UNIT 1

BASICS OF ORE GEOLOGY

Structure

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1.1 INTRODUCTION

In our daily life, we use culinary items for cooking, electronic gadgets such as mobile phones, computers, televisions and for transportation,we use cars, trains, and aeroplanes etc. They are made of commonly used metals like **iron and copper** etc. **All these metals are naturally occurring and are mined from the Earth's crust.** Except for a few, metals don't occur in their native form, they occur in the form of minerals and all these minerals combine to form rocks. However, it is important that all the rocks must not be appreciated for mining because they do not host valuable mineralisation. On the whole, the mineralisation can be considered as an ore for economical use when it occurs in substantial concentrations combined with other factors such as mining costs, time and place, and market value of the mineral. In mineralisation, various geological processes are involved and to know these influential processes, it is imperative to study the science known as '**ore geology'**.

Now in this unit, we will discuss the basic terminology used in ore geology, reserves and resources, and United Nations Framework Classification (UNFC) for resources. We will also discuss the basics of ore microscopy.

Expected Learning Outcomes

After reading this unit, you should be able to:

- ❖ define the commonly used terminology in ore geology;
- ❖ discuss the concept of reserve and resource;
- ❖ describe the UNFC classification of resources; and
- ❖ know the basics of ore microscopy.

1.2 OVERVIEW OF ORE GEOLOGY

You are quite aware that whatever the minerals are extracted it is only from the Earth's crust. But the mineralisation that takes place in the Earth's crust can only be called as an ore deposit when it occurs in adequate quantity and quality and mined for profit. However, if the mineral concentrations occur in minor quantity or low grade for extraction purposes, it is termed as mineralisation or occurrences.

Ore deposits are essentially volumes of valuable rocks formed by significant concentration of element/s greater than that of their characteristic crustal abundance. Natural processes of formation of mineral deposits are considered to be similar to that of the common rocks. There are many significant methods of mineral exploration. But considering the geochemical abundance of Earth's crust, the mineral enrichment can be studied by their chemical properties. The exploration results can be materialised if it is found that there is an economic viability and further procedures can be followed for mining of the ore deposit. A mineral resource is generally considered as ore reserve if its economic viability for extraction status is examined and hopefully reported.

1.3 BASIC TERMINOLOGY

We have discussed the overview of ore geology in the earlier section. Now in this section, we will learn about the basic terminology that you should be aware of while studying ore geology.

- **Ore Deposits**: The occurrence of large chunks of mineral concentrations in the crustal part of the Earth are called ore deposits. They comprise ores of metals and non-metals, industrial minerals, precious and semi-precious minerals, fuel minerals and rocks used as aggregate for building stone, and coal and oil shale.
- **Occurrence or Mineralisation**: If the concentration of mineral/minerals is low or with low grade and not feasible for mining it is known as occurrence or mineralisation.

- **Ore**: The naturally occurring material from which a mineral or minerals, normally metals, of economic value can be extracted with profit. In simple words, ore can be defined as an aggregate of ore minerals and gangue.
- **Gangue**: It is a commercially unwanted material that exists in close association with the ore mineral.
- **Sample**: In ore reserve context, the sample represents a small portion of an ore deposit which acts as a typical representative of a certain part of the deposit.
- **Ore minerals**: There are nearly 3800 known minerals that have been identified and classified. Out of these minerals, only a few minerals in Earth's crust constitute the majority of rocks as rock-forming minerals. Just as the common rock-forming minerals, some of the ore minerals are commonly distributed in igneous, metamorphic and sedimentary rocks as accessory minerals. But some of the ore minerals are specifically found in ore deposits. The ore minerals are concentrated as native elements (metals), oxides and hydroxides, silicates, sulfides, sulfosalts, carbonates and other minerals in the Earth's crust (table 1.1). Let us study with examples that makes an ore mineral.

Table 1.1: Classification of ore minerals into different classes. (Source: Modified after Robb 2005)

Element	Native metals	Sulfides, sulfosalts, arsenides	Oxides, hydroxides	Silicates, carbonates
Fe		Pyrrhotite FeS	Magnetite Fe_3O_4	
		Pyrite FeS_2	Haematite Fe_2O_3	Siderite $FeCO_3$
			Goethite $FeO(OH)$	
Mn			Pyrolusite MnO_2	Rhodochrosite $MnCO_3$
Al			Gibbsite $Al(OH)_3$	
			Boehmite $AlO(OH)$	
Cr			Chromite $FeCr_2O_4$	
Cu		Chalcopyrite $CuFeS_2$		
		Bornite Cu_5FeS_4		

		Chalcocite Cu_2S		
Zn		Sphalerite ZnS		
Ti			Ilmenite $FeTiO_3$	
			Rutile TiO_2	
Pb		Galena PbS		
Ni		Pentlandite $(Ni,Fe)_9S_8$		
Mg				Magnesite $MgCO_3$
Sn		Stannite Cu_2FeSn_4	Cassiterite SnO_2	
Mo		Molybdenite MoS_2		
U			Uraninite UO_2	
Ag	Silver	Argentite Ag_2S		
Au	Gold			

'Ore Mineral' has a higher concentration of metal in it and has a fixed mineral composition like any other mineral. Let us discuss this with an example. Hematite (Fe_2O_3) is an ore mineral of iron. It has higher concentration of Fe. Let us take olivine with Fe content in it. Olivine ((Mg Fe) SiO_4), which is commonly present in ultramafic and some mafic rocks, is not an ore of iron as it has lesser concentration of iron in comparison to hematite.

It is important to note that an ore should have concentration of the specific metal in quantity that should yield metal at a higher profit after taking into account the cost involved in liberation of the metal from the ore. A few examples of ores are: chalcopyrite (ore of copper), hematite and magnetite (ore of Iron), bauxite (ore of aluminium), chromite (ore of chromium), etc.

- **Industrial Minerals**: Besides metallic minerals from which metals are extracted, there are other type of minerals known as industrial minerals such as calcium, fluorite, pyrite, quartz, garnet, etc. These minerals are used in industries such as in cement, chemical and refractory industries.

  You may think that pyrite (iron sulfide) to be an ore of iron, but it is actually used for extraction of sulphur and not iron. The minerals which have huge application in diverse industries such as chemical, fertilizer, glass and ceramic, refractory etc. are classified as industrial minerals. Examples of industrial minerals are: quartz, garnet, calcite, gypsum, pyrite, phosphate, halite(common salt) etc. The industrial minerals at times may also include metallic ores, these are exception depending on the grade of the ore. A certain grade of chromite can be used in refractory and chemical industries.

Industrial minerals include rocks such as granite, gabbros, dolerite, granulite, charnockite, sandstone, limestone and many more and their derivatives like sand or gravel (commonly referred to as aggregates/bulk materials) which have application in different industries such as construction and dimensional stone industry.

What are industrial minerals?

Noetstaller in 1988 defined industrial minerals as any rock, mineral or other naturally occurring substance of economic value, exclusive of metallic ores, mineral fuels and gemstones.

Other than the ore and industrial minerals, there are other categories of minerals known as fuel minerals and radioactive minerals. Coal, petroleum and natural gas form good examples of fuel minerals and uranium and thorium are some examples of radioactive minerals. Apart from these, the gemstones fall in the class of precious and semi-precious minerals. Some minerals like diamonds, rubies, sapphires, and emeralds are good examples of precious minerals. It is interesting to know that low quality gemstones such as diamonds, garnets, tourmaline or quartz which fall in the category of precious and semi-precious class also are used in industrial applications.

- **Host Rock**: It is the rock that hosts and encloses the ore deposits. Similar to gangue minerals it has no commercial value.
- **Tenor**: It is an estimation of concentrated metallic content present in an ore. Generally, the tenor of an ore is calculated in percentage.
- **Grade**: Grade is the metal concentration/content in an orebody. The grade of ore is expressed in percent or as parts per million (ppm) or part per billion (ppb) for metallic contents. Ore grade is the quality expression and can be low, medium and high, depending on the concentration of metal in the orebody. The disseminated ore mineral in a large orebody will generally give low grade and the concentrated ore mineral in closely spaced veins and lodes will have high grade. Colour, strength of the material and impurities present are also considered in grading of ore. The other factors like size, shape and distribution of ores are also taken into account while grading the ore body.Many factors play a significant role in defining a grade of an ore.
- **Assay Value**: The proportions of metallic or non-metallic elements in an ore sample is known as assay value. It is measured in form of percentage of the total weight. The process of calculating the assay value is termed as assaying.
- **Cut-off grade**: This term is used for knowing the lowest grade, which is set for mining an orebody. Mostly economic, but at times political necessities alter the definition of cut-off grade for a particular metal with time. Its definition can change with many factors such as economic, political,

technological, etc. For example with the discovery of porphyry type of copper deposits in around 1970, the cutoff grade for Cu went down to 0.5% which was earlier 1.5 to 2 wt% Cu.

- **Tonnage**: The term is used to represent the total quantity of the material in the designated orebody. Tonnage includes the ore and the associated unwanted material called gangue along with it. For example, let us assume the ore to be present throughout the ore body in disseminated form, then it will be of low grade and on other hand, if the ore is confined to a vein its grade will be higher.
- **Concentration Factor**: To define an orebody, the concentration factor plays a decisive role. The metals/elements concentration in an orebody should be higher than the average crustal abundance. The technical advances and infrastructure development in mining and ore extraction combined with reduction in transportation expenses have enabled to decrease the economic grade for most of the metals. For considering the economic grade of ore we should be familiar with the terms like Clarke and Clarke of concentration (concentration factor) which you have already studied in Course BGYCT-133, Block 3 and Unit 11. Now let us refresh these terms in detail:
- **Clarke**: It denotes the average abundance of a specific element in the crustal part of the Earth. The Clarke also known as Clarke value and is synonyms to crustal abundances.

  Clarke of concentration: It isthe ratio of average minimum exploitable grade (%) to its average crustal abundance (%) i.e. Clarke value. It is a unitless number known as concentration factor. It denotes the concentration of an element in a specific rock or ore in relation to its average concentration in the Earth's crust, or its Clarke value.

$$\textbf{Concentration factor} = \frac{\textbf{Average minimum exploitable grade (\%)}}{\textbf{Average crustal abundance (Clarke Value)}}$$

For example, if the average crustal abundance of iron is 5% and the average minimum exploitable grade is 30%, then the concentration factor of iron is 30/5=6. The concentration factor/Clarke of concentration for iron is, thus 6.

Learners, you have learnt the commonly used terminology in ore geology. Now, spend few minutes to perform an exercise to check your progress.

SAQ 1

a) Define ore and gangue.

b) How grade of an ore is defined? What is the relationship between grade and tonnage?

c) What are industrial minerals? Give two examples of industrial minerals.

d) Calculate concentration factor for an element ‘X’ which has average crustal abundance 2% and average minimum exploitable grade 20%.

1.4 RESERVES AND RESOURCES

Minerals of economic importance play a vital role in all walks of human life. This leads us in the search of new mineral deposits and in their detailed investigations. Mineral deposits of a country are its natural wealth upon which depends its growth and prosperity. Mineral resources and reserves are the basis for the future viability of a country. So, let us discuss the terms reserves and resources.

- **Reserves**: They are part of the mineral resources of a country that are economically viable and have been fully evaluated based on many geological and non-geological parameters with no legal or engineering obstructions for mining.
- **Resources**: Besides the reserves, the resources include the ore bodies which are unworked and which may become a potential economic interest in near future based on their intrinsic geological properties and plethora of non-geological factors such as market demand, feasibility to transport the materials, cheap and sturdy technology of extraction and processing, wartime exigencies etc. (Fig.1.1).

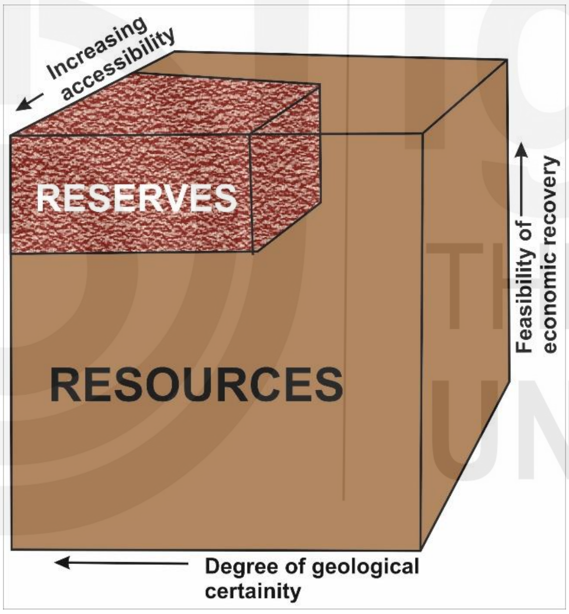


Fig. 1.1: Schematic diagram showingthe concept of resource and reserve
(Modified after : https://www.bgs.ac.uk/mineralsuk/mineralsYou/resources Reserves.html)

Let us discuss the ore reserves in detail. The ore reserves can be classified into three categories as i) proved (measured), ii) probable (indicated) iii) possible (inferred).

i) **Proved**: The ore reserves are thoroughly assessed in terms of its tonnage and average grade that fall in this category.

ii) **Probable**: In this category, the tonnage and grade can be assessed in a reasonable confidence way with some limitations. Even though the sampling from drilling and other activities may not have taken place, but there is sufficient evidence to be certain about tonnage and grade of the probability of ore.

iii) **Possible**: In this category, only partial information on tonnage and grade can be assessed.

The resources for a country are the sum-total of ore reserves, uneconomic deposits and the deposits which are not yet discovered (also called hypothetical). The Fig.1.2 gives a tabular classification of reserves and resources.

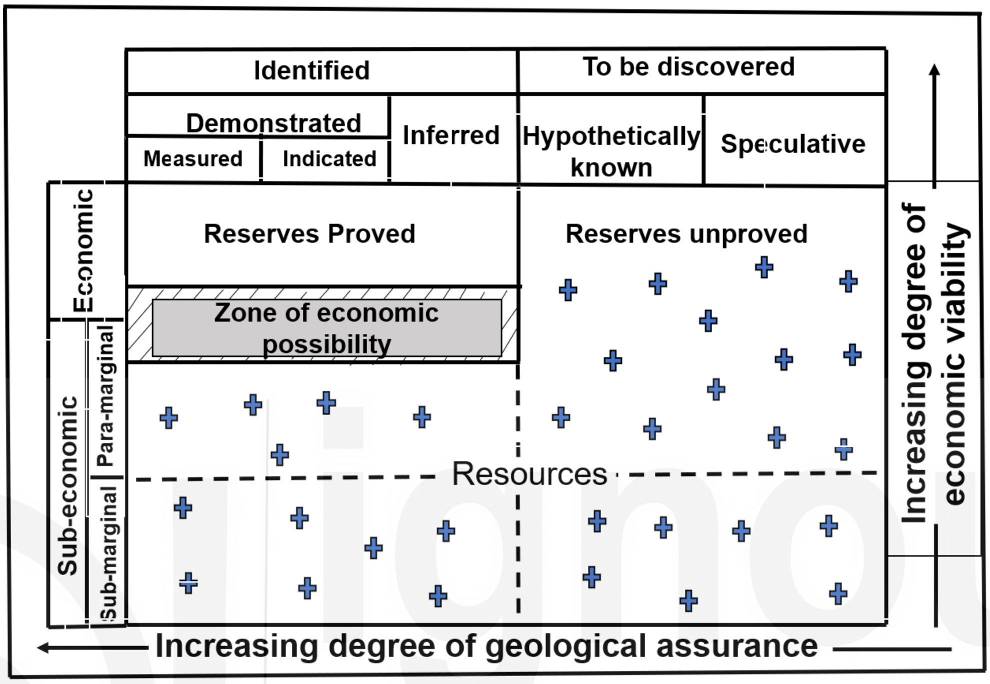


Fig.1.2: Scheme for classification of reserves and resources. (Modified after Evans, 1992 and references cited there in)

The economic or marginally economic resources turn into mineral reserves with increasing degree of geologic assurance. The subeconomic deposits may become economic with changing technology and socioeconomic or political situations.

1.5 RESERVE ESTIMATION

In the previous section you have been introduced to the terms like reserves and resources. Now let us discuss the reserve estimation. Reserve estimation is a crucial task in the mining industry in which one or more minerals or elements or mineral assemblages are estimated quantitatively for economic viability from an ore deposit. Estimation of ore reserves is a significant phase in the planning and development of ore deposits. This process involves the estimation of average grade and tonnage of ore deposits commonly known as ore-reserve estimates. Due to geological complexity and mining issues, it is not possible to estimate the ore reserves in precision.

The primary task in ore reserves estimation is the field work in sample measurement, collection, preparation and assaying. For better understanding and knowing the ore reserve estimation related to sampling various methods are followed. The main purpose of ore reserve estimation is to authenticate the quality and quantity of ore and cost estimation involved in extraction and further related activities for preparing the ore deposit for mining. There are many factors that influence reserve estimation. Let us discuss them one by one.

1.5.1 Factors Influencing Reserve Estimation

i) **Geological factors**: These features play an important role and interfere in reserve estimation and sometimes, they become more pronounced and influence the kind of mineralisation. Some of the main aspects that influence mineralisation are the folds, faults, layering, ore shoots and change in the habit of mineralisation etc. Let us take an example of the folds. In these features we can notice the change in attitude, thickness change between two limbs and cause duplication.

ii) **Data density**: In ore reserve estimation, the main data used is samples collected from the exposed mineralised body or core samples collected from drilling of subsurface body. The samples collected for the whole area of mineralisation are combined to give an idea about the exposure of the whole ore body. However, the statistical approaches will enhance the process of data handling and in showcasing the relation between the mineralisation and the ore deposit.

iii) **Grade**: It is a basic measure for estimating the value of ore. At best minimum grade limit is desired to start mining.

1.5.2 Methods of Reserve Estimation

The main methods of ore estimation are i) geometric and ii) geostatistical. Let us discuss these methods in detail:

i) **Geometric methods**: These are one of the oldest methods that still have good recognition and practiced even today. Geometric methods are purely built on the geometry of the ore body. These methods have advantage in estimating the tonnage unbiasedly. But the disadvantage with these methods are point estimates that do not permit the impartial evaluation of quality. The geometric methods are estimated by different methods named as a) triangle b) polygon c) rectangle or block d) cross section and e) contour. Let us discuss about these methods:

a) **Triangle method**: It is a simple method of reserve estimation and is based on standard triangle calculations (Fig.1.3a).

b) **Polygon method**: This method of reserve estimation is somewhat advantageous than the triangle method (Fig.1.3b). But for practical applications, the standard triangle and the polygon methods show identical results.

c) **Rectangular method**: It is also called as block method and is a special case of representation of the polygon method (Fig.1.3c). This method is not frequently used in reserve estimation.

d) **Cross-section method**: This method is considered as a specific application of the polygon method (Fig.1.3d). It is particularly used in cases of reserve estimation where the data is found laterally across the sequences of geological cross-sections.

e) **Contour method**: This method follows the hybrid pattern where it is grouped between the cross-section and mathematical methods (Fig.1.3e).

ii) **Geostatistical methods**: In mining operations, geostatistical methods are commonly applied and especially in reserve estimation for handling the numerical data. They are considered to be more accurate method. As it is helpful in enumerating the geological characteristics in both theoretical and practical basis for reserve estimation.

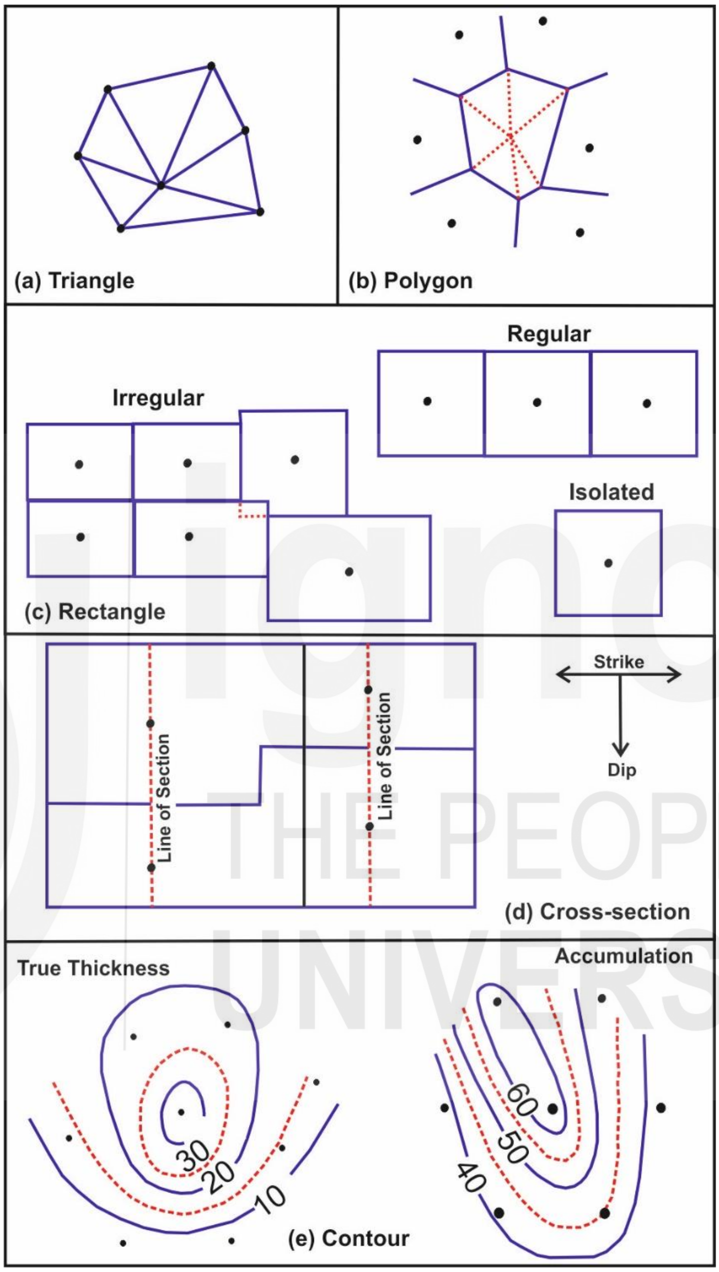


Fig. 1.3: Methods of ore estimation: a) Triangle; b) Polygon; c) Rectangle showing regular continous, irregular continuous and isolated blocks; d) Cross-section and e) contour for thickness and accumulation. (Source: Mendelsohn, 1980)

1.6 UNITED NATIONS FRAMEWORK CLASSIFICATION FOR RESOURCES

United Nations Framework Classification for Resources (UNFC) was developed by the United Nations Economic Commission for Europe's (UNECE) expert group on resource classification. In the course of development, UNECE published the United Nations Framework Classification for Reserves and

Resources of Solid Fuels and Mineral Commodities (UNFC-1997) in the year 1997. The main objective of the UNECE was to classify the solid minerals and fuels as a unifying system at the international level.

Further in the progress of development, the simplified United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources (UNFC-2009) had evolved. It is an international standard for classification which is universally accepted for classifying/evaluating resources such as fossil energy and mineral reserves and resources.

The UNFC is a more accessible system designed to facilitate and address the requirements at various levels. It enhances the institutional, industry, national, and international requirements by supporting the balanced usage of resources, energy supplies and related financial management. It uses three fundamental criteria such as economic and social viability (E), field project status and feasibility (F), and geological knowledge (G) for classification (Fig.1.4). This scheme of classification is to be used for fossil energy and mineral reserves and resources located on surface or inside the Earth. Let us study these three axes of fundamental criteria in detail.

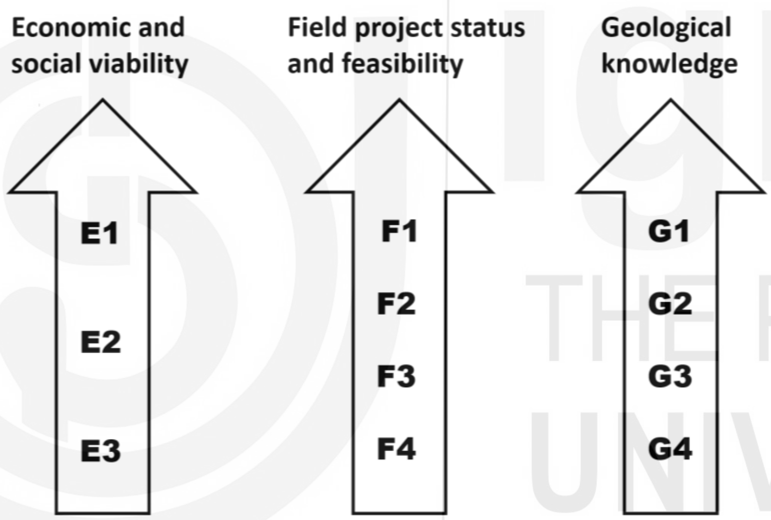


Fig. 1.4: Three-dimensional coding of UNFC.

- **E-axis**: It designates the economic and social viability taking into account of the market prices and relevant legal, regulatory and environmental conditions. Studies related to potential socio-economic conditions, environmental aspects, financial viability, and other related mechanisms are measured while considering the sequential aspects of pre-feasibility and feasibility.
- **F-axis**: It describes the field project status and feasibility taking into account of the initial exploration efforts to the stage of extraction and selling a commodity. It forms an essential characteristic in a mining project. Besides playing a key role in sequential studies related to geological aspects at apreliminary stage, it follows pre-feasibility and feasibility studies for the task of mining.
- **G-axis**: It designates geological knowledge in terms of the confidence level of recovering the resources. It considers the sequential phases of definite degree of geological assurance. It includes different stages such as

reconnaissance survey, overall prospecting and exploration, followed by in detail survey and investigation, and generating report of detailed information for geological feasibility.

Considering the three fundamental criteria of economic and social viability (E), field project status and feasibility (F), and geological knowledge (G) the UNFC had resulted in a three-dimensional arrangement with use of numerical coding system. The economic and social viability (E), has three codes in decreasing order (E1, E2, E3) (Table1.2). Likewise, the field project status and feasibility (F) has four codes (F1, F2, F3, F4) (Table1.3). Geological knowledge (G), has four codes (G1, G2, G3, G4) (Table1.4).

Table 1.2: Description of E-axis category.

Category	Description
E1	Extraction and sale procedures are comprehensive indicating economic feasibility.
E2	Extraction and sale procedures are prospective indicating economic feasibility.
E3	Extraction and sale procedures are not indicating economic feasibility in near future. Besides, it is in advance to judge the economic viability.

Table1.3: Description of F-axis category.

Category	Description
F1	Feasibility of extraction/development by a justified growth of a project or mining process/operation has been established.
F2	Feasibility of extraction/development by a definite growth of a project or mining process/operation is of conditional assessment.
F3	Feasibility of extraction/development by a definite growth of a project or mining process/operation is undefined because of restricted technical data.
F4	Advances in extraction/development of a project is not confirmed or mining operation is yet to be initiated.

Table 1.4: Description of G-axis category.

Category	Description
G1	Load related to an identified deposit and geological conditions can be valued with a reliable level of assurance.
G2	Load related to an identified deposit and geological conditions can be valued with a reasonable level of assurance.
G3	Load related to an identified deposit and geological conditions can be valued with a low level of assurance.
G4	Load related to a probable deposit and geological conditions is based on indirect sources.

In 2019, the UNFC was updated to UNFC 2019 and the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 was renamed as United Nations Framework Classification for Resources. Together the categories (E1, E2, E3; F1, F2, F3, F4 and G1, G2, G3, G4) and sub-categories (e.g. G1.1 etc.) form the foundation of the UNFC system of classification (Fig.1.5).This scheme has been devised with the intent to cater to the needs of sectors pertaining to energy and mineral studies, resources management functions, corporate business processes and financial reporting standards.

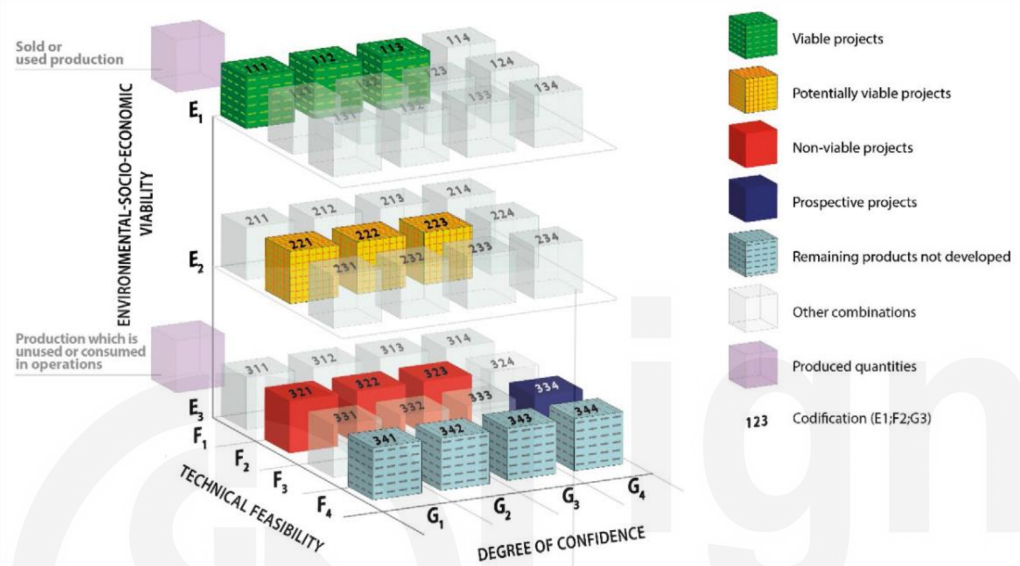


Fig. 1.5: UNFC categories and examples of classes. (Source: https://www.unece.org/fileadmin/DAM/energy/se/pdfs/UNFC/publ/UNFC_ES61_Update_2019.pdf)

1.7 INTRODUCTION TO ORE MICROSCOPY

You have already studied about a polarising microscope and its functioning in Unit-8 of BGYCT-133. Ore microscope is the prerequisite to study important economic minerals. This microscope is different from polarizing/petrological microscope which uses transmitted light to study minerals. The ore minerals are studied under ore microscope to understand the nature of ore-and the gangue material and their relationship with each other, and their environment of formation. Ore microscopy finds its applications in various branches of geology (Fig. 1.6).

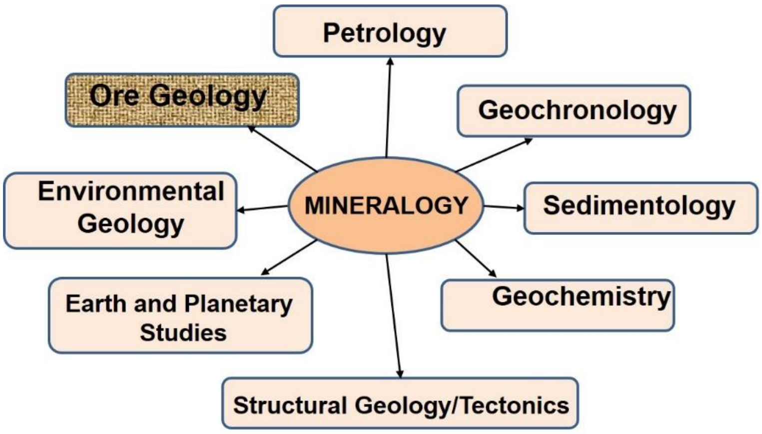


Fig. 1. 6: Ore geology (branch of mineralogy) showing its relationship with other branches of Earth science. (Source: after Klein, 2002)

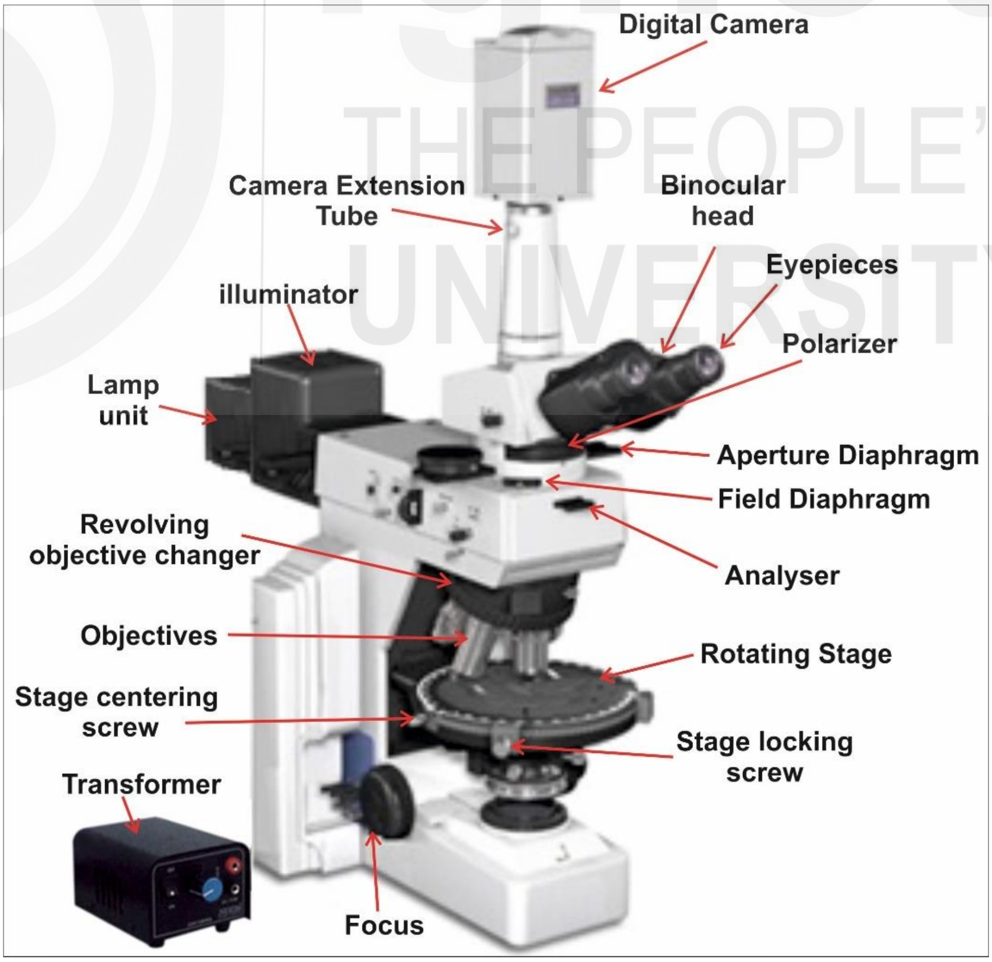
What is an ore microscope?

The minerals which do not permit the light to pass through thin sections are said to be opaque minerals. Especially treated sections of **opaque minerals** are studied under reflected light with the help of **reflecting or ore microscope**. Thus the microscope (basic instrument) which is used to petrographically examine economic minerals together is recognised as the "ore" or "opaque" minerals is known as **ore microscope**. Thus, the study is known as **ore microscopy**. It is also called as **metallographic microscope** due to its use in understanding the microscopic properties of metals and alloys.

1.7.1 Difference Between Ore Microscope and Polarising Microscope

The term ore is quite often used synonymously with opaque mineral. Most of the ore minerals are opaque i.e. in the plane polarised light in a transmitted light microscope they appear totally dark. For example, magnetite and chromite are opaque minerals. But there are exceptions and not all ore minerals are opaque. For example, sphalerite and cassiterite are not opaque.

However, the ore microscope is different from a transmitted light microscope in terms of placement of its light source. Otherwise it is quite identical to transmitted light microscope in terms of polariser, analyser, diaphragms, lenses, stage etc (Fig. 1.7a).



(a)

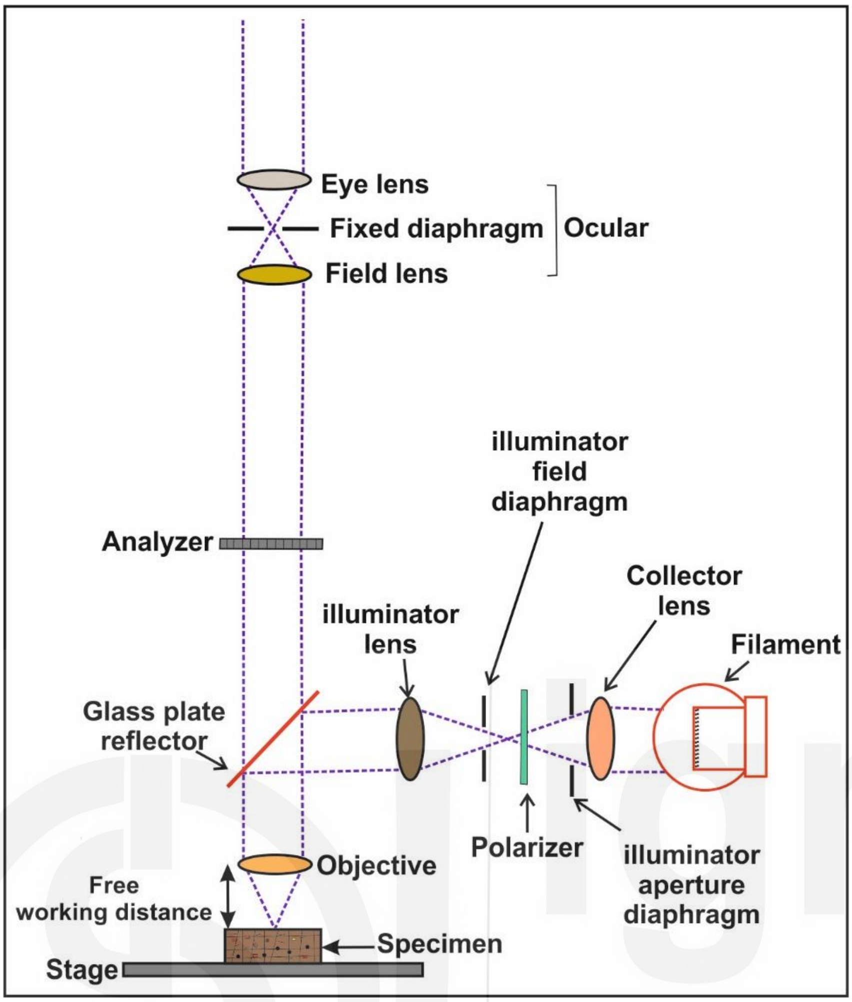


Fig.1.7: a) Ore microscope; and b) Schematic cross sections of reflected light microscope. (Source: redrawn from Craig and Vaughan, 1994)

The source of light is placed above the sample contrary to placement of light source below the sample in transmitted light microscope. A doubly coated glass plate is placed which acts as a reflector and reflects light falling on it. The sample to be placed on the stage of the reflected light microscope has to be polished unlike the samples used for transmitted light. The Figure1.7b is a schematic cross-section of a reflected light microscope with important components. It is important to notice the source of light and the path of light through the system and the whole-field doubly coated glass plate reflector.

1.7.2 Major Components of Ore Microscope and their Adjustment

We have studied the difference between ore microscope and petrographic microscope. Before we discuss about the components of ore microscope, let us briefy discuss about the preparation of polished section.

Preparation of polished section is an important part of the ore microscopy. For microscopic study, a plane polished surface of an ore, free of pits, scratches, fractures and pores is required. Earlier these polished sections were prepared manually (hand polishing), now-a-days automatic polishing (Fig. 1.8) machines are available. Thus, a paper-thin layer of an polished ore section is prepared by cementing thin slices of glass to it or an polished block (ore mounted upon resin) is prepared (Fig. 1.9).

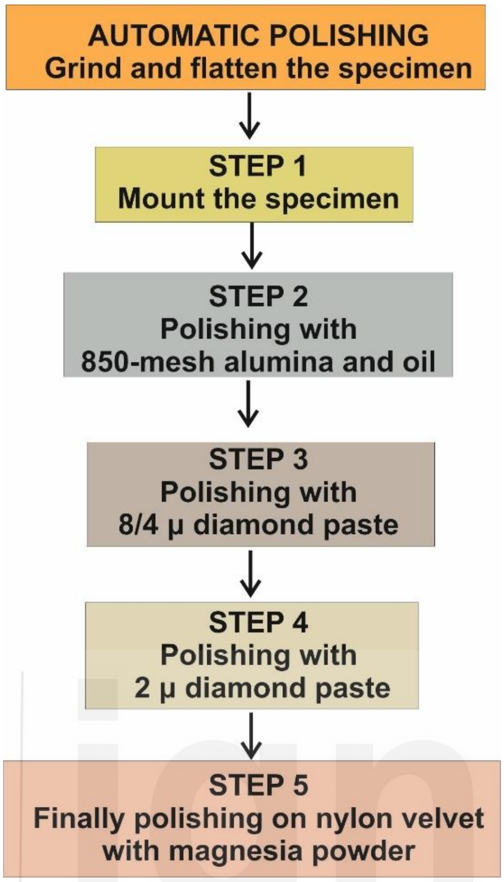


Fig. 1. 8: Steps for preparation of polished surface in an automatic polishing machine.

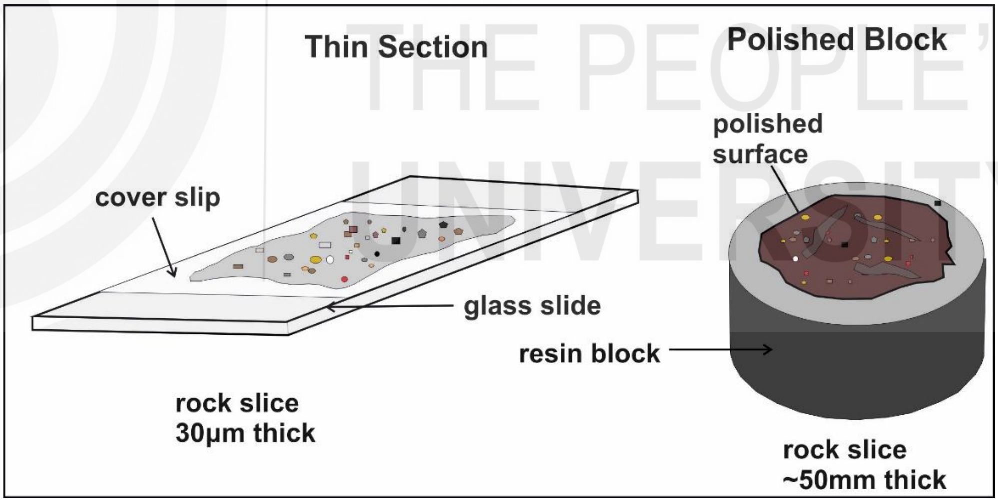


Fig. 1.9: Polished thin section and block section. (Source: Redrawn from Shrivastava and Rani, 2012)

Now, let us discuss the major components of ore microscope and their adjustment.

i. **Graduated Rotating Stage**: The graduated rotatable stage lies in between the two nicols (polariser and analyser) and is used for placing the polished mineral specimen. It must be freely rotatable through 360° angle and can be locked at any point. It should be positioned in centre in comparison to the objectives and must be vertical (90°) to the axis of light transmitted in the microscope.For example, as you can see in Fig. 1.10(a) when the stage is rotated by 360º, the grain remains in its original position, the objective is set to be perfectly centered. If the objective is not centred Fig. 1.10(b), the grain can be brought close to centre/cross-wire by adjusting the screws either clockwise or anticlockwise attached to the objective. The angular degree markings on the edge of the stage helps to measure certain properties during rotation of the specimen.

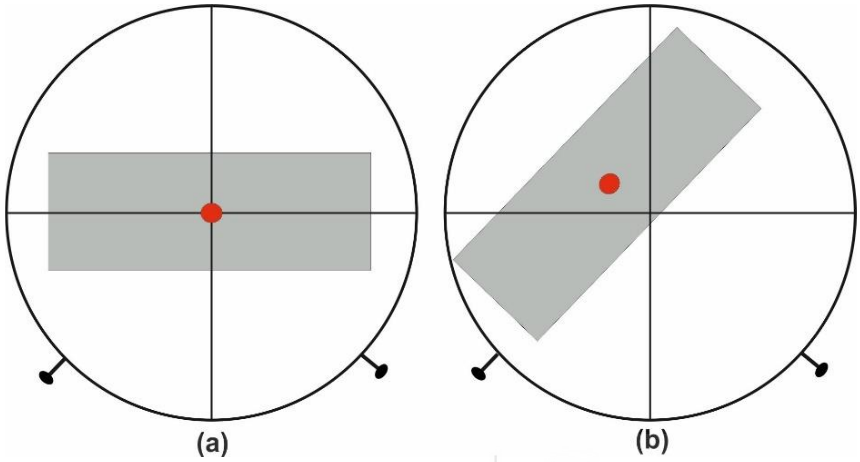


Fig. 1.10: Centring of the objective by rotating and adjusting the rotatable stage: a) perfectly centered; and b) not centered.

ii. **Objective Lenses**: The classification of objective lenses is normally based on the type of lens, magnifying capacity and numerical aperture, lenses that are of oil immersed or normal air used. Rarely, the focal length of the objective lens is also considered. The type of lens used may be apochromat (decreases spherical and chromatic aberration), achromat or fluorite(semi-apochromat). Spherical (lens curvature) and chromatic (colour) aberrations are two dissimilar image defects caused due to transmission of light through an image. However, the most commonly used is achromat lens because of its economic viability.

iii. **Ocular Lenses**: The ocular system is an arrangement of eyepiece lens. In this system, one can look through the naked eye for greater magnification of the image generated by objective lens. In maximum number of microscopes '**Huygenian oculars**' (systematic arrangement of two planoconvex lenses in eye piece for magnification) with a magnification ranging between 5x and 12x are commonly used.

iv. **Illuminating Systems**: Illuminating systems relate to use of bulb/lamp in ore microscopes. The incandescent filament lamp and the gas discharge lamp are the basic types normally used for illumination. The lamp should provide adequate light, even and illumination throughout the field of view.To make it clear that the light source is in centre or not, close the field diaphragm, remove the eyepiece, the point of light source on the centre of cross-wire is observed. If this point of light is centred, then it is said that the reflector is orientated properly (Fig. 1.11). If not orientated properly, than the reflector can be positioned correctly by removing and placing the light source propely in the microscope until it is centered (Fig. 1.11).

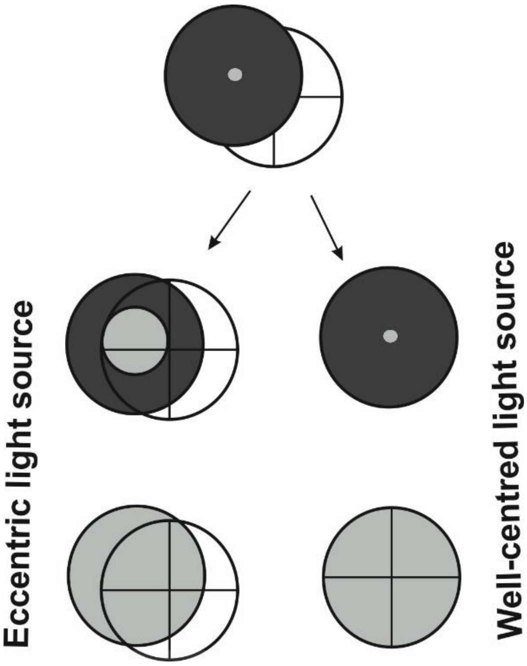


Fig. 1. 11: Showing field of view while centering of the light source. (Source: Shrivastava and Rani, 2012)

v. **Reflector**: It is one of the main constituents of the ore microscope that acts as a source for vertical focusing of light on the surface of a polished specimen. How you would know that the light source is in centre or not? For this, you have to remove the eyepiece, close the field diaphragm and observe the point of light. If the point of light is in centre, then the reflector is said to be properly oriented or vice versa.

vi. **Polariser and Analyser**: Polariser in a standard ore microscope is placed inside the illumination system between the lamp and the collector lens but may be located between the diaphragms. The analyser is positioned over the objective lenses. Polariser as well as analyser are used for the transmission of light in one plane. For the application of this aspect, they are equipped with a polaroid plate.

vii. **Accessories**: Monochromators (to provide incident light of specified wavelength), photometers (to measure the reflectance of mineral grains), stage micrometres (accurate measurement of grain sizes; 1 mm scale subdivided into hundredths), sample holders are some of the other accessories used in the operation of ore microscope.

1.7.3 Terminologies Related to Ore Microscopy

Now in this section, we will learn about the basic terminology that you should be aware of while studying ore microscopy.

i. **Reflectance (R)**: The reflectance (brightness) is a characteristic mineral property which is used in quantitative and qualitative ore microscopy. Reflectance of a phase depends on two parameters:

- **Refraction (refractive index n),** and
- **Absorption (absorption coefficient k)**

Reflectance (R) depends on the medium (air, water, or oil) in which reflection takes place. Many optical properties of ore minerals are more distinctive with the help of oil immersion objectives. Two minerals which have small differences in their R values in air are difficult to distinguish, whereas the same small difference in oil is more distinct. The following Fresnel equation is used for reflectance, i.e.

$$R= (n - N)^2 = k^2/ (n + N)^2 = k^2$$

Where, the refractive index of the medium (N) N = 1 for air, N = 1.518 for oil. Depending on the medium used the expressions (n - N) and (n + N) changes. Reflectance is especially reduced for minerals with low values of k.Reflectance of stronger absorbing minerals with higher k is less strongly reduced.

ii. **Colour Impression (CI)**: Colour impressions in the mineral profiles are only given for oil immersion objectives. Using oil immersion objectives the colour intensity of a mineral is generally increased and more easily visible. Minerals with strong CI were described only by colour. For less strong coloured minerals each colour impression is preceded by white or grey, depending on the overall reflectance, e.g. whitish blue, greyish brown, greyish white.

iii. **Bireflectance**: It is an optical property similar to pleochroism where the mineral appears to change in intensity in different orientations while illuminated by plane polarized light on rotation of the stage. The polarizers are not crossed to observe **bireflectance**. It is usually the sum of two different effects, i.e., the changing of colour impression and reflectance. Reflection pleochroism (Rpl) means the colour impression of a mineral varies according to the position of the crystal to the polariser. Bireflection (BR, also called bireflectance) means the mineral shows different reflectance values.

BR <Rpl: Minerals show mainly Rpl and less BR

BR ~ Rpl: Minerals show BR as well as Rpl

BR >Rpl: Minerals show mainly BR

iv. **Anisotropism Effects**: Anisotropism effects are observed under crossed polars. They are variations in brightness and/or colour of an anisotropic mineral grain in an optimal orientation if the specimen is rotated. There should be four positions, each 90° apart. The mineral grain shows minimum brightness or maximum darkness is called normal position. Four positions where the grain shows maximum brightness is called 45° or diagonal position.

v. **Extinction**: The normal position of the specimen on the stage with minimum brightness, may be used for the identification of minerals. On rotation of the stage through 360º angle, you can make observations of colours and extinction. You will notice that on rotation of stage four times a mineral becomes extinct and between two extinction positions it shows range of polarisation colour.

vi. **Twinning**: Crystal twinning occurs when two separate crystals share some of the same crystal lattice points in a symmetrical manner. A twin boundary surface separates the two crystals, so it will be very helpful for the mineral identification. The typical twinning of a given mineral is classified due to the orientation, form and frequency. Twinning of crystal (contact, penetration, simple, multiple,polysynthetic/lamellar) can be observed by crossing the polars with a slightly uncrossed analyser.

vii. **Cleavage**: If a mineral shows cleavage planes, it can be an important feature for the identification. Minerals with good cleavages in hand specimens do not necessary show this feature in polished section. The polishing process has great effect on the visibility of cleavage planes, which can be seen as oriented fine black lines on the mineral surface. Thus, one should be careful in polishing process.

viii. **Qualitative Hardness**: Hardness of a mineral is its resistance to scratching. There are three types of hardness: **polishing hardness,scratch hardness** and **microindentation (Vickers) hardness**. The first two can be examined with the standard ore microscope by comparing the relative hardness of adjacent phases. During the polishing process, harder minerals will stand out in relief, compared to softer minerals in the polished section. Kalb light line is made used to determine the relative hardness between two adjacent grains. Kalb light line is a line of “fuzzy” light that is produced upon reflection at the contact between two minerals of contrasting hardness.

- **Vickers Hardness (VHN)**: The measurement of hardness on the microscopic scale has involved a variety of instruments and types of indenter. The most common indenters is the Vickers (a square-based pyramid). This technique has been widely adopted in ore microscopy. The Vickers indenter is a square-based diamond pyramid with a 130° included angle between opposite faces. So that a perfect indentation is seen as a square with equal diagonals. The area of the Vickers indentation can be expressed in terms of the length of the diagonal d (in µm) as:

$$\mathbf{VHN = 1854.4 \times L/}\boldsymbol{d}^{\mathbf{2}}\ \mathbf{g/mm^2}$$

Physical and optical properties of some common ore minerals are summarised below in Table 1.5.

Table 1.5: Physical and Optical Properties of common ore minerals. (Abbreviation used **Refl**: Reflectance; Source: modified from Marshall et.al. 2004)

Physical Properties (Hand Specimen)			Optical Properties (Polished Section)	
Chalcopyrite ($CuFeS_2$)	**Colour**: Brass yellow	**Lustre**: Metallic	**Colour**: Yellow to brass yellow	**Bireflectance**: Weak
	Hardness (Mohs): 3.5 – 4.5	**Streak**: Greenish Black	**Anisotropy**: Weak to distinct, grey-blue to yellow -green	**Cleavage**: {011}, {111} Poor
	Density: 4.1 – 4.3	**Cleavage**/ Fracture:	**Refl (546nm)**: 35.7 – 36.9	**Refl (589nm)**: 36.7 – 39.8

		Conchoidal, uneven brittle	**Polishing hardness**: >galena, <sphalerite	**Hardness (Vickers) (kg/mm^2)** VHN_{100} = 187
Chromite $(Fe,Mg)(Cr,Al)_2O_4$	**Colour**: Iron black to brownish black	**Lustre**: Sub-Metallic	**Colour**: Dark grey to brownish grey	**Cleavage**: None
	Hardness (Mohs): 5.5	**Streak**: Brown	**Anisotropy**: Very weak; usually absent	**Bireflectance**: Absent
	Density: 4.6	**Cleavage/ Fracture**: Uneven, brittle	**Refl (546nm)**: 12.0	**Refl (589nm)**: 11.7
			Polishing hardness: >magnetite, <hematite	**Hardness (Vickers) (kg/mm2)** VHN_{100} = 1278 -1456
Copper (Cu)	**Colour**: Copper-red, brown-red	**Lustre**: Metallic	**Colour**: Deep pink, tarnishes brown	**Cleavage**: Absent
	Hardness (Mohs): 2.5-3	**Streak**: Copper red	**Anisotropy**: Isotropic	**Bireflectance**: Weak
	Density: 8.9	**Cleavage/ Fracture**: None	**Refl (546nm)**: 47.5	**Refl (589nm)**: 65.9
			Polishing Hardness: >chalcocite	**Hardness (Vickers) (kg/mm2)** VHN_{100} = 77–99
Galena (PbS)	**Colour**: Lead grey, bluish tint	**Lustre**: Metallic	**Colour**: White	**Cleavage**: {100} Perfect
	Hardness (Mohs): 2.5	**Streak**: Lead grey	**Anisotropy**: Isotropic	**Bireflectance**: Not present
	Density: 7.4-7.6	**Cleavage/ Fracture**: Perfect cubic	**Refl (546nm)**: 42.2	**Refl (589nm)**: 41.5
			Polishing Hardness: ~chalcocite, <chalcopyrite	**Hardness (Vickers) (kg/mm2)** VHN_{100} = 79 –104
Goethite (FeO.OH)	**Colour**: Metallic black, yellowish to dark red-brown	**Lustre**: Adamantine	**Colour**: Grey with bluish tint	**Cleavage**: {010} Perfect

	Hardness (Mohs): 5- 5.5	**Streak**: Brownish yellow or ochre yellow	**Anisotropy**: Distinct, grey-blue to grey-yellow, brown	**Bireflectance**: Weak, distinct in oil
	Density: 3.3- 4.3	**Cleavage/ Fracture**: One good cleavage	**Refl (546nm)**: 13.2 -14.5	**Refl (589nm)**: 12.7- 13.9
			Polishing Hardness: Variable; for crystalline material, <magnetite, hematite	**Hardness (Vickers) (kg/mm2)** VHN_{100} = 667
Hematite (Fe_2O_3)	**Colour**: Red-brown earthy), steel grey – iron black	**Lustre**: Dull	**Colour**: Grey-white with bluish tint	**Cleavage**: Absent; {0001}, {1012} only partly due to twinning
	Hardness (Mohs): 3.5-4	**Streak**: Cherry Red	**Anisotropy**: Distinct, grey-blue, grey- yellow	**Bireflectance**: Weak
	Density: 5.2- 5.3	**Cleavage/ Fracture**: Sub-Conchoidal	**Refl (546nm)**: 27.0 - 30.6	**Refl (589nm)**: 26.0 - 29.7
			Polishing Hardness: Very high, variable; >magnetite, ilmenite.	**Hardness (Vickers) (kg/mm2)** **VHN_{100} = 1000-1100**
Magnetite (Fe_3O_4)	**Colour**: Iron black	**Lustre**: Metallic or sub-metallic	**Colour**: Grey with brownish tint	**Cleavage**: {111} Imperfect
	Hardness (Mohs): 5.2	**Streak**: Black	**Anisotropy**: Isotopic, slight anomalous anisotropism	**Bireflectance**: Not present
	Density: 5.2- 5.3	**Cleavage/ Fracture**: Sub-Conchoidal	**Refl (546nm)**: 20.4	**Refl (589nm)**: 20.6
			Polishing Hardness: <ilmenite, <<hematite	**Hardness (Vickers) (kg/mm2)** VHN_{100}= 681 - 792
Pyrite (FeS_2)	**Colour**: Brassy yellow	**Lustre**: Metallic	**Colour**: Yellowish white	**Cleavage**: {001} Poor
	Hardness (Mohs): 6-6.5	**Streak**: Black	**Anisotropy**: Weak	**Bireflectance**: Not present

	Density: 5 - 5.2	**Cleavage/ Fracture**: Conchoidal, uneven brittle	**Refl (546nm)**: 54.1	**Refl (589nm)**: 55.2
			Polishing Hardness: Very high; >marcasite	**Hardness (Vickers) (kg/mm2)** VHN_{100} =1505 -1520
Pyrolusite (MnO_2)	**Colour**: Iron black	**Lustre**: Metallic	**Colour**: Creamy white	**Cleavage**: {100} perfect
	Hardness (Mohs): 2 - 6.5	**Streak**: Black or bluish black	**Anisotropy**: Very strong, yellowish, brown, blue	**Bireflectance**: Distinct in oil, yellowish white to grey - white
	Density:4.4-5.1	**Cleavage/ Fracture**: Brittle, soils finger	**Refl (546nm)**: 18.7 - 31.3 Refl (589nm): 18.4 – 30.4	**Polishing Hardness**: Variable
Sphalarite (ZnS)	**Colour**: White, yellow, brown, black – darkening with increased Fe	**Lustre**: Resinous to adamantine	**Colour**: Grey	**Cleavage**: {011} Perfect
	Hardness (Mohs): 3.5-4	**Streak**: White, reddish brown	**Anisotropy**: Isotropic	**Bireflectance**: Not present
	Density:3.9 - 4.1	**Cleavage/ Fracture**: Conchoidal, brittle	**Refl (546nm)**: 16.6	**Refl (589nm)**: 16.4
			Polishing Hardness: Variable	**Hardness (Vickers) (kg/mm2)** VHN_{100} = 208–224

Learners, now spend few minutes to perform an exercise to check your progress.

SAQ 2

a) Define mineral resources.

b) Give classification of reserves.

c) What are the main objectives of UNFC classification?

d) Define an ore microscope. How is it different from transmitted light microscope?

1.8 SUMMARY

Let us sum up what we have studied in this unit.

- Ore deposits are basically volumes of valuable rocks formed by substantial concentration of element/s larger than that of their distinctive crustal abundance. A mineral resource is usually considered as ore reserve if its economic viability is examined and reported.

- Ore mineral is known as a mineral which has higher concentration of metal in it and has a fixed mineral composition like any other mineral. Minerals such as calcium, fluorite, pyrite, etc., are used in industries are known as industrial minerals.
- Grade is the metal concentration/content in an orebody. Tonnage is the total quantity of the material in the designated orebody. Clarke value isthe ratio of average minimum exploitable grade (%) to its average crustal abundance (%).
- Ore deposits are the masses of rock that contain one or more ore bodies. From these ore bodies commodity (ore) of economic value are extracted. However, extraction is limited and not the entire ore body will be extracted. The ore bodies are grouped into reserves and resources.
- The process that involves the estimation of average grade and tonnage of ore deposits is called as ore-reserve estimates. The main purpose of ore reserve estimation is to validate the quality and quantity of ore and cost of estimation involved in extraction and further for preparing the ore deposit for mining. Factors involved for the ore estimation are the geological features, data density, grade. The main methods involved in ore estimation are i) geometric and ii) geostatistical.
- UNFC is an international standard for classification which is universally accepted for classifying/evaluating mineral resources. UNFC-2009 uses three fundamental criteria of economic and social viability (E), field project status and feasibility (F), and geological knowledge (G) for classification. It was designed to furnish the requirements of sectors relating to energy and mineral studies, resources management functions, corporate and financial reporting standards.
- Ore microscopes are used to study the nature of ores and the gangue material and their relationship, and the environments of their formation. The ore microscope is different from transmitted light microscope in terms of placement of its light source. Major components of the ore microscope are i) rotatable stage ii) objective lens iii) ocular lenses iv) illuminating systems v) polarizer and analyser vi) other accessories.

1.9 ACTIVITY

The tables given below shows (E-axis) economic and social viability (E) and (F-axis) the field project status and feasibility (F). Write the description for missing (E1 and E3) and (F2 and F4) categories.

Category	Description
E1	
E2	Extraction and sale procedures are prospective indicating economic feasibility.
E3	

Category	Description
F1	Feasibility of extraction/development by a justified growth of a project or mining process/operation has been established.
F2	
F3	Feasibility of extraction/development by a definite growth of a project or mining process/operation is undefined because of restricted technical data.
F4	

1.10 TERMINAL QUESTIONS

1. Give a brief account of ore minerals and classify them into different classes with examples.
2. What is the concentration factor? Discuss Clarke of concentration with an example.
3. Discuss the methods of reserve estimation with neat diagrams.
4. Explain the three-dimensional arrangement numerical coding system of UNFC.
5. Describe the major components of ore microscope.
6. Discuss qualitative hardness in ore microscopy.

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1.12 FURTHER/SUGGESTED READINGS

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1.13 ANSWERS

SAQ 1

a) Ore is a naturally occurring mineral or an aggregate of minerals from which one or more elements, mostly metallic,can be extracted with a profit at a given point of time. Gangue is a commercially unwanted material that exists in close association with the ore.

b) Grade is defined as the metal concentration/content in an orebody. The relationship between grade and tonnage is that lower the grade, higher the tonnage and higher the grade, lower the tonnage.

c) Industrial minerals are defined as any rock, mineral or other naturally occurring substance of economic value, exclusive of metallic ores, mineral fuels and gemstones. The two examples of industrial minerals are granite and quartz.

d) 10

SAQ 2

a) Mineral resources include the ore bodies which are unworked and which may become potential and of economic interest in near future. The potentiality is based on their intrinsic geological properties and plethora of non-geological factors.

b) The ore reserves can be classified into 3 categories as i) proved (measured), ii) probable (indicated) iii) possible (inferred).

c) The main objective of UNFC classification is to facilitate and address the requirements at various levels. It helps to enhance the institutional, industry, national, and international requirements by supporting the balanced usage of resources, energy supplies and related financial management.

d) The ore microscope is a basic instrument used to petrographically examine economic minerals together known as the ore or opaque minerals. The ore microscope is different from transmitted light microscope in terms of placement of its light source.

Terminal Questions

1. Please refer to sub section 1.3.
2. Please refer to sub section 1.3.
3. Please refer to sub-section 1.5.2.
4. Please refer to sub-section 1.6.
5. Please refer to sub-section 1.7.2.
6. Please refer to sub-section 1.7.3.