Ordinary Chondrites from North-East India

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A Raman and Infrared Spectroscopic Approach

By

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Dedicated to my Parents
&
To my primary school Teachers
who introduced me
“Alphabets”

TABLE OF CONTENTS

PREFACE

The study of dust particles in the universe is an exciting and challenging area of current astronomy and astrophysical science. The research of meteorites and micro-meteorites bridges the gap between geology, the study of Earth’s rocks and landforms, and astronomy, the study of the Sun, planets, moons, and stars in space. Moreover, meteorites provide an important source of extra-terrestrial matter. They are some of the oldest remnants of the solar system available for laboratory studies. The chemical and physical characteristics, texture and internal structure of these extra-terrestrial matters contribute to our understanding of the birth and early history of our solar system. Another important aspect of comprehensive meteorite study is to understand the minerals which have lost its original form due to condensation and accretion.

The Fourier transform infrared spectroscopic and Raman spectroscopic approaches can be considered non-destructive analytical techniques. These two spectroscopic approaches also present the advantage of being able to determine at a scale of a few microns compared with other analytical techniques. Furthermore, the sharp spectral features of Raman spectra are widely recognized to provide an explicit and accurate chemical characterization of inorganic and organic compounds. Therefore, these analytical techniques are highly appreciated for analysing precious samples such as meteorites. Furthermore, the infrared and Raman spectra of a given sample usually differ because infrared activity requires a change in the dipole moment during the transition whereas Raman activity requires a change in polarizability, hence each technique can provide complementary information regarding the sample.

The study of meteorites is interesting and wide-ranging, leading into many areas of technology and science. This book is intended to give a brief insight into the falls and finds of meteorites in the North-eastern region of India to those readers who are interested in the spectroscopic studies of planetary materials. There are 151 documented meteorites from India (to date), but only seven meteorites have been officially recognized from the North-eastern region of India with various sizes and chemical classes by the international Nomenclature Committee of the Meteoritical Society. In comparison to the international scenario, the fall or find ratio of meteorites in the North-eastern region of India is very few. This book covers all falls or finds of meteorites from the North-eastern region of India including the most recently fallen meteorite named Natun Balijan.

The focus of this book is especially confined to present some basic finding using the Raman and infrared spectroscopic techniques on some selected meteorites. Raman and infrared spectroscopic identification and structural characteristics of the minerals are based on the comparison of the Raman and infrared spectra of our meteorite specimens with the corresponding literature data for the analogous mineral species originating from all over the world. Herein, emphasis is given to the application of the spectroscopic tool in ordinary chondrites only. Silicate compounds are an important and abundant ingredient of matter almost everywhere in the Universe. The laboratory study of silicates remains an essential component of studying silicates in space. In this book, particular emphasis is given to the silicate minerals of the ordinary chondrites. These spectroscopic results may support enhancement of a degree of comprehension of the nature and composition of the silicates in astrophysical environments. The book also focuses on carbon materials found in the selected ordinary chondrites so that a useful understanding of this material in these meteorites can be developed. Moreover, this book is the first catalogue of meteorites that fall and are found in the North-eastern region of India.

This book emphasizes the application of Raman and infrared spectroscopy as a useful tool in the mineralogical classification of planetary materials like meteorites. Only a few have access to meteorite samples and a micro Raman spectroscopic facility for analysis together. Through this study, I would like to motivate spectroscopists to undertake studies on planetary materials. Finally, I expect the possibility of future research on these meteorites that may be undertaken using the benefits and advancements made in this work.

Bhaskar J. Saikia
2020

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CHAPTER ONE

STONES FROM OUTER SPACE: METEORITES

Introduction

We often search for the answer to a basic question: how were the Earth, our Solar System and the Universe formed? We all are familiar with the process of *nucleosynthesis* (i.e. the study of the nuclear processes responsible for the formation of the elements which constitute the baryonic matter of the Universe), where hydrogen atoms are processed to make other elements. These new atoms form dust and molecules in space and are then incorporated into new stellar systems as well as planets and life. This gives the impression that we all are made of stardust. Most rocks on the Earth are a few hundred million years old or less, but meteorites endow us with a chance to touch one of the oldest pieces of rock. Some meteorites remained unaltered for 4.5 billion years, and therefore they preserved evidence of the conditions under which they formed.

Before 1800, nobody even thought of the possibility of a fall of meteorites from space. In 1794, Ernst Florens Friedrich Chladni, a German physicist published the book "*On the origin of the Pallas Iron and other similar to it, and on some associated Natural Phenomena*" where he compiled all available data on the meteorite fall and find. Chladni was the first physicist who suggested that the meteorites come from space. This led many scientists to take another look at all of those mysterious rocks that peasants had assembled years before and they realized that these were unique objects. Chladni's finding opened up a new branch of science called *Meteoritics*. The term "*meteorite*" is derived from the Greek. It means that which originates in the atmosphere. A meteorite is a rock from outer space that was once a meteor and has fallen to the earth. In other words, rocks of extra-terrestrial origin that penetrate the atmosphere and reach the Earth's surface are called meteorites. Some meteorites are made of broken up pieces of planets. Other meteorites may be parts of comets. Scientists have estimated that nearly 30,000 meteors hit the Earth's atmosphere each year and some of them become meteorites. It is difficult to estimate exactly how many meteorites hit Earth each year. However, different study estimates for the mass of material that falls on Earth each year range from 37,000-78,000 tons. Most of this mass would come from dust-sized particles. The arrival of a meteorite is a totally unpredictable event. More than 50,000 meteorites have been found on Earth. Approximately 99.8 percent of these meteorites come from asteroids and the remaining 0.2 percent of meteorites are split roughly equally between meteorites from Mars and the Moon. Scientists observed that the spectra of several classes of meteorites match those of some asteroid classes which are 4.5 to 4.6 billion years old. The eucrite, diogenite, and howardite igneous meteorites match with the third-largest asteroid Vesta, and these meteorite groups are regarded as of asteroid origin. Almost 60 known Martian meteorites were blasted off Mars by meteoroid impacts. Likewise, nearly 80 lunar meteorites are similar in mineralogy and composition to Apollo mission Moon rocks. Studies of lunar and Martian meteorites complement studies of Apollo Moon rocks and the robotic exploration of Mars (see https://solarsystem.nasa.gov/meteors).

The systematic analysis of the bulk composition, mineralogy, and petrology of meteorites can be used to constrain planet formation processes as well as the evolution of the solar nebula [1, 2]. Determination of linkage between meteorites and their parent bodies is one of the critical goals of asteroid and meteorite studies. A multidisciplinary approach to the documentation and interpretation of a meteorite provides interesting opportunities for the understanding of this diverse scientific field (e.g., [3]). Meteorites provide the most substantial evidence of the chemical and physical makeup of asteroids. The study of meteorites describes the earliest formation history of the solar system, the various physicochemical processes involved in their time scales and the present state of the solar system, the connection of the solar system with the stellar environment, evolution of terrestrial planets, exploration of the origin and evolution of life, organic matter, and the dynamical processes involved in meteorite delivery to Earth, etc. In general, the fields of geology, chemistry, physics and astronomy are needed to understand meteorites and their relationships to bodies in the solar system. Planetary geology is another new science which began when we were first able to study other planets and the Moon closely. The explosive growth of the meteorite inventory has been accompanied by a steady growth in the science of meteoritics, and associated fields of observational small body astronomy, cosmochemistry, and astrobiology.

Meteorite Fall and Recovery

Meteorites which are recovered soon after they impact on the surface of the Earth with an observed fall event are called *falls*. These impacts by the meteorites produce some *impactites* (the melts, glass, etc., that are created during the impact of a meteorite). The meteorites that are collected with no visual evidence at the time of their fall event are considered *finds*. In the case of *finds*, it is worthwhile to consider careful chemical trends, as they may be affected by chemical interaction with the terrestrial environment depending on the time they spent on Earth. The best area in the world for collecting meteorites is the icy desert of Antarctica; from where more than 17,000 meteorite fragments have been collected by various teams of scientists from different countries.

Types of Meteorite

There are different types of meteorites that impact on Earth from different regions of the solar system and they have formed in a diverse environment in dissimilar ways. However, meteorites are broadly classified into two categories: Undifferentiated and Differentiated. Undifferentiated meteorites are also known as chondrites whereas achondrites, of stony iron and irons are examples of differentiated meteorites. Undifferentiated chondrites are the most primitive objects accreted very early from a solar nebula and identified by the presence of chondrules.

The stony meteorite is the most common type. The stony meteorites are generally made of rocks with small amounts of iron. This type of meteorite is further characterized into chondrites and achondrites. The chondrites are considered as the most common type of meteorite. The most notable point of chondritic meteorites is that they have not undergone any alteration or changes since they were formed. The chondritic meteorites are made up of circular mineral globules called *chondrules*. These chondrules were formed in space billions of years ago and became clumped together over the years. Therefore, chondritic meteorites are considered as the oldest rocks of our solar system. On the other hand, achondrites contain melted minerals which make them different to chondrites. In achondrites, the changes and alternation process of minerals happen because they are formed on the bodies with enough mass to support a molten interior. The achondrites are commonly younger than chondrites. The textures and mineral compositions of achondrites provide information about the formation history of their parent body. The iron meteorites are composed of pure nickel and iron metal with graphite and troilite as impurities. This type of meteorite is rare and very resistant to weathering. In contrast, the stony-iron meteorites are a mixture of both metallic and rocky material. Stony-iron meteorites are extremely rare. Like stony meteorites, the stony-iron meteorites are also characterized into pallasites and mesosiderites. Pallasite meteorites have solid metallic bodies of nickel and iron but also contain large translucent crystals of olivine within a metallic body. The mesosiderites are composed of equal amounts of metallic elements and silicate minerals.

Discriminate Meteorites from Terrestrial Rocks

As compared to terrestrial rocks, meteorites have unusual weight. It is one of their special characteristic features. The iron meteorites are generally 3.5 times heavier compared to ordinary terrestrial rocks, while the stony meteorites are about 1.5 times heavy then ordinary terrestrial rocks. Additionally, all meteorites have effectively passed through the atmosphere. Therefore, the meteorites have suffered from frictional forces which generate temperatures of more than 1800°C and hence their external morphology has gone through extraordinary changes in this process. At this high temperature, some minerals of the meteorites cannot re-crystallize but get deposited within the burn crust of the meteorites. Consequently, we can easily see the *fusion crust* on the surface of a meteorite. The thickness of the average fusion crust is generally less than 1 mm. This special feature has not been seen in any terrestrial rock. When the meteorite passes through the atmosphere, it becomes incandescent and rapidly loses mass due to melting which develops some surface pits or *regmaglypts* (human thumb print like impression) or on the fusion crust of the meteorite. In general, the generated temperature during the passage in the atmosphere causes the elemental iron of meteorites to oxidize and form the iron oxide and magnetite. It produces another important characteristic of the meteorite, that is – the meteorites have a magnetic property. This feature has also not been observed in any terrestrial rock.

In summary, the basic characteristics of meteorites used to discriminate them from terrestrial rocks are:

(i) Almost all meteorites contain at least some metal.
(ii) The density of meteorites is generally greater compared to regular rocks.
(iii) A lot of meteorites contain shiny iron-nickel metal grains or consist largely of iron-nickel metal and they are attracted by the magnet.

(iv) The primitive meteorites contain little round pieces of stony material called *chondrules*. These chondrules look somewhat like the spherical particles found in some sedimentary and volcanic rocks.

(v) While passing through the atmosphere, the meteors begin to heat up due to the extreme compression of the atmosphere. This heat melts the outer surface of the meteors, which produces a thin black/brown coating on the surface of the rock called a *fusion crust*.

(vi) During entry into the atmosphere, the surface melt of the meteorites is not uniform. Some surfaces of the meteorites are eroded by the melting more than others, which causes a little scraping out of material. The resulting surface looks like thumbprint impressions or *regmaglypts*. Generally, these *regmaglypts* have a size of less than a centimetre up to as much as 10 centimetres.

(vii) In general, most meteorites would not leave a streak, but the surfaces of some meteorites might leave a reddish streak if they have been oxidized (rusted).

Chondrules

Chondrules are composed of fine-grained dust particles of different compositions formed by rapid heating [4-6]. Detailed studies of different chondrites by Grossman et al. and Jones et al., suggested that there are numbers of different chondrule reservoirs with a variation of compositions found in our solar system [4, 7]. In general, chondrules of different chondritic groups show different features such as size, oxygen isotopic ratios, petrography, bulk composition, etc., but have similar overall properties among the chondritic groups [8-9]. This smaller variation allows us to classify chondrites in subgroups [7].

The major minerals found in chondrules are: olivine and low calcium pyroxene. They normally contain troilite (FeS), metallic Ni-Fe, and some oxides like chromite and phosphates (merrillite) [6]. The classifications of subgroups of chondrites are normally based on their compositions. The majority of chondrules are dominated by Fe and Mg, therefore it reveals ferromagnesian with a variation in Mg/(Mg+Fe) ratios [7]. The other chondrules which are dominated by Al, contain a higher amount of feldspar [10]. Based on the nature of silicates the chondrules are classified into two types (types I and II). The type I chondrules contain metallic Fe, and the Mg/(Mg+Fe) ratio is generally found to be higher than 0.9 in silicate minerals of the chondrules. They are also known as FeO-poor reduced chondrules. Alternatively, the type II chondrules contain minor metallic Fe, with the Mg/(Mg+Fe) ratio in between 0.6 and 0.9. The type II chondrules are also called FeO-rich oxidized chondrules [6-7, 11].

Igneous textures with some specific natures (e.g., shape) have been shown by both types of chondrules (types I and II). Depending on the textural variation, chondrules can be further categorized into porphyritic and non-porphyritic. The porphyritic chondrules are generally irregular in shape, and allow the formation of crystals of several micrometres in size due to partial melting with a very slow cooling rate of the fine-grained materials [4, 7, 12]. Based on the dominant minerals, porphyritic chondrules are characterized as porphyritic olivine, porphyritic pyroxene, and porphyritic olivine–pyroxene. However, the non-porphyritic chondrules have appeared as a spherical shape. These spherical shapes are due to the extensive heat which allows the grained materials to melt sufficiently following a fast cooling rate [6]. The type I porphyritic chondrules are further divided into two types: type IA and type IB. The olivine- and Ca-rich porphyritic chondrules are termed as type IA, in the same way; pyroxene and volatile components rich in chondrules are termed as type IB [12]. Generally, olivine-rich chondrules are also rich in refractoryinclusions and they can be changed into pyroxene-rich chondrules under some specific mechanisms [13]. Although, the type II chondrules exhibit variations of volatile components which reflect different formation conditions and processes like condensation of a melt [6, 14].

Classification of Meteorites

The pioneers of the meteorite classification scheme were Rose and Maskelyne, who initiated the classification scheme of the meteorite collection at the University Museum of Berlin and the British Museum collection in the early 1860s [16-17]. Maskelyne classified meteorites into irons (siderites), stony-irons (siderolites), and stones (aerolites). Rose was the first to categorize stones into chondrites and nonchondrites. In 1883, Tshermak made some modifications of the Rose classification and this modified classification scheme is known as the Tshermak-Rose classification scheme. Further, Brezina made some modifications of the Tshermak-Rose classification scheme. The chemical composition-based meteorite classification was first proposed by Farrington in 1907. In 1920, Prior developed a comprehensive meteorite classification scheme based on the previous classification schemes [17-20]. The Prior classification scheme was later modified by Mason in 1967 [21-23]. The current meteorite classification system is based on Prior and Mason's classification scheme and its modifications. This is the basic and brief development of the meteorite classification schemes.

Based on the bulk compositions and textures, meteorites can be divided into two major categories, *chondrites* and *nonchondritic* meteorites; the latter include the *primitive achondrites* and *igneously differentiated* meteorites. The modern meteorite classification scheme is based on structure and mineralogy, using chemical, isotropic and structural analysis. Another term *clan* is used for those chondrites which have chemical, mineralogical, and isotopic similarities suggesting a petrogenetic relationship, but have petrologic and/or bulk chemical characteristics which challenge a group relationship.

The statistical record shows that stony meteorites constitute 92.8% of all meteorites, stony-iron meteorites constitute nearly 1.5% and iron meteorites are found with an abundance of 5.7%. We have already mentioned in the previous section that stony meteorites are similar to common terrestrial rocks, and their mineral composition is dominated by silicates with little metal. This type of meteorite contains approximately 75-90% silicate (stony) minerals (mostly olivine and pyroxene) and 10-25% nickel-iron metal and iron sulphide. The chondrules are made from a number of minerals, mainly olivine and pyroxenes, and are the deposits of dust aggregates from the early solar system. The matrix of the chondrites is full of fine-grained silicate minerals like forsterite, anorthite, and pyroxene. These minerals play a vital role in the formation of chondrites. In contrast, the iron meteorites are mostly metallic in composition. They commonly consist of an alloy of iron (Fe) and nickel (Ni), in varying proportions. However, the stony-iron meteorites contain silicate and metallic phases approximately in equal amounts. The subgroup of stony meteorites, chondrites, contains chondrules. The vast majority of falls are stones (92.8%), most of which turn out to be chondrites (85.7% of all falls). The other subgroup, achondrites, makes up approximately 7% of all falls and finds and they are thought to be lavas or impact breccias from the surface of asteroids. The various classification schemes of primitive meteorites are shown in Fig.1-1.

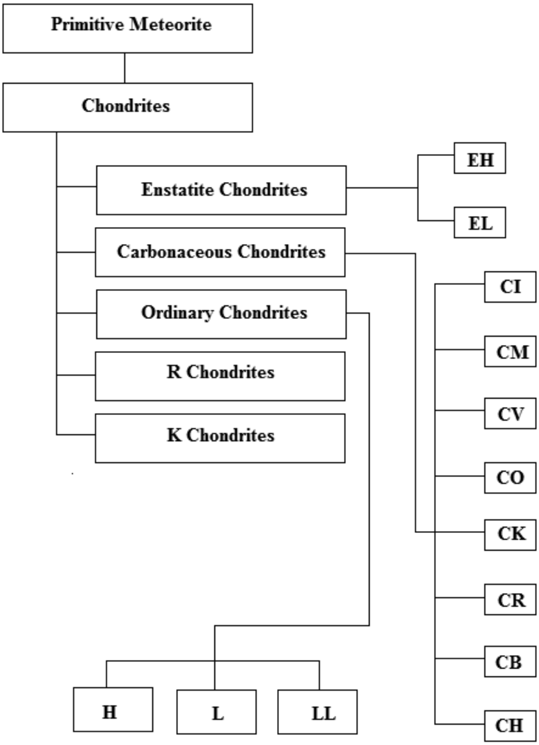

Fig. 1-1. The chondritic meteorites are subdivided into three major classes: Enstatite, Carbonaceous, and Ordinary. Two other groups: Rumuruti (R) chondrites and K chondrites are also shown.

Enstatite Chondrites

The meteorites belonging to enstatite chondrites or E chondrites are relatively rare. Only about 2% of all stony meteorites are categorized as E chondrites. Generally E chondrites are formed in an oxygen depleted environment. The iron contents in an E chondrite occur either as metal or as iron sulfide. The pyroxenes found in E chondrites are almost free from iron. As a result, this type of meteorite has nearly pure magnesium silicate or enstatite with less than 1 mole% iron-bearing fayalite. Due to this reason meteorites of this type are called enstatite chondrites or E chondrites. Depending on the total iron contents, the E chondrites are subdivided into H and L groups. The EH chondrites have about 30% total iron with more metal whereas the EL chondrites have about 25% total iron with less metal. These meteorites are further classified into EH3, EH4 and EL6 depending on their metamorphic and petrographic grade.

Carbonaceous Chondrites

The carbonaceous chondrites or C chondrites are very rare but extremely interesting. They make up only 2 or 3 percent of all meteorite falls and finds. Carbonaceous chondrites follow the petrographic and chemical classification scheme of the ordinary chondrites as they tend to have a dark matrix and well-defined chondrules. The fusion crusts of carbonaceous chondrites are dark grey to black in colour and their interiors are equally dark. Visually, they resemble charcoal briquettes and structurally they are very fragile in nature. Generally, higher abundances of magnesium, calcium, and aluminium are seen in carbonaceous chondrites relative to silicon than that found in ordinary chondrites. Carbonaceous chondrites are chemically the most oxidized of all chondrites. Their matrix also contains whitish irregular-shaped specks known as calcium aluminium-rich inclusions (CAIs). The mineralogy of CAIs is complex, being composed of highly refractory oxides such as melilite (calcium aluminium oxide), spinel (a magnesium aluminium oxide) and anorthite (a calcium aluminium silicate), etc. The CAIs consist of minerals uncommon on Earth, with high concentrations of refractory elements such as titanium. Another important fact is that, almost all carbonaceous chondrites show signs of aqueous alteration. There are eight subgroups of carbonaceous chondrites, these are: CI, CM, CV, CO, CR, CK, CB and CH.

Ordinary Chondrites

The chondrules are melted and made of very hard yellowish crystallized spherical-shaped inclusions of silicate minerals which are thought to have formed by flash heating as the solid matter in the solar system condensed. Generally, chondrules are submillimeter- to millimeter-sized. Details of chondrules have already been discussed in the previous section. The meteorites which contain chondrules are called chondrites. According to Weisberg et al., the term "*chondrites*" describes the chemical, mineralogical, and isotopic similarities that indicate the petrogenetic relationship, but they have petrologic and/or bulk chemical characteristics that challenge a group relationship [24]. Chondrites show wide variations in chondrule density as well as the description from specimen to specimen. Chondrites are the oldest known rocks formed during the birth of the solar system which makes samples available to study in the laboratory the best evidence of the origin of the solar system. Ordinary chondrites consist of variable amounts of metal and chondrules in the matrix of mainly silicate minerals. On the basis of the high abundance of large chondrules with various textures and mineral compositions, ordinary chondrites are categorized into the H, L, and LL groups. Normally, the chondrites are ultramafic in composition consisting mainly of iron, magnesium, silicon, and oxygen. The interiors of most ordinary chondrites commonly contain a uniform distribution of iron nickel metal grains. A wide range of similar composition but of different petrographic types (ordinary chondrite types 3, 4, 5, and 6) is found in ordinary chondrites. Some evidence of organic compounds (e.g., Dergaon) [25] and aqueous alternation is also reported by various workers in ordinary chondrites (e.g., Semarkona and Bishunpur) [e.g., 26-30]. The H, L, and LL groups of ordinary chondrites have similar and overlapping petrologic characteristics. The H group of ordinary chondrites contains 25-30% of total iron by weight; in which, between 15 and 19 wt.% of the iron is in the uncombined elemental state with the remnants chemically bound to the silicates. The L group of ordinary chondrites has 20 to 25 wt.% of total iron. This amount of iron is almost similar to that of the H chondrites. But the amount of metal in the L group of ordinary chondrites is much lower, its value in between 1 and 10 wt.%. However, in the LL group of ordinary chondrites the total combined iron is between 19 and 22 wt.%, but the iron as metal reaches the lowest amount, between <1 to about 3 wt.%.

R Chondrites

The Rumuruti-like, Rumurutiites or R chondrites are the most oxidized among all the chondrites. A high abundance of matrix can be seen in R chondrites. The refractory lithophile elements and moderately volatile element abundances are similar to those found in ordinary chondrites. The absence of significant reductions in manganese and sodium and enrichment in volatile elements (e.g., gallium, selenium, sulphur, and zinc) distinguish R chondrites from ordinary chondrites.

K Chondrites

A grouplet of two chondrites, Kakangari and Lewis Cliff 87232, is chemically and isotopically distinct from the ordinary, enstatite, and carbonaceous classes, although these meteorites have properties related to each [31-34]. The high matrix abundance (70-77 vol.%) of K chondrites is similar to that of the carbonaceous chondrites. The metal abundances in K chondrites are 6-9 vol.%, which are also similar to those of H chondrites. The mineralogical matrix composition is comparable to that of enstatite. However, the whole-rock oxygen isotopic compositions of K chondrites are below the terrestrial compositions.

Petrologic Types of Chondrites

The petrologic classification scheme is based on the degree of thermal and aqueous alteration experienced by a chondrite [34]. In this scheme, chondrites are divided into petrologic (or petrographic) types 1–6. The sequence of these types represents an increasing degree of chemical equilibrium and textural recrystallization, most likely due to thermal metamorphism. Type 1 represents a higher degree of aqueous alteration compared to type 2, based on the abundance of hydrous silicates. Type 3 chondrites are generally least modified by secondary processes. Type 3 and type 6 are correspondingly known as unequilibrated and equilibrated chondrites. Type 3 ordinary, CO, and CV chondrites are commonly subdivided into 10 subtypes (3.0–3.9), of which 3.0 is considered as the least metamorphosed one [35-36]. However, there are several ordinary and enstatite chondrites that experience extensive recrystallization and melting; these are commonly designated as type 7.

The degree of shock metamorphism in a chondrite is determined from a variety of mineralogical and textural parameters [e.g., see 38-39]. The shock classification scheme is based on the shock effects observed in the olivine and plagioclase of meteorites. As olivine is rare in enstatite chondrites, therefore the shock classification scheme is extended to orthopyroxene later [see 40].

Minerals in Chondrites

The International Mineralogical Association defines minerals as a chemical element or a chemical compound which is normally crystalline and that has been formed as a result of geological process. The geologic processes of the Earth have allowed nearly all of the naturally occurring chemical elements to participate in the formation of minerals. The minerals found in the primitive meteorites represent some process of the Universe that is responsible for the formation of those primitive minerals. Approximately 4,000 minerals have been identified up to now, out of those more than 280 minerals are found in meteorites. The terrestrial rocks are the different combinations of oxygen (O), silicon (Si), sodium (Na), calcium (Ca), potassium (K), aluminium (Al), magnesium (Mg), and iron (Fe). It is remarkable that the abundant minerals of meteorites are also composed of these elements. Some trace abundances of sulphur (S), chromium (Cr), phosphorus (P), carbon (C), and titanium (Ti) are also found in meteorites. Among these elements, the most abundant combination is the "silicon-oxygen tetrahedron" (its chemical formula is SiO_4^{-4} which is the building block of all silicate minerals), which is also common in meteorites. The most abundant minerals of chondrites, olivine and pyroxene, are also formed by different amounts and proportions of metal atoms among the silicon-oxygen tetrahedron or the silica tetrahedra produced in a variety of three-dimensional crystal lattices. Some common minerals found in meteorites are listed in Table 1-1.

Table 1-1. List of common minerals found in meteorites.

Mineral	Chemical formula
Albite	$NaAlSi_3O_8$
Akaganeite	β-FeO(OH, Cl)
Anorthite	$CaAl_2Si_2O_8$
Augite	$Mg(Fe, Ca)Si_2O_6$
Awaruite	Ni_3Fe
Bronzite	$(Mg, Fe)SiO_3$
Bytownite	$(Na, Ca)Al_2Si_2O_8$
Calcite	$CaCO_3$
Chromite	$FeCr_2O_4$
Clinoenstatite	$MgSiO_3$
Clinopyroxene	$(Ca, Mg, Fe)SiO_3$
Coesite	SiO_2
Cohenite	$(Fe, Ni)_3C$
Copper	Cu
Diamond	C
Diopside	$CaMgSi_2O_6$
Enstatite	$MgSiO_3$
Fayalite	Fe_2SiO_4
Feldspars	$(K, Na, Ca) (Si, Al)_4O_8$
Forsterite	Mg_2SiO_4
Goethite	α-FeO(OH)
Graphite	C
Hypersthene	$(Mg, Fe)SiO_3$
Ilmenite	$FeTiO_3$
Kamacite	γ-(Fe, Ni)
Lonsdaleite	C
Magnetite	Fe_3O_4

Maskelynite	$(Na, Ca)(Si, Al)_3O_8$
Mellilite	$(Ca, Na)_2 (Al, Mg)(Si, Al)_2O_7$
Olivine	$(Mg, Fe)_2SiO_4$
Orthoclase	$KAlSi_3O_8$
Orthopyroxene	$(Mg, Fe)SiO_3$
Pentlandite	$(Fe, Ni)_9S_8$
Perovskite	$CaTiO_3$
Pigeonite	$(Fe,Mg, Ca)SiO_3$
Plagioclase	$(Na, Ca)(Si, Al)_3O_8$
Plessite	(Fe, Ni)
Pyrrhotite	Fe1-xS
Quartz	SiO_2
Ringwoodite	$(Mg, Fe)_2SiO_4$
Schreibersite	$(Fe\ Ni)_3P$
Serpentine	$Mg_3Si_2O_5(OH)_4$
Silicon Carbide	SiC
Spinel	$MgAl_2O_4$
Stishovite	SiO_2
Taenite	γ-(Fe, Ni)
Troilite	FeS
Whitlockite	$Ca_9MgH(PO_4)_7$
Wollastonite	$CaSiO_3$

The most important and abundant mineral in ordinary chondrites is olivine. It is composed of varying amounts of iron and magnesium in combination with the silicon-oxygen tetrahedra with the chemical formula $(Fe, Mg)_2SiO_4$. The relative amounts of magnesium and iron ionic substitutions in solid solution determine the different types of olivine. Pyroxenes are one of the most abundant minerals in ordinary chondrites. The major difference between the olivines and pyroxenes is that the olivines have more metal than pyroxenes. Ordinary chondrites primarily contain low calcium orthopyroxene and enstatite ($MgSiO_3$). The metal found as the primary mineral in ordinary chondrites is elemental iron nickel (FeNi). Generally, iron in a meteorite is always seen as alloyed with nickel. In a meteorite, about 23% of total iron can be in the elemental state and the remaining iron can be observed in a combined form of iron oxide, carbides, sulphides, or combined in olivines and pyroxenes. The most common oxide of iron in meteorites is magnetite. Magnetite has a strong magnetic property and is considered as a major accessory mineral. In general, magnetites are formed and deposited in the fusion crust of stony meteorites when they burn up in the passage through the Earth's atmosphere.

In stony meteorites small amounts of iron sulphide (FeS) are found as accessory minerals. It is commonly referred to as troilite. Feldspars are another major accessory mineral found in meteorites. Feldspars are also common minerals found in the Earth's crust. In general, feldspars are found in accessory amounts in stony meteorites and stony-iron meteorites, but they are observed in large amounts in basaltic achondrites. The common feldspar in ordinary chondrites is plagioclase, which is formed by solid solution with variable properties of sodium and calcium ions.

However, glass is commonly found in many chondrites and achondrites. But, since glass has no crystalline structure, therefore it is not considered as a mineral. Glass is formed in meteorites, when molten silicate material cools rapidly and crystals have insufficient time to grow. Glass can be crystallized if heated (but not to melting) and then slowly cooled down. Minerals can turn into glass due to high-pressure impact. Maskelynite is one of the common examples of impact glass.

CHAPTER TWO

METEORITE FALLS AND FINDS IN NORTH-EAST INDIA

Introduction

The Meteoritical Bulletin has a database of recorded *falls* and *finds* of meteorites in India since 1621 (see the Appendix). This meteoritic database has also recorded two ancient impact craters of India. These ancient impact craters of India named Dhala (1700-2100 Ma) and Lonar (52000 ± 6000 Ma) are correspondingly found at Madhya Pradesh and Maharashtra. Studies of meteorites in India were initiated in the late 1960s. In this journey of meteorite studies, some remarkable outcomes have been achieved. For example, scrupulous studies of isotopes recorded in early solar system solids using secondary ion and noble gas mass spectrometry techniques at the Physical Research Laboratory (PRL), Admedabad, which led to the identification of fossil records of short-lived nuclides of stellar origin in early solar system solids; identification of the short-lived nuclide ^{26}Al as the heat source for early melting of planetesimals, etc. In comparison to the Indian meteorite recovery ratio, the *falls* and *finds* of the meteorite recovery rate in the north-eastern region of India are very low, yet some very special *finds* have been recovered (e.g., Goalpara Ureilite). This chapter discusses a rapid chronological survey of all meteorites from north-eastern India, including some of the most extensively-researched examples, with emphasis on the subjects of research in this field. The meteorite documentation era of the north-eastern region of India began with the documented meteorite Assam (L5) chondrite (1846) by Silberrad [41]. It is worthwhile to mention here that out of 151 documented meteorites from India (to date), only seven meteorites have been officially recognized by the international Nomenclature Committee of the Meteoritical Society from the north-eastern region of India with various sizes and chemical classes. A list of *falls* and *finds* of meteorites in the north-eastern region of India is presented in Table 2-1.

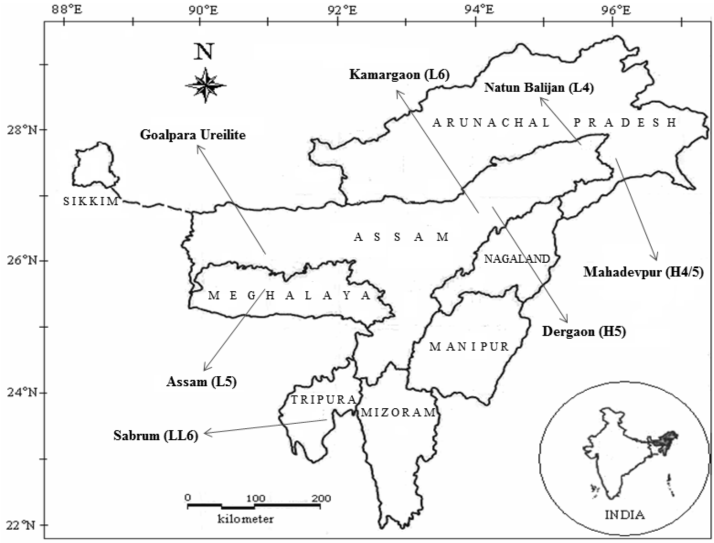

Fig. 2-1. Locations of meteorite *falls* and *finds* in the North-eastern region of India

Table 2-1. List of meteorite *falls* and *finds* in north-east India during the last two centuries

Meteorite	Fall/ Find	Year of Fall/Find	Weight (kg)	Fragments	Type
Assam	Find	1846	2.7	Three	L5
Goalpara	Find	1868	2.7	Single	Ureilite
Sabrum	Fall	30 April 1999	0.478	Single	LL6
Dergaon	Fall	2 March 2001	12.5	Multiple	H5
Mahadevpur	Fall	21 February 2007	70.5	Multiple	H4/5
Kamargaon	Fall	13 November 2015	12.1	Single	L6
Natun Balijan	Fall	5 June 2017	3.0	Single	L4

Brief Descriptions of and Research on these Meteorites

All meteorites from the north-eastern region of India belong to ordinary chondrites except Goalpara, which is a stony achondrite. As meteorites from this region are the most common type (i.e. ordinary chondrites), therefore, it is believed that they have originated from the debris of the solar nebula (e.g., [42-43]). Due to their unique origin, these chondrites are also regarded as the sole witness for the formation of the early solar system. Moreover, the Dergaon (H5) chondrite reports several significant observations that help to understand both nebular and asteroidal processes (e.g., [44]). The olivine group minerals found in these meteorites have been investigated by many authors (e.g., see [45-49]) which also throws light on the nature of the meteoritic olivines. The presence of nanodiamonds in the Dergaon (H5), Mahadevpur (H4/5), and Natun Balijan (L4) chondrites is also significant (usually carbon is rarely found in this type of meteorite). The finding of nanodiamonds in these meteorites has important implications concerning the origin of meteoritic diamonds. Meteorites still hold many secrets about our earth and other solar system bodies that are yet to be deciphered. The researches on the meteorite *falls* and *finds* in the north-east region of India will undeniably contribute to the understanding of these secrets.

(i). Assam (L5) Chondrite

Assam (Lat. 26°00′N; Long. 92°00′E) is the first documented meteorite *find* in the North-eastern region of India. The total known weight of this meteorite was 2.7 kg in the form of three fragments, and it was recovered from Meghalaya in 1846 [41]. The meteorite "Assam" is a fine representative of one of the most abundant meteorite classes, L5 chondrite. The photograph of the Assam (L5) chondrite is shown in Fig. 2-2.

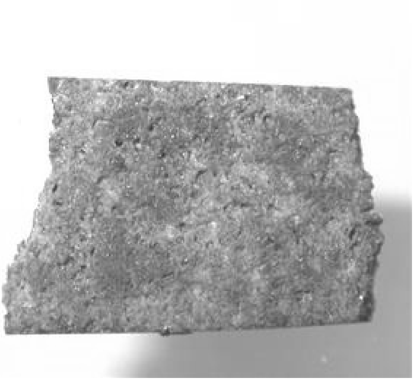

Fig. 2-2. Photograph of Assam L5 (*Credit: Encyclopaedia of Meteorites; Photo custody: Don Edwards*)

(ii). Goalpara Ureilite

The Goalpara (Lat. 26°10'N, Long. 90°36'E) meteorite was found in 1868, and classified as a stony meteorite that belongs to the ureilite achondrite. The ureilites are considered as a rare type of stony meteorite with a unique mineralogical composition which can be distinguished from other stony meteorites. The most important petrological properties of ureilite are: almost all ureilites are predominantly composed of anhedral to euhedral olivine and low- Ca clinopyroxene with un-inverted pigeonite. The major constituents of ureilites are carbon polymorphs, graphite, diamond, lonsdaleite, Fe-Ni metal, sulphides, and other accessory phases. Another distinguishing feature can be observed on the rare earth element pattern (REE) of ureilites. Generally, the characteristic chondrite-normalized rare earth element pattern for ureilites shows a V-shaped pattern, which displays both light (LREE) and heavy (HREE) enrichment with a marked depletion of intermediate-sized ions, particularly Eu [50].

In last few decades, the Goalpara ureilite has become arguably the most-researched meteorite from the north-eastern region of India. The total known mass of the Goalpara ureilite is 2.7 kg. Figure 2-3 shows the photograph of the Goalpara Ureilite.

The Goalpara ureilite is massive among all the ureilites that *fall* and *find* in India. Only three of this rare meteorite class have been documented from India, among them (except for the Goalpara ureilite) both the Dyalpur ureilite (1872) and the Lahrauli ureilite (1955) are reported *falls*. The Goalpara ureilite was also regarded as the most massive of this class known before the recovery of the Kenna ureilite in 1972. Berkley et al. investigated the composition of the Goalpura ureilite and found olivine group minerals: olivine ($Fo_{78.6}$, $Fa_{21.4}$) and pyroxene ($En_{76.3}$, $Fs_{19.0}$, $Wo_{4.7}$) [51]. The kamacite and troilite in the Goalpara ureilite were reported as 3.2 percent and 1.6 percent respectively. Generally, ureilites are carbon-bearing olivine-pigeonite achondrites [45]. An identical REE pattern for the Kenna ureilite, Goalpara ureilite, and Novo Urei ureilite has been observed by Boynton et al. [e.g., see 51]. The presence of organic carbon in the Goalpara ureilite was found by Vdovykin in the 1970s [52], while similar features of organic carbon were also measured in other ureilites (the Novo Urei and Dyalpur ureilites).