1

Minerals and Meteorites

Historical Foundations and Current Status

The use of minerals and rocks by primates for making primitive tools is not confined to our species. Some chimpanzees, long-tailed macaques, and wild bearded capuchin monkeys use stone tools to crack open nuts and fruits, and in the case of coastal-dwelling macaques, shuck oysters. Hominins were using stone tools to scrape flesh from ungulate carcasses 3.4 million years ago. By 1.6 million years ago, hominins had discovered that some rocks (e.g., flint, chert, rhyolite, quartzite) were more suitable than others (e.g., limestone, sandstone, shale) for making hand axes; they presumably developed crude criteria (e.g., color, heft, friability, location) for distinguishing them.

In the Upper Paleolithic and Neolithic eras, modern humans began to produce tools made of flint (opal and chalcedony) and jade (jadeite and nephrite) to manufacture arrowheads and spearpoints. They used gold for ornaments, and native copper for knives, bowls, and cups. Mineral pigments for cave painting and body decoration were made from hematite, red and yellow ocher (hematite mixed with clay), and white chalk. These materials were often used in conjunction with charcoal (from burnt wood) or carbon black (from charred wood, bone, ivory, vines, and stems). The oldest known cave painting (dating more than 40,000 years before the present) is of a four-footed animal, perhaps a banteng (a species of wild cattle), drawn in red ocher on the wall of a cave in Borneo.

Copper mining had begun in Europe by 5400 BCE – there is evidence that miners of the Vinča culture had sunk 20-m shafts at a site at Rudna Glava in Serbia. Within the limestone at that site, miners worked veins of copper ore, mainly malachite ($Cu_2CO_3(OH)_2$) and azurite ($Cu_3(CO_3)_2(OH)_2$), formed by the gradual weathering and decomposition of chalcopyrite ($CuFeS_2$) associated with magnetite (Fe_3O_4). The availability of copper in the Balkans and other regions helped usher in the Bronze Age. On the Iranian Plateau, the Bronze Age began in the fifth millennium BCE when arsenic-laden copper ore was smelted to make arsenical bronze. It took another 2,000 years before bronze was commonly made with tin. [Tin ore, primarily cassiterite (SnO_2), was smelted and added to molten copper to make tin bronze.] The advantage of tin over arsenic is twofold: arsenical bronze had to be work-hardened to become as strong as tin bronze, and it was easier to add specific amounts of tin to molten copper to achieve desired results than to rely on chemically heterogeneous arsenic-bearing copper ore. Both types of bronze are harder than copper and were used to make durable tools, weapons, and armor. New mineral pigments were also adopted: malachite (green), azurite (blue), and cinnabar (red).

There are several examples of metallic iron artifacts from the Bronze Age; specimens that have been analyzed appear to have been manufactured from meteoritic metal. These relics

Figure 1.1 A Chinese early Chou Dynasty bronze weapon with meteoritic iron blade. Photo from Gettens et al. (1971); used with permission from the Smithsonian Institution. (A black-and-white version of this figure will appear in some formats. For the colour version, please refer to the plate section.)

include knives, blades, and axes from China (Figure 1.1), Tutankhamun's dagger from Egypt, an axe from Syria, and needles and bracelets from Europe.

Toward the end of the second millennium BCE, craftsmen began smelting terrestrial iron ore (magnetite, hematite, goethite, limonite,[1] and siderite) and adding small amounts of carbon via local plants to make pig iron. Because iron ores tend to be impure, fluxing agents such as limestone were often used to remove slag. Iron tools and weapons proved superior to those made of bronze and within a few hundred years the technology spread through much of Europe, Asia, and the Middle East.

The Hebrew Scriptures (the earliest parts of which were probably written down in about the sixth century BCE) mention six metals (gold, silver, copper, tin, lead, iron) and one metallic alloy (bronze) as well as about a dozen precious and semiprecious gems (including emerald, topaz, ruby, beryl, turquoise, and several varieties of silica – carnelian, amethyst, agate, onyx, jasper) (New International Version translation).

As humans learned to utilize the resources of their geological environment more effectively, it eventually became apparent to scholars that a systematic approach was necessary to classify minerals and rocks. The more inquisitive yearned to understand the origin of these materials.

The earliest detailed discussions of minerals came from the Greeks. In the fourth century BCE, Aristotle wrote *Meteorologica* (*Meteorology*) and presented his ideas on how metals and minerals were formed: after being heated by the Sun, the Earth produced both moist and dry exhalations. Moist exhalations congealed within dry rocks to form metals such as iron, gold, and copper; dry effluvia may have caused certain rocks to burn and form infusible materials such as realgar, cinnabar, sulfur, and ocher. The idea that Earth emitted gases was well supported by observations of steam and smoke from volcanoes, hot springs, and fumaroles.

Aristotle's student, Theophrastus of Eresus, wrote the first mineralogical treatise, *Peri Lithon* (*On Stones*), in about 314 BCE. He cataloged numerous minerals that were being used and traded in Attica; he also characterized minerals by such physical properties as color, luster, transparency, fracture patterns, hardness, weight (density), and fusibility. He described contemporary techniques for extracting metals and testing their purity.

In the first century CE, the Roman naturalist Pliny the Elder wrote *Naturalis Historia* (*Natural History*), a compendium of the knowledge of the ancient world. In the last five

[1] Although limonite is not an IMA-approved mineral, it is a commonly used term referring to poorly characterized mixtures of hydrous iron oxides such as goethite. The name is often applied to weathering veins and rinds around metallic Fe-Ni grains in chondritic meteorite finds.

volumes of this massive work, he listed numerous minerals and gemstones, reported their crystal shapes, physical properties, and practical uses, and discussed the mining of metals. He cited numerous authorities who had previously written treatises on precious stones, but of these, only Theophrastus's work has survived.

The next known major mineralogical text is *Aljamahir fi Maerifat Aljawahir* (known in English as *Gems*), written 1,000 years later (in the eleventh century CE) by the Persian polymath, Abu Rayhan Muhammad Ibn Ahmad al-Biruni. Al-Biruni discussed the physical properties of minerals and explained how he had constructed a device for measuring specific gravity. He detailed the sources of metals and gemstones, reported their prices, and related anecdotes about specific specimens.

During the 1250s, Albertus Magnus, a German Catholic Dominican friar (later canonized a saint), wrote a monumental work, *Book of Minerals*, covering such topics as the hardness, porosity, density, and fissility of rocks (i.e., their propensity to split along planes of weakness), the properties of gems, the distribution of stones, and the taste, smell, color, and malleability of metals. He discussed whether stones have mystical powers such as curing abscesses, ridding the body of poison, bringing victory to soldiers, and reconciling the hearts of men.

Georgius Agricola (the Latinized name of Georg Bauer) was a sixteenth-century German physician, often called "The Father of Mineralogy." Agricola wrote *De natura fossilium* (*The Natural Minerals*) in 1548, which is essentially the first comprehensive mineralogy textbook. He introduced a systematic classification of minerals, described many new species, and discussed their physical properties and relationships. (The word *fossil* is from the Latin *fossilis* meaning "obtained by digging"; it was often used in this period in reference to minerals.) Agricola's most famous work is *De re metallica* (*On the Nature of Metals*),[2] which was published posthumously in 1556; it covered all aspects of mining including mineral exploration, mine construction, metal extraction, smelting, and refining; he even discussed the legal issues involving mine ownership and labor management. The metals included gold, silver, lead, tin, copper, iron, and mercury. The other mineral categories in Agricola's system were "earths" (mainly powdery argillaceous soils that turned into mud when moistened), "stones" (all manner of hard dry rocks, specifically including limestone, marble, gems, and geodes), and "congealed juices" (consisting of "salts" such as rock salt and alum, and "sulfurs" such as coal and bitumen).

Carl Linnaeus, the Swedish naturalist known as the "Father of Modern Taxonomy," introduced binomial nomenclature for living organisms in the first edition of *Systema Naturae* (*System of Nature*) in 1735. In the ensuing decades, expanded editions were published, eventually leading to the classification of more than 10,000 species. Linnaeus divided the natural world into the animal, plant, and mineral kingdoms. In the 10th edition of his great work (1758), the mineral kingdom was itself divided into three classes: (1) rocks, (2) minerals and ores, and (3) fossils and aggregates. He applied the binomial scheme to minerals, classifying quartz, for example, into white quartz (*Quartzum album*), colored quartz (*Quartzum tinctum*), and clear quartz (*Quartzum aqueum*).

Linnaeus was held in high regard by his contemporaries. The Genevan political philosopher Jean-Jacques Rousseau wrote that he (Rousseau) knew of "no greater man on Earth." Linnaeus

[2] The first English translation of *De re metallica* was made in 1912 by mining engineer and future US President (1929–1933), Herbert Hoover, and his wife, Lou Henry Hoover, a geologist and Latinist. The work was widely acclaimed for its clarity of exposition and informative footnotes.

appears to have shared this view. He often proclaimed "*Deus creavit, Linnaeus disposuit*" ("God created, Linneaus organized") and wrote in his autobiography that "No one has more completely changed a whole science and initiated a new epoch." Linnaeus was ennobled in 1761 and assumed the name Carl von Linné.

One of Linnaeus' most ardent devotees was Abraham Gottlob Werner,[3] a German geologist best known for his theory of neptunism, the subsequently discredited idea that all rocks on the Earth's surface precipitated successively from a deep, hot, viscous, mineral-laden globe-encircling ocean. Rocks of each type were envisioned by Werner as having been deposited all over the Earth at the same time; for example, granites in North America were supposed to be the same age as granites in Europe, Africa and Asia. However, stratigraphic relationships (and, much later, radiometric dating) showed this was not the case. Werner also maintained that basalt had an aqueous origin despite field studies demonstrating it erupted from volcanoes.

Werner's first important work was *Von den äusserlichen Kennzeichen der Fossilien* (*On the External Characteristics of Minerals*), published in 1774. In that treatise he developed a mineral classification scheme, which allowed field geologists to identify minerals accurately by using only qualitative measurements of their external physical properties, e.g., color, hardness, shape, luster, specific gravity, odor, etc. He divided the subject of mineralogy into three major fields of study: (1) identification and classification, (2) distribution, and (3) formation. The book was translated into several languages and used as a field manual by many European and American geologists.

Throughout the eighteenth century, scholars became well acquainted with the physical properties of a wide range of mineral specimens, but the modern science of mineralogy could not flourish until further advances were made in petrography, crystallography, and mineral chemistry. The pioneers in these fields are often honored as founding fathers.

Petrography. The Scottish geologist, William Nicol, invented the polarizing microscope in the early nineteenth entury using Iceland spar (a transparent form of calcite); in 1815 he developed a technique for making thin sections of rocks and minerals. These advances were put to good use by British geologist Henry Clifton Sorby, sometimes called "The Father of Microscopic Petrography" for his detailed studies of terrestrial-rock thin sections in transmitted light with the polarizing microscope (Marvin 2006). Sorby also earned the sobriquet "The Father of Metallography" for his reflected-light microscopic studies of acid-etched iron and steel. He is best known in the meteoritics community for suggesting in 1877 that one possible origin for chondrules is as "droplets of fiery rain" that condensed from interplanetary gas early in the history of the Solar System.

Crystallography. Abbé René-Just Haüy, an eighteenth-century French mineralogist, is often called "The Father of Crystallography." In his seminal 1801 work, *Traité de Minéralogie* (*Treatise on Mineralogy*), he reported examining some crystals that were broken and other crystals that had been deliberately cut into smaller indivisible chunks. He noted their congruent shapes and compared the primitive crystal forms of different classes of minerals. He studied

[3] One of Werner's students was the Prussian naturalist Alexander von Humboldt who eschewed neptunism after studying volcanic rocks and ash in the Andes. Humboldt was among the first to propose that Africa and South America had once been joined, implicitly invoking continental drift. One of Humboldt's close friends was the great German writer Johann Wolfgang von Goethe (of *Faust* fame) who had amassed the largest private collection of minerals in Europe. By the time Goethe died in 1832, he had collected nearly 18,000 rock and mineral samples. The mineral goethite (α-FeO(OH)) is named in his honor.

cleavage planes, measured interfacial angles, and explored pyroelectricity. Haüy explained that "A casual glance at crystals may lead to the idea that they were pure sports of nature, but this is simply an elegant way of declaring one's ignorance. With a thoughtful examination of them, we discover laws of arrangement" (Levin 1990). Ultimately, Haüy described all known minerals by crystal class and chemical composition. It was not until the early twenthieth century that the British father-and-son team of William Henry Bragg and Lawrence Bragg developed X-ray crystallography and explored the structures of crystals in unprecedented detail.

Mineral chemistry. The Swedish chemist, Torbern Bergman, made great advances in the quantitative chemical analysis of mineral species. His 1774 study of a magnesian ankerite ($Ca(Fe,Mg)(CO_3)_2$) may be the first complete chemical analysis of an individual mineral (Hey 1973). Over the next decade, Bergman analyzed other phases and developed a mineral classification scheme based on their chemical and physical properties. In 1784 (the year of Bergman's death), Irish geologist Richard Kirwan published his first edition of *Elements of Mineralogy*, in which he listed the bulk chemical analyses of 74 rocks and minerals. As advances in inorganic chemistry led to an increase in the number of recognized elements (from 23 in 1789 – excluding 10 erroneous entries from a list published by Antoine-Laurent Lavoisier – to 42 in 1800), mineral analyses became more accurate. The first full textbook on mineral chemistry – *Handbuch zur chemischen Analyse der Mineralkörper* (*Handbook on the Chemical Analysis of Mineral Bodies*) – was published in 1801 by the German pharmacist and chemist, Wilhelm August Lampadius.

The Swedish chemist Baron Jöns Jacob Berzelius was the first to designate chemical elements by one- or two-letter symbols (e.g., H, O, Fe, Au), create molecular formulas (e.g., H_2O in modern form), and discover that the constituent elements of pure mineral phases are in constant proportions (e.g., $Ca_1C_1O_3$). He used the formulas to denote chemical reactions, e.g., $H_2SO_4 + Cu \rightarrow CuSO_4 + H_2$. By 1824 he had recognized that the chemical behavior of minerals was influenced more by their anion components (e.g., CO_3, O, S) than their cations (e.g., Ca, Fe, Mg) and divided minerals into groups accordingly, e.g. carbonates, oxides, sulfides, etc. He also identified the elements silicon, selenium, thorium, and cesium. Johan August Arfwedson, a Swedish chemist working in Berzelius's lab, discovered lithium in petalite ore (castorite, $LiAlSi_4O_{10}$) in 1817.

The American mineralogist James Dwight Dana published the first edition of his *System of Mineralogy* in 1837, adopting Linnaean binomial nomenclature (e.g., *Adamas octahedrus* for diamond) and grouping minerals by superficial appearance into higher orders [e.g., diamond, quartz, sapphire, and beryl were lumped into the order *Hyalinea* (hyaline means glassy or transparent)]. However, by the third (1850) and fourth (1854) editions, Dana had revised the nomenclature, coupling the approaches of Berzelius and Haüy. He formulated primary mineral groups: native elements, sulfides, halides, and oxides, and divided oxides into silicates, phosphates, sulfates, and carbonates. This system had been universally adopted by the 1870s, and an expanded version is used today in every mineralogy textbook.

With the development of modern analytical techniques (see McSween and Huss 2010), the number of recognized mineral species jumped from about 200 in 1750 to more than 5670 in early 2021. A periodically updated list of approved minerals is currently available online from the International Mineralogical Association (IAU): www.ima-mineralogy.org; click on "List of Minerals."

Comprehensive mineralogical studies of meteorites had to wait until meteorites were recognized as genuine extraterrestrial objects. There had long been reports of rocks falling from the sky. Joshua 10:11 (New Revised Standard Version) (written in the sixth or seventh century BCE) states: "As [the Amorites] fled before Israel, while they were going down the slope of Beth-horon, the Lord threw down huge stones from heaven on them as far as Azekah, and they died. . ." The passage conflates these huge stones with hailstones: "There were more who died because of the hailstones than the Israelites killed with the sword." Revelations 16:21 (NRSV) (first century CE) states that "And there fell upon men a great hail out of heaven, every stone about the weight of a talent. . ." (King James Version) (i.e., in the range of 33 to 50 kg). The largest authenticated hailstones are only ~1 kg, so stones much more massive than this could not be hail. In the play, *Prometheus Unbound* (attributed to the fifth-century BCE Greek tragedian Aeschylus), an enraged Zeus hurls a shower of stones down to Earth. Falling stones were later discussed by Livy (64 or 59 BCE to 12 or 17 CE), Pliny the Elder (23–79 CE) and Plutarch (46–120 CE). In his book, *Liber Prodigiorum* (*Book of Prodigies*), the pseudonymous fourth-century CE Roman historian, Julius Obsequens, described six events of stones raining on the Italian peninsula between 188 BCE and 94 BCE (Franza and Pratesi 2020).

The idea of rocks falling from the sky was bolstered by numerous observations of meteors and fireballs, but most eighteenth-century CE scientists remained unconvinced. There were reasons for their skepticism. No less an authority than Isaac Newton had declared in 1704 in *Opticks* that interplanetary space was devoid of small solid objects: ". . .to make way for the regular and lasting Motions of the Planets and Comets, it's necessary to empty the Heavens of all Matter, except perhaps some very thin Vapours, Steams, or Effluvia, arising from the Atmospheres of the Earth, Planets, and Comets." Newton's views on the barrenness of space were similar to those of Aristotle and were widely accepted. Also muddling the situation was the fact that actual observations of falling rocks (some with good documentation) were mixed in with fantastic reports of all sorts of objects dropping from the sky: flesh, blood, milk, wool, bricks, paper, money, and gelatin (Burke 1986). It was hard to separate the wheat from the chaff (neither of which was reported to have fallen to Earth).

Some scientists accepted the idea that rocks fell from the sky but averred that they were terrestrial rocks ejected from volcanoes (akin to volcanic bombs), borne aloft by hurricanes, generated by the Northern Lights, or, following Aristotle, precipitated in cold regions of the atmosphere. In 1789, Antoine-Laurent de Lavoisier, often called "The Father of Modern Chemistry," published his seminal textbook, *Traité élémentaire de chimie* (*Elementary Treatise on Chemistry*). He suggested that dust (consisting of stony and metallic particles), entrained in gas, emanated from the Earth and rose high into the atmosphere. There it was ignited by electricity and fused into solid bodies that fell to the ground. [American polymath and Founding Father, Benjamin Franklin (1706–1790), had shown decades earlier that lightning was an electrical phenomenon.]

Five developments in the late eighteenth and early nineteenth centuries finally established the reality that extraterrestrial rocks fall to Earth.

(1) In 1794, the German physicist, Ernst Chladni (already famous as "The Father of Acoustics") published a monograph, *Über den Ursprung der von Pallas gefundenen und anderer ihr ähnlicher Eisenmassen und über einige damit in Verbindung stehende*

Naturerscheinungen (*On the Origin of the Iron Masses Found by Pallas and Others Similar to it, and on Some Associated Natural Phenomena*), postulating that material from space entered the Earth's atmosphere, produced fireballs and dropped meteorites. The book was widely discussed but initially received mixed reviews.

(2) At the suggestion of Chladni, two German physicists, Johann Benzenberg and Heinrich Brandes, simultaneously observed the sky in September and October 1798 from sites 15.6 km apart to determine the height and speed of meteors (Marvin 2006). They made numerous simultaneous observations and concluded that meteors are visible at altitudes ranging from 170 to 26 km and travel at 29–44 km s^{-1}. (In modern usage, the bodies traversing the atmosphere are meteoroids, not meteors.) It was hard to imagine rocks lofted from the Earth reaching those heights or matching those speeds.

(3) In 1802, the British chemist, Edward Charles Howard, published a groundbreaking report in *Philosophical Transactions* titled "Experiments and Observations on Certain Stony and Metalline Substances, Which at Different Times are Said to Have Fallen on the Earth; Also on Various Kinds of Native Iron",[4] showing that several meteoritic stones had similar compositions; they all contained nickel as did all meteoritic irons. This indicated a common origin. [Nickel had been discovered in 1751 in niccolite (NiAs) by the Swedish mineralogist and chemist Baron Axel Fredrik Cronstedt. The mineral cronstedtite ($Fe_2^{2+}Fe^{3+}(SiFe^{3+})O_5(OH)_4$) (found intergrown with tochilinite in many CM chondrites) was named after him.]

(4) There was a spate of well-documented meteorite falls including Siena (Italy, 1794), Wold Cottage (England, 1795), Portugal (from the town of Évora Monte, 1796), Salles (France, 1798), Benares (India, 1798), L'Aigle (France, 1803), and Weston (Connecticut, USA, 1807).

(5) The discovery of asteroids proved that interplanetary space was not empty of small bodies after all: Ceres in 1801, Pallas in 1802, Juno in 1804, and Vesta in 1807. Along with the Moon, asteroids provided a potential source of extraterrestrial material. This idea became more plausible after Wilhelm Olbers suggested in 1803 that Ceres and Pallas were remnants of a planet that had been destroyed after suffering an internal explosion or a catastrophic collision with a comet.

A few scholars acknowledged the existence of extraterrestrial rocks and theorized that they had been blasted out of lunar volcanoes. (At the time, most scientists thought lunar craters were volcanic.) These workers cited the English physicist Robert Hooke who had concluded (after some hesitation) in *Micrographia* in 1665 that lunar craters were volcanic after he examined pits formed at the surface of boiled alabaster. This idea was consistent with sporadic observations of short-lived luminous events on the Moon. The great British astronomer William Herschel (discoverer of Uranus in 1781) reported seeing three luminous red spots beyond the terminator on the night side of the Moon on 19 April 1787; he suggested these were glowing gases disgorged from active lunar volcanoes. Other British, French, and German astronomers made

[4] Associated with this paper is one by Jacques-Louis, Count de Bournon, "Mineralogical Description of the various Stones said to have fallen upon the Earth," that contains the first published descriptions of chondrules ("small bodies, some of which are perfectly globular, others rather elongated or elliptical") as well as fine-grained silicate matrix material (a whitish gray substance with "an earthy consistence"). He also described (although not for the first time) two phases: troilite (characterizing it as nonmagnetic "martial pyrite") and fine-grained metallic iron.

similar observations in this time period. Two centuries after Hooke's monograph, English amateur-astronomer and media personality Patrick Moore termed such luminous events *lunar transient phenomena* (LTPs).

To nineteenth-century scientists, a lunar origin for meteorites was consistent with their chemical similarities (all contained Ni and were presumed to be from a common source) and the fact that the average specific gravity of stony meteorites (~3.34 g cm^{-3}) is the same as that of the bulk Moon.[5]

But there were problems with the suggestion that meteorites were all derived from lunar volcanoes: (1) The velocities of meteors (i.e., meteoroids) were observed to be tens of kilometers per second, seemingly far too great for those objects to have been disgorged from lunar volcanoes. (2) In 1859, American astronomer Benjamin Gould calculated that only 0.00006 percent of rock fragments from lunar volcanoes were likely to reach Earth (and of those few fragments, more than 70 percent would fall in the ocean). The paltry number of expected lunar volcanic ejecta fragments in the hands of scientists seemed grossly inconsistent with the relatively large number of meteorites known at the time (~160). (3) The German physician and astronomer, Franz von Paula Gruithuisen, suggested in 1828 that lunar craters formed by collisions. Grove Karl Gilbert, senior geologist at the United States Geological Survey, wrote an article in 1893 titled "The Moon's Face: A Study of the Origin of its Features," endorsing the impact theory. He measured lunar-crater depth/diameter ratios and explained central peaks as rebounded target material, crater rays as impact ejecta, and terraces inside craters as slumped crater walls.

There *are* volcanic features on the Moon. These include the maria (vast plains of flood basalt), sinuous rilles (collapsed lava tubes), and the Marius Hills (small volcanic domes). But major volcanism on the Moon probably ended more than a billion years ago. No meteorites have been hurled to Earth from lunar volcanoes; the lunar meteorites in our collections (~0.5 percent of samples) were launched by high-velocity collisions of asteroids with the Moon.

[5] The question may arise as to how nineteenth-century scientists knew the density of the Moon. It is a complicated story. The size of the Earth was determined long ago by Eratosthenes. On the summer solstice in c. 230 BCE at local noon, he observed the Sun close to the zenith, i.e., directly over a deep well in Syene, Egypt (now Aswan); in Alexandria at noon on the same day one year later, a vertical rod (a gnomon) cast a shadow. Eratosthenes measured the length of the shadow, and using geometry found that the Sun was 7.2° south of the zenith. The two Egyptian cities were a known distance apart (5,000 stadia, where 1 stade = 184.8 m) and were approximately on a north–south line. He assumed the Earth was a sphere because it cast a curved shadow on the Moon during total lunar eclipses. He divided 7.2° by 360° and found that the distance between these cities was 2 percent of the Earth's circumference. He multiplied the linear distance between the cities by 50 to determine the circumference of the Earth to within about 15 percent of the actual value. Of course, by the nineteenth century, the Earth had been circumnavigated (starting with the Magellan–Elcano expedition, 1519–1522), its size was well known, and accurate maps were available.

In 1686 Isaac Newton published his Law of Universal Gravitation [$F_{\rm grav} = G \cdot ((m_1 \times m_2)/r^2)$], where F_{grav} is the force of gravity, m is mass, r is distance, and G is the gravitational constant; the following year, Newton presented his second law of motion, showing that $F_{\rm grav} = m \times g$, where g is the acceleration of gravity at the Earth's surface. Experiments showed that g is 9.8 m s^{-2}. Using a torsion balance in 1789, Henry Cavendish determined an accurate value for the gravitational constant G. These parameters plus simple algebra allowed measurement of the mass of the Earth.

The distance to the Moon was first estimated by Aristarchus in c. 270 BCE by timing how long it took the Moon to pass through Earth's shadow during total lunar eclipses. He timed it at about 3 hours and calculated that the Earth's shadow was approximately 2.5 times the apparent diameter of the Moon. By using simple geometry, he found that the Moon is about 60 Earth radii away, within 1 percent of the actual value. The Earth–Moon distance can also be computed by parallax if two observers situated a long (and known) distance apart observe the Moon against the background stars at the same time and note the apparent shift in perspective. Trigonometry then provides the distance. Subsequent refinements of the Earth–Moon distance allowed nineteenth-century scientists to determine the Moon's mass from the Law of Universal Gravitation (as the Earth's mass and the value of g were already known).

The Moon subtends an angle of ~0.5° in the sky; because the distance between the Earth and Moon was known, simple geometry yielded the Moon's diameter (and hence its volume). Because density = mass/volume, once the latter values were measured, the Moon's density was easily calculated.

Modern explanations for LTPs include small meteorite impacts (but most are relatively faint and last less than a second as observed in Earth-based telescopes),[6] outgassing through fractures, electrostatic forces, thermoluminescence, terrestrial atmospheric turbulence, bad telescopic optics, and overactive imaginations.

In 1857, the German chemist, Karl Ludwig von Reichenbach, became the first to study meteoritic minerals in the microscope. By 1870, British geologist, Mervyn Herbert Nevil Story-Maskelyne, and his assistant, Austrian chemist Viktor von Lang, had studied the microscopic properties of more than 140 meteorites. Six years later, Austrian mineralogist Gustav Tschermak von Seysenegg initiated a project of photomicroscopy of meteorite thin sections, resulting a decade later in his monograph, *Die mikroskopische Beschaffenheit der Meteoriten* (*The Microscopic Properties of Meteorites*). In that work, Tschermak identified 16 meteoritic minerals as well as maskelynite and igneous glass.

By the middle of the twentieth century, the list of recognized meteoritic minerals had expanded only modestly, reaching 26 in 1960 and 38 in 1962 (Rubin 1997a). In the following decades, the widespread use of reflected light microscopy, the development and continual improvement of analytical techniques down to micro- and nanoscales (e.g., X-ray diffraction, electron microprobe analysis, scanning electron microscopy, and transmission electron microscopy), the recovery of tens of thousands of meteorites from hot and cold deserts, and a sharp increase in the number of meteorite researchers led to the identification of numerous minerals in meteorites. Toward the end of the twentieth century, Rubin (1997a, 1997b) compiled a list of about 300 meteoritic minerals. Two decades later, Rubin and Ma (2017) added another ~135 species to the list.

The number of meteoritic minerals is large because meteorites are derived from many different bodies, each with a distinctive geochemical character. Meteorites are now thought to come from about 100 to 150 asteroids[7] as well as from the Moon and Mars. Micrometeorites are derived mostly from asteroids; a minority (particularly those with ultracarbonaceous compositions) are likely from comets. Because interplanetary dust particles (IDPs) (also known as cosmic dust) are also meteoritic materials, the number of source bodies delivering extraterrestrial material to Earth may be several hundred to several thousand. But these are not the only bodies represented among meteoritic materials: primitive chondrites contain tiny presolar grains

[6] On the night of 20–21 January 2019, a small meteorite or comet, modeled as a mass of ~10 kg, crashed into the Moon during a total lunar eclipse. It produced a brief (0.3-second) yellow-white flash observed by multiple telescopes.

[7] The inference that the vast majority of meteorites are derived from asteroids is based on more than a dozen links pertaining to parent-body size, orbital characteristics, and physical properties: (1) The metallographic cooling rates of many stony and iron meteorites are in the range of 1–100°C/Ma, suggesting they were derived from bodies a few hundred kilometers in size; (2) the presence of solar-wind-implanted noble gases in regolith breccias indicates that these rocks are from bodies too small to retain significant atmospheres; (3) the relatively high concentrations of solar-wind gas are consistent with implantation at about 3 AU away from the Sun; (4) the old formation ages of most meteorites (~4.56 Ga) indicate they came from small bodies that cooled very early in the history of the Solar System; (5) the gravitational influence of Jupiter is expected to perturb some main belt asteroids into resonances that facilitate transfer to the inner Solar System; (6) the cosmic ray exposure (CRE) ages of many stony meteorites are in the range of 30 ka to 70 Ma, consistent with the time inferred for bodies in the asteroid belt to achieve Earth-crossing orbits; (7) the orbits of more than a thousand fireballs (including about three dozen that yielded recovered meteorites) were determined to be very similar to those of Earth-crossing asteroids; (8) the spectral reflectivities of some asteroids match those of meteorites measured in the lab; (9) the brecciated nature of many meteorites is consistent with the extensive cratering evident on many asteroids; (10) material returned from asteroid 25143 Itokawa matches that of LL chondrites; (11) the *Dawn* spacecraft's measurements of the composition and mineralogy of the surface of asteroid 4 Vesta match those of HED meteorites analyzed in the lab; (12) asteroid 2008 TC_3, which crashed into the Sudan ~19 hours after its discovery, yielded the Almahata Sitta polymict ureilite breccia; and (13) asteroid 2018 LA, which crashed into Botswana ~8 hours after discovery, yielded about two dozen howardite specimens.

that formed in the outflows of evolved stars and as supernova ejecta. Most of these particles appear to predate the Solar System by a few hundred million years, but at least 8 percent of the largest grains are more than a billion years older than the Sun (Heck et al. 2020).

Meteorites formed under a variety of conditions: primitive chondrites are interpreted to be products of the processes that occurred in the solar nebula (modified by impact-induced compaction and minor to extensive alteration on their parent asteroids), most iron meteorites formed deep within the cores of differentiated asteroids, regolith breccias formed near the surface of their (atmosphere-less) parent bodies and contain solar-wind-implanted noble gases, most eucrites formed from basaltic lava in the near-surface regions of a single differentiated asteroid (probably 4 Vesta), and martian and lunar meteorites formed as igneous rocks on substantially larger planetary and subplanetary bodies.

Meteorites exhibit diverse oxidation states, ranging from highly oxidized CI carbonaceous chondrites (which contain ~11 wt% H_2O^+ (indigenous water), mainly bound in fine-grained phyllosilicates) to highly reduced enstatite chondrites and aubrites (which contain graphite, Si-bearing metallic Fe-Ni, sulfides bearing Na, Mg, K, Ca, Ti, Cr, Mn, and Fe, and enstatite with very low FeO). The diversity in oxidation state among meteorites is reflected in the set of meteoritic minerals: e.g., elemental C, carbides, and carbonates; alloyed metallic Mo and molybdates; phosphides and phosphates; alloyed metallic Si, silicides, and silicates; elemental S, sulfides, and sulfates; and metallic Fe, wüstite (containing ferrous iron), magnetite (containing both ferrous and ferric iron), and hematite (containing ferric iron).

About 470 minerals have so far been identified in meteorites (Tables 1.1 and 1.2) and more are in the pipeline; this is about 8.3 percent of the total number of well-characterized mineral phases. Meteorite mineral species include native elements, metals and metallic alloys, carbides, nitrides and oxynitrides, phosphides, silicides, sulfides and hydroxysulfides, tellurides, arsenides and sulfarsenides, halides, oxides, hydroxides, carbonates, sulfates, molybdates, tungstates, phosphates and silico phosphates, oxalates, and silicates from all six structural groups (Table 1.1).

Although water ice is not a meteoritic mineral, it may have left traces in the matrices of primitive chondrites in the form of small ultraporous regions. Ice currently occurs on planets (e.g., Earth, Mercury, Mars); dwarf planets (Pluto, Haumea, Eris); moons (e.g., Moon, Europa, Titan); and asteroids. It was detected at the surface of 24 Themis (a 198 km-wide C-asteroid) (Campins et al. 2010; Rivkin and Emery 2010) and found within pyroxene grains from 25143 Itokawa (a subkilometer S-asteroid) (Jin and Bose 2019). Because ice would sublimate quickly at the surface of asteroids in the main belt, there has probably been recent outgassing of water vapor from the interior of Themis and condensation of ice around regolith grains (Rivkin and Emery 2010).

The astronomical menagerie includes such diverse objects as asymptotic giant branch stars, white dwarfs, black holes, neutron stars, Bok globules, Herbig–Haro objects, and planetary nebulae. Our knowledge of the cosmos deepens with the discovery of new members of the menagerie and the discernment of their interrelationships. Our knowledge of the bodies in the Solar System increases with the discovery of new mineral phases and the determination of their formation histories. The study of meteoritic minerals has broadened our understanding of the solar nebula, the geological history of asteroids and comets, the evolution of the Moon and Mars, impact phenomena, alteration and weathering processes, the physics of dying stars, and the nature of the interstellar medium.