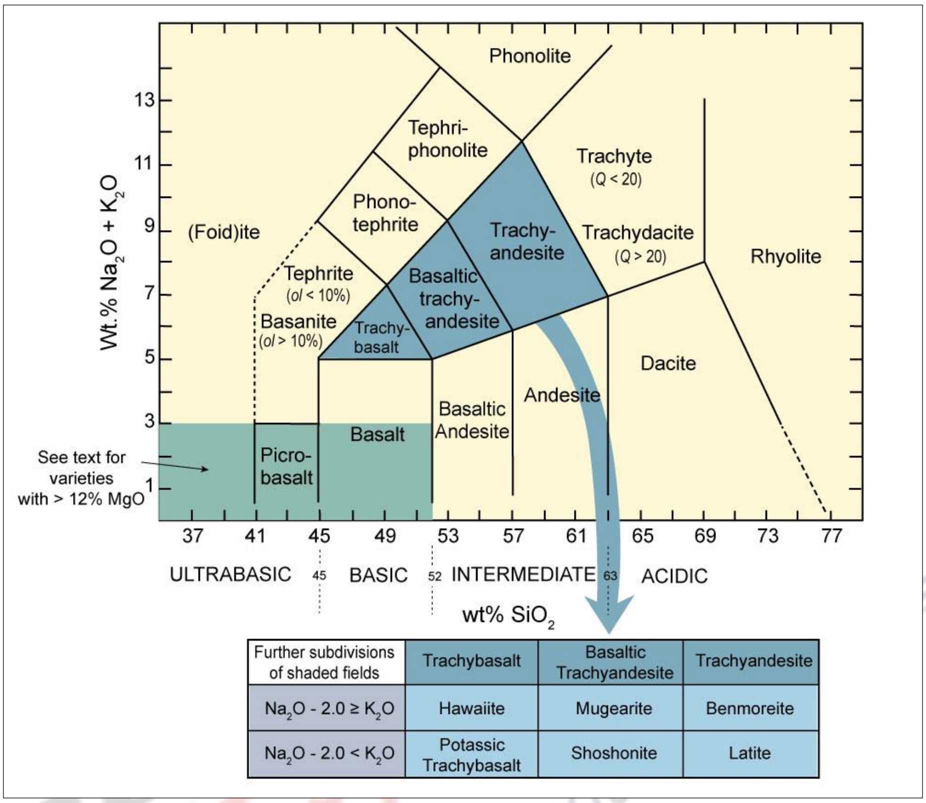


Fig. 7 A chemical classification of volcanics based on total alkalis vs. silica (after LeMaitre, 2002).

High-MgO volcanic rocks can be distinguished by the criteria; 1) if SiO_2>52%, MgO>8% and TiO_2<0.5%, the rock is *boninite*; 2) if 52%>SiO_2>30%, MgO>18% and Na_2O+K_2O<2%, then the rock is *komatiite* if TiO_2 <1% or a *meimechite* if TiO_2>1%; 3) if 52%>SiO_2>30%, MgO>12%, and Na_2O+K_2O <3%, it is *picrite*. It should be noted that this scheme is different from LeMaitre (1989). The lowering of MgO for picrite from 18% to 12% and increasing the alkalies from 2% to 3% makes many rocks into *picrites* that were previously classified as *picrobasalt*.

3.3.2 Classification of Carbonatite

3.3.2.1 Mineralogical Classification

Carbonatite may be plutonic or volcanic in origin. The classification should be used only if the rock contains more than

50% modal carbonates. *Calcite-carbonatite* is used when main carbonate is calcite, and if the rock is coarse grained it may be called *söviet*, and if fine to medium grained *alvikite*. Dolomite carbonatite is named when main carbonate is dolomite. This may also be called *beforsite*. *Ferrocarbonatite* is used when main carbonate is iron-rich. *Natrocarbonatite* is essentially composed of sodium, potassium and calcium carbonates. Qualifications, such as dolomite-bearing, may be used to emphasize the presence of a minor constituent (less than 10%). Similarly, igneous rocks containing less than 10% of carbonate can be called *calcite-bearing ijolite*, *dolomite-bearing peridotite* etc. while those with between 10% and 50% carbonate minerals may be called *calcitic ijolite* or *carbonatitic ijolite* etc.

3.3.2.2 Chemical Classification

If the carbonatite is too fine grained to which mineral mode cannot be determined or if the carbonatite is complex Ca-Mg-Fe solid solution, then chemical classification as shown in Figure 8 can be used for carbonatite with SiO2<20%.

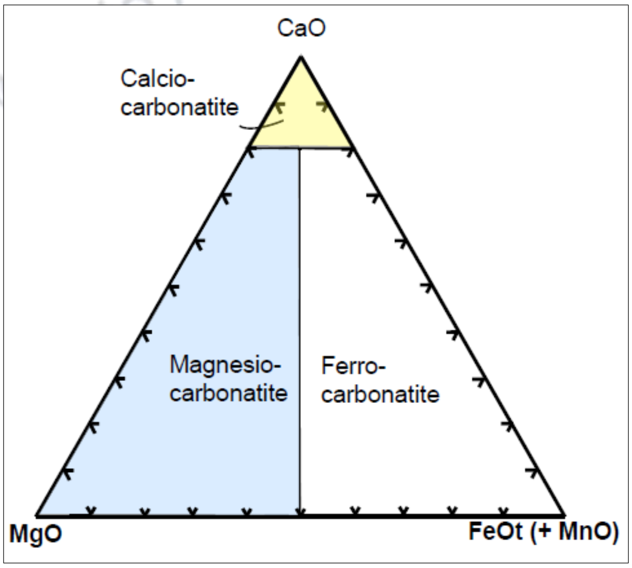


Fig. 8 Chemical classification of carbonatite (after Woolly and Kemp, 1989).

4. A Suggested Format for Keeping the record of an Igneous Rock

A simple format (Table-1) is suggested to keep the record of megascopic and microscopic petrographic features, magnetic susceptibility and nomenclature of an igneous rocks.

Table 1: A simple format as given below can be used to record the description of igneous rocks.

Rock Field name: Location: Magnetic Susceptibility Value ($\times 10^{-3}$SI): Hand specimen/Outcrop description:			Number: Thin Section Sketch
Mineralogy: Composition	Name	Modal %	Optical Properties
Essential: Accessory:			
Textures: (Primary) (Secondary)			
Petrogenesis:			

Kumar, 2007 (slightly modified after Philpotts, 1989)

Frequently Asked Questions-

Q1. What is one way that igneous rocks are classified?

Q2. What are the two categories of igneous rocks based on composition?

Q3. What is felsic igneous rock?

Q4. What is mafic igneous rock?

Q5. What is the same about granite and rhyolite? What is different?

Q6. What is the same about gabbro and basalt? What is different?

Q7. Define the following terms: (a) plutonic rock (b) volcanic rock?

Q8. Draw the basalt tetrahedron and label all planes and volumes within it?

Multiple Choice Questions-

1. Igneous rocks that have lowest content of silica are known as

a. Mafic rock
b. Felsic rock
c. Porphyry
d. ultramafic rock

Ans: d

2. When magma cools quickly what kind of crystal or texture does a rock have?

a. coarse grained or large crystal
b. a mixture of all types of grains or sizes of crystal
c. medium grained or medium crystal
d. fine grained or small crystal

Ans: a

3. The major difference between extrusive and intrusive igneous rock is

a. whether they solidify
b. their chemical composition
c. the type of mineral they contain
d. all the above

Ans: a

4. Which is not an intrusive rock type

a. gabbro
b. diorite
c. granite
d. andesite

Ans: d

5. The difference in texture between plutonic and volcanic rock caused by

a. different mineralogy
b. different rates of cooling and crystallization
c. different amounts of water in the magma
d. different chemical composition

Ans: a

6. The two important criteria used for igneous rock classification are

a. texture and temperature
b. mineral composition and temperature
c. temperature and viscosity
d. texture and mineral composition

Ans: d

7. An igneous rock made of pyroclasts has a texture called:

a. fragmental
b. porphyritic
c. vesicular
d. fine grained

Ans: a

8. The fine grained equivalent of a granite is:

a. rhyolite
b. gabbro
c. andesite
d. basalt

Ans: a

9. The coarse grained equivalent of a basalt is:

a. rhyolite
b. gabbro
c. andesite
d. basalt

Ans: b

10. Which of the following minerals is the most abundant mineral in ultramafic rocks

a. amphibole
b. olivine
c. sodium plagioclase
d. quartz

Ans: c

11. Mafic igneous rocks contain

a. about 50% silica
b. about 60% silica
c. less than 50% silica
d. about 70% silica

Ans: a

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