ENVIRONMENTAL GEOSCIENCES

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Lecture-26

Magma & its Composition and Constitution

Welcome to the SWAYAM NPTEL course on Environmental Geosciences. We are continuing the module 5 that is the concepts of rocks, magma composition and constitution, description of common igneous, sedimentary and metamorphic rocks. Already we have covered in lecture 1 the concepts of rocks. Before that we have already discussed the introduction about the earth's interior, The different spheres that is atmosphere, lithosphere, biosphere and hydrosphere and then the types of weathering, erosion, transportation and geological work of wind, river, glacier and dip, strike, folds and faults.

Topics we have already discussed in the previous lectures. Apart from these topics, we have also discussed the crystals, its characteristics, different crystal classes, then the mineralogy, important silicates minerals, oxides minerals, sulfide minerals and now we are discussing about the rocks. Already we have covered in lecture 1 the first topic that is the concepts of rocks. Now today we will discuss the lecture 2 which is related to the magma and its composition and constitutions. In this lecture 2, the important concepts will be covered like introduction to magma, composition and constitution of magma, chemical composition, mineralogical compositions, crystallization of magma, types of magma, Bowen reaction principle, differentiation, assimilation.

So these topics will be covered in this lecture. One by one we will discuss these things. Now let us know what is magma. First we will start from magma. Magma is a natural rock plate beneath the earth crust.

It is just because we have when we were discussing about the interior of the earth. We have seen that the earth's interior is having three major parts. That is first is the core. Second is the mantle core. And the third is the crust.

So this is the crust. So three different layers we have seen when we were discussing about the interior of the earth. At the greater depth, we are getting the magma. So magma is a natural rock fluid beneath the earth crust. It consolidates to form intrusive igneous rocks like granite.

Granite is an igneous rock. When magma erupts to the surface, then the same magma, suppose this is the magma when it will just pass through the mantle to the crust and then erupt out to the surface, then the same magma is termed as lava. So lava cools and solidifies to form the volcanic rocks like basalt. Inside we have seen granite we are getting because it is intrusive igneous rocks. Outside we are seeing the volcanic igneous rocks that is the basalt.

Magma consists of liquid, solid crystals and dissolved gases. So this magma is consisting of liquid also, solid crystals also and dissolved gases also. Types of magma include basaltic type, andesitic type, rhyolitic type, and these different types are classified on the basis of the silica content. Magma viscosity depends on temperature, silica, and gas content. Magma originates from the partial melting of the mantle or crystal rocks.

It contributes to the formation of mineral deposits and geothermal energy resources. Now, what is the composition and constitution of magma? So, magma is a mixture of solid, liquid and dissolved gases we have seen in the previous slides, primarily composed of very hot silicate melts. It contains large quantity of water and varying amounts of highly reactive fluids like hydrochloric acid, hydrofluoric acid and gases in solution. Magma does not have a constant composition. always it is varying, composition is varying always as its constituents vary depending on its geological environment.

These reactive fluids and gases within magma influence its behavior and interactions with the surrounding rocks contributing to its dynamic in nature. So these characteristics play a critical role in various geological processes including its movement, crystallization and the formation of diverse mineralogical and structural features in the earth crust. Although the composition of different magma undoubtedly vary, many are close to the two different compositions that is first is the chemical composition and second is the mineralogical composition. Now, first we will understand the chemical composition. In terms of oxide,

The composition of a magma primarily consists of SiO_2 - 59 %, followed by significant amount of Al_2O_3 - 15 %, then CaO - 5 %, other notable components include Na_2O - 3.8 %, MgO - 3.5 %, and FeO - 3.5 %. Smaller percentages are also contributed by Fe_2O_3 - 3 %, K_3O - 3 %, S_2O - 1 %, and TiO_2 - 1 %. Trace elements such as phosphorus pentoxide, P_2O_5 - 0.3 %, CO_2 - 0.1 %, and MnO - 0.1 % are also present but in much lower amounts.

So this is the, just the chemical composition in terms of the oxide. Now, in terms of elements, we will understand.

In magma, elements like oxygen, silicon, aluminum, iron, calcium, sodium, potassium, magnesium, titanium, etc. together constitute more than 99 % of the fixed constituent of any magma. The elemental composition of magma primarily consist of variety of oxides formed from various chemical elements. The most common elements found in magma include, first the silicon present mainly as SiO_2, silica, making up the majority of the magma's compositions, particularly in felsic and intermediate magmas. SiO_2 is remaining there. Now second is the oxygen.

The most abundant element in magma is oxygen found in many oxides such as SiO_2, Al_2O_3, Fe_2O_3 and others. Next is the aluminium found in Al_2O_3, aluminium oxide which is a significant component in many magmas. Next is the iron. Iron is found as FeO, iron two oxide and Fe_2O_3, iron three oxide, contributing to the color and density of the magma. Next is the calcium, present as CaO, important in determining magma's viscosity and its ability to crystallize.

Next is the magnesium, magnesium found in MgO, magnesium oxide, contributing to the basic nature of certain magmas like basalt. Next is the sodium, present as Na_2O, sodium oxide, contributing to the fluidity of the magma. Next is the potassium, found in K_2O, potassium oxide, often present in felsic magmas. Titanium present as TiO_2, titanium dioxide found in mafic magmas and influencing the mineral formations. So these elements form the mineral components of magma which can vary in the composition affecting the magma viscosity, crystallization, temperature and eruption characteristics.

So these are the elements which are remaining present in the magma. Now mineralogical composition. We have discussed the chemical composition, now we are discussing the mineralogical compositions. Mineralogical composition of a magma is dominated by feldspar mineral, that is 59 % remaining, which is a major rock forming mineral, contributing to the formation of both granite and basalt. We have already known that granite and basalt are the igneous rock.

Yes, next important mineral is the pyroxene and amphibole. Together make up near about 17 %. And these are the key minerals in mafic and intermediate type of magmas. Influencing magma viscosity and crystallization. Then the quartz.

Primarily composed of silica. Is found in felsic magmas. And plays a role in magma texture and flow. Next is the mica 4 %. contributing to the crystallization processes and is found in both granite and basalt.

The remaining 8 % consists of various other minerals, various other types of minerals, contributing to the overall diversity of magma's mineral content. So in the diagram also you can see the x-axis is the types of minerals, whereas y-axis is the percentage. So we are seeing here that feldspar is remaining near about 59 %, highest in the percentage. Next is the crystallization of magma. Now we have already understood the composition.

Now crystallization, how the mineral magma is crystallizing, this we will discuss here. So crystallization of a magma is a crucial process that leads to the formation of various rock types. Because from magma only we are getting the different types of rocks through differentiation and assimilation processes. These are the processes which are ultimately making the different variety of rocks inside the earth's surface. So the rate of crystallization is influenced by several factors.

Suppose different types of rocks are just coming out from the magmas. So differentiation, assimilation plays very very important role. And the, some of the factors also play very important role for the different types of rock type. So, the first factor is the temperature. Temperature, the cooling rate affects the crystal size and texture of the rock.

Viscosity, higher viscosity slows the movement of ions and affecting the crystal growth. Next is the composition. This is also important factor. The chemical makeup of magma determines the mineral that crystallize. Which type of mineral will crystallize.

Then volatiles, the concentration of gases like water vapor can lower the crystallization temperature. Next is the pressure, the depth at which cooling occurs influences the stability of minerals and their crystallization. These factors collectively save the resulting rock textures and the mineral content. Here in the figure also you can see from higher temperature to lower temperature the different types of crystallization of the minerals from magma A to magma B. Next we will discuss the types of magma. So magma usually consists of a number of components and therefore most igneous rocks are multi-component.

Unicomponent rocks are extremely rare. The crystallization can be better studied in a unicomponent, bicomponent and multicomponent system. First we will discuss the unicomponent magma. In the study of unicomponent magma, two distinct temperature regions are observed. So different, two distinct temperature regions are generally observed.

The metastable region where crystal formation occurs slowly and the labile region where crystallization occurs rapidly. So, slow cooling leads to the formation of coarse-grained texture. If the cooling is taking place slowly, then the texture will be coarse-grained. If the rapid cooling will take place, definitely it will form the glasses. So, these are the different types of textures depending upon the mode of their cooling.

Now, the bicomponent magma. The crystallization of bicomponent magma is governed by the principle that the melting point of any of the component is lowered down to the variable extent due to the presence of variable amounts of the other one. So, this results in variable crystallization behavior depending on the proportion of components. So, this is about the bi-component magma. Now, bicomponent magma shows two types of relationships, it shows two types of relationships and method of crystallization.

First, the eutectic crystallization and second, the solute solution or mixed crystals. Now, we will understand the eutectic crystallization. In eutectic crystallization, two components with distinct freezing points experience a reduction in their freezing points when combined. So as soon as it will remain alone, the freezing point will be different. But as soon as it will just combine, then there will be the reduction in their freezing points.

At a specific temperature and composition, known as eutectic temperature and eutectic point, both components crystallize simultaneously. So this type of crystallization gives rise to the intergrowth of two minerals and results in a peculiar graphic texture. Notable examples include perthite. In case of parthite, orthoclase and albite remains in the ratio 42 is to 58 and graphic the ratio will be 72.5 and 27.5 for orthoclase and quartz. So these eutectic relationships highlight the dynamic interplay between temperature, composition, and crystallization in bicomponent magmas.

The resulting intergrowths provide insights into the cooling history and chemical interactions within magmas that contribute to the diverse mineralogical and textural characteristics observed in igneous rocks. So this is about the eutectic crystallization. Now second is the solid solution or mixed crystals. Here you can see that in a binary magma it is observed that both components can sometimes be isomorphous and mixable in all proportions in the solid state forming homogeneous crystals. The best examples are plagioclase and pyroxenes.

These are the best examples. In a temperature composition diagram, just side of our text, you can see there are two curves representing the crystallization. The first curve is the solidus, that is the melting point curve, this one is the melting point curve, and liquidus, the freezing point curve. Here you can see such crystals do not melt at a definite temperature, but melting is spreading over a wide range of temperature, with the solidus as the lower limit, this solidus is the lower limit, and the liquidus is the upper limit. If a mixture of two components, having a particular percentage of their composition, start cooling down, the crystallization will only start when a particular temperature is reached.

For example, if a magmatic mixture of composition P is cooled to 1400ºC, Then the crystals of composition Q will begin to form. Here you can see the composition Q has begun to form. As the temperature continues to fall, the liquid gets enriched with the albite component. by withdrawal of anorthite content. So here you can see, if the temperature is just decreasing, then the liquid is niching with the albite and withdrawing the anorthite crystals.

In this way, the continuous crystallization of solids, their reaction with the melt, and consequent changing over to newer solids of ever-changing compositions, continue till the composition of the solid phase is the same, as that of the original composition of the melt. So this is very important. Now third type of magma is the tricomponent. These are ternary magmas in which the relationship between all the three components may include both solid solution and or eutectic characteristics. So these are about the tricomponent magma.

Now, one of the very important principle known as Bowen reaction principle. According to the studies made by Dr. N. L. Bowen on the crystallization and reactions in basaltic magma as it cools, which leads to the formulation of Bowen reaction principle. This principle explains how a magma may solidify as a single rock type or may give rise to many different rock types. As magma cools, equilibrium is maintained between solid crystals and liquid magma. Early formed crystals react with the liquid, causing compositional changes.

The sequence of crystallization, as has been worked out by Bowen in the year 1922, it is known as Bowen reaction series. The temperature range from which the Bowen reaction series has been worked out is from 1100ºC to 573ºC. After the crystallization of the minerals of the spinel group at a temperature of about 1100ºC, the first signs of crystallization of silicate minerals begin to take place. So, this reaction principle tells about the formulation of single rock type or different different types of the rocks from the magma.

Now, the two series we have discussed just now. So here we can see the two different series. One is starting from the olivine ending to the potash feldspar and other is starting from the anorthite and it is also ending to the potash feldspar. So initially the spinel group, spinel group mineral crystallize at around 1100ºC, followed by the crystallization of the silicate minerals. Two parallel series describe this process.

First is the discontinuous series and second is the continuous series. So, in first series, discontinuous series, ferromagnesian minerals change structure and composition with cooling, whereas in second series, continuous series, plagioclase minerals crystallize while changing of composition. So both series converge to form a single series. Both series are just converging to form a single series. This sequence reflects the order in which minerals crystallize from cooling of basaltic magma.

Here you can see olivine, then magnesium pyroxene, then iron pyroxene, then hornblende, which is amphibole, then biotite, and then it is converging to the potash feldspar. Second series, that is the continuous series, this is the discontinuous series, and this is the continuous series. Here you can see anorthite, then bytownite, then labradorite, then andesine, then oligoclase, then albite, and then ultimately the potash feldspar. Hereafter, you can see the muscovite, quartz, zeolite and the water rich solution. So this is telling about the two different series.

Bowen reaction series is telling about the two different series. One is the discontinuous series, another is the continuous series. And in this way, the different, different materials are crystalizing in the rock and we are getting single type rock type and also we are getting the multiple type of rock type. So in Bowen reaction series unless early form crystals are removed from the melt or the magma becomes compositionally stagnant that is magnetically dead reactions between the magma and the crystal continue to produce new minerals now one by one we will discuss the two series first is the discontinuous reaction series the first mineral to crystallize is the magnese olivine If olivine is not removed, it reacts with the magma to produce a mineral with which the phase is saturated under the existing temperature.

For example, Mg-olivine converts to iron-olivine and then to magnesium pyroxene (clino-enstatite). Magnesium pyroxene converts to calcium pyroxene, then to amphibole that is hornblende and finally to biotite as cooling progress. These transitions form a chain of reactions called reaction pairs where one mineral reacts to form the next one. The content of the reaction process depends on the degree of fractionation. Complete reactions lead to the dominance of late-stage minerals in the final rock as earlier minerals dissolve and are reabsorbed.

However, if cooling is too rapid or other conditions prevent complete reactions, relics of early-formed minerals from both reaction series may remain in the final rock and preserving incomplete crystallization sequences. Reaction rims are formed surrounding the early-formed crystals. Thus, olivine is surrounded by pyroxenes, pyroxene by amphibole, and amphibole by biotite-mica. Minerals of discontinuous series are characterized by incongruent melting i.e. they have no definite melting point. Melting is incongruent melting i.e. having no definite melting point but upon heating break up into some other minerals and liquid.

For example, magnesium pyroxene breaks up into the olivine and liquid. Each mineral of a discontinuous reaction series may itself be a member of a continuous reaction series. And both kinds of reaction series may coexist within the same magma. So these are about the discontinuous reaction series. Now we will discuss the continuous reaction series.

This is the series consisting of plagio-clases, which begin crystallizing more or less simultaneously with olivine or a little later. In this case, the first formed crystals are richest in lime. As the reaction goes on and the temperature rises, the crystal becomes progressively more sodic. This implies that the reaction is normally progressive and the continuous series of homogeneous solid solution is produced. This fact is well recorded in zoned plagioclases in which the core which is more calcic is surrounded by successive soda-rich zones.

Now what are the importance of Bowen reaction principle. The first importance is it illustrates how a magma may solidify as a single rock type or may give rise to many different rock types. The primarily rich magma may solidify as a gabbro consisting of olivine and calcium plagioclase or it may give rise to rocks varying from dunite through gabbro, diorite, tonalite, granodiorite to granite depending upon the degree of fractionation and the extent to which the early formed minerals are removed from further reaction with the melt. The atomic structure becomes more complicated from early-formed minerals like olivine to minerals like quartz, zeolite.

So, olivine will be less complicated whereas quartz, zeolite will be more complicated in their atomic structure. Third importance is the early-formed crystals are denser than the late-formed minerals in the Bowen reaction series. Fourth importance is it indicates the process of fractional differentiation in magma. How? It is widely accepted that there is only one parental magma of basaltic composition and all the different varieties of igneous rocks were supposed to have originated from this magma of uniform composition.

The origin of diverse igneous rocks with regards to mineralogical composition and texture can be attributed to two causes. First cause is the differentiation and second cause is the assimilation. Now differentiation, it may be defined as the process whereby a magma originally homogeneous splits up into, contrasted parts which may form separate bodies of rocks or may remain within the boundaries of single unity mass. The process of differentiation is usually favored by two factors. The first factor is the rate of cooling and second factor is the settling of early crystallized heavy minerals.

Now stages of differentiation. According to Tyrell, there are two stages. In the first stage, there is a preparation of units such as crystals, liquid submagma, etc. In the second stage, the prepared units are separated and accumulate separately to form nesting masses. Differentiation in igneous magma involves processes like fractional crystallization, gravity separation, filter pressing, liquid emissibility, and the gaseous transfer.

So the first stage of differentiation is the fractional crystallization. With the cooling of the magma, crystallization begins and the earliest minerals start crystallizing. Differentiation may be brought about by at least two distinct processes. First is the localization of crystallization aided by diffusion and convection. Second is the localized accumulation of crystals in several different ways with the concomitant segregation of the liquid magmatic residuum.

Crystallization may be localized at a cooling margin where the temperature is lower than the central parts of the magma. Thus, two phases, a solid and a liquid, are formed. The concentration of molecules of the growing crystals at the site of crystallization is supposed to be due to, first, free ionic diffusion of that substance from all parts of the magma, second, by convection current with a concomitant movement of other substances in the opposite direction. But these suppositions were later on found untenable. During crystallization, there is a tendency for equilibrium to be maintained between the solid and liquid phases.

To maintain equilibrium, early formed crystals react with the solid and changes in composition take place. In case of plagioclase, for instance, the first formed crystals are those richest in lime But as reaction proceeds with falling temperature, the crystals become progressively sodic. Thus a continuous series of homogeneous solid solution is produced which constitute the continuous reaction series. Second is the gravitational settling.

It is the tendency of the heavy metals to sink to the bottom and those having lower specific gravity then the melt rise up and float at the top of the magma chamber. The perfection of this process depends on the size, shape and specific gravity of the individual crystals and also on the viscosity of the magma. Olivine seems to be the most important mineral affected by this process and its gravitational settling forms stratification in igneous rocks. Next is the filter pressing. As crystallization continues, a loose mesh or framework of crystals with residual liquid in the interstices will ultimately be formed.

At this stage, deformation of the mass occurs either by the lateral earth pressure or downward pressure of the lifted strata, the interstitial liquid will be squeezed out. The liquid will tend to move towards the region of least pressure. This process of separation of solid crystals from the fluid magma is known as filter pressing and is found to be very helpful in bringing about effective and appreciable differentiation in magma. Next is the liquid immiscibility. A mix of two different components may be homogeneous at a particular temperature but with falling of temperature, both of them become immiscible fractions and separate from each other by the difference in specific gravity.

In a similar manner, components of an igneous magma may be perfectly miscible at higher temperature but with gradual cooling, the magma mass may separate out into distinctly different and mutually immiscible components. Next is the gaseous transfer. Being excellent solvents, volatile constituents continually go on collecting the otherwise sparsely disseminated metallic and nonmetallic constituents as they rise upwards through the magma chamber. Again the escaping gas bubbles may attach themselves to growing crystals and float them upwards. The volatile constituents are capable of making selective transfer of material from lower to higher levels.

In this way, pronounced heterogeneity may develop in magma. Now we will discuss about the assimilation process. Assimilation is an important factor in bringing about diversity in igneous rocks. This is the process whereby rock masses are incorporated by magmas. There is also blend of two liquid magmas.

Since these processes involve the remixing of rocks, they represent the reverse of the differentiation processes and heterogeneity results when the mixing is incomplete and non-uniform. The laws of assimilation are governed by the same general laws of fractional crystallization. Reaction between magma and wall rock is a normal accompaniment to igneous intrusion. In the course of this reaction, the magma becomes contaminated by incorporating materials originally present in the wall rock. This broad process of modification is described as assimilation.

The incorporation of foreign rock matter by a magma occurs in three ways as first is the mechanical incorporation, second is the reactions involving partial solution of the incorporated matter and third is the total dissolution. Now, first mechanical incorporations without chemical reaction. This is the first way. Second, the reactions involving partial solution of the incorporated matter and the precipitation involving the replacement of one solid phase by another. And third is the total dissolution involving total disappearance of the solid phase.

In general, it is a complex process of reciprocal reaction between magma and embedded rock. During the process of reaction, due to ionic exchange between liquid and crystals, minerals are changed into those crystalline phases with which the liquid was already saturated. The end product is a contaminated igneous rock which was at no time entirely liquid and which is made up of materials contributed partly by the original rock and partly by the walled rock. Formed in this way is naturally of hybrid origin, which are particularly common along the borders between intrusive and invaded rocks. Now just summarizing the lecture, two that is magma.

Magma is a molten or semi-molten rock beneath earth crust forming intrusive igneous rocks, e.g. is granite or volcanic igneous rock, e.g. is basalt, upon cooling. It is composed of liquids, solid crystals and dissolved gases. Its viscosity and eruption characteristics depend on silica content, temperature and gas composition. Secondly, we have learned that composition and constitution of magma, we have seen that magma is dynamic mixture of silicate melts, reactive fluids and gases. It varies in chemical and mineralogical compositions depending on its geological environment.

Third, we have learned that the crystallization and types of magma, magma crystallizes based on factors like temperature, composition, viscosity and volatiles influencing rock texture and mineral content. Types of magma we have seen uni-, bi- and tricomponent differ by silica content and crystallization mechanisms such as eutectic crystallization and solid solution formations. Then we have studied Bowen reaction series which explains the sequence of mineral crystallization from cooling basaltic magma. Then we have learned the Bowen reaction principle which explains the sequence of mineral crystallization from cooling of basaltic magma divided into discontinuous, i.e., ferromagnetic mineral series, i.e., continuous plagioclase mineral reaction series. Bowen reaction series highlights the fractional differentiation in magma, where primary magma evolves into diverse igneous rock types based on crystal removal and compositional changes.

And lastly, we have discussed about the processes of magmatic differentiation and assimilation. Magma evolves through processes like fractional crystallization, gravitational settling, filter pressing. liquid immiscibility and gaseous transfer. These processes contribute to the formation of distinct rock types immunological compositions. Thank you very much to all.