

## ***April 2004 Mineral of the Month: Kamacite***

"The fireball was so bright that it cast moving shadows in broad daylight. . . . Nearly every witness saw it changing color; red predominated, especially toward the end of the flight. An enormous, boiling, multicolored smoke train extended behind the fireball, marking its southerly path across the sky."

--O. Richard Norton, *Rocks From Space*

### *PHYSICAL PROPERTIES*

Chemistry: (Fe,Ni), alpha-Nickel-iron, low-temperature phase, iron-nickel alloy with small amounts of cobalt

Class: Native Metals    Group: Iron-nickel

Occurrence: Primarily in iron meteorites

Crystal System: Isometric

Crystal Habits: Massive, consisting of uniformly indistinguishable crystals

Color: Iron-black to steel-gray

Luster: Metallic

Transparency: Opaque

Streak: Gray

Cleavage: Indistinct

Fracture: Hackly, often showing jagged, torn surfaces typical of fractured metal

Hardness: 4.0

Specific Gravity: 7.9

Distinctive Features and Tests: Density, hardness, metallic luster when scratched, occurrence in meteorites

Dana Classification Number: 1.1.11.1

### *NAME*

Pronounced KAY-ma-site, the name kamacite derives from the Greek *kamask*, meaning "shaft" or "lath," and is of uncertain reference. Kamacite has also been known as "balkeneisen" and "kamacita."

### *METEORITES*

A piece of another planet! Even non-mineral lovers are fascinated by meteorites and their origins, including their dynamic means of arriving to Earth. We are happy to (at last) be able to feature these extra terrestrials in our 98<sup>th</sup> month, and thought we should modify slightly our usual format to suit them, starting with an introduction.

The words "meteorite," "meteor," "meteoroid," and similar words stem from the Greek *meteōron*, meaning "phenomenon in the sky." *Meteoroids* are fragments of asteroid parent bodies (small planetary bodies ranging in size from one-half mile to nearly 500 miles) which orbit the Sun. A *meteor* is a meteoroid that becomes directly observable by incandescence produced by frictional heating upon entering the atmosphere. A *meteorite* is a fragment of a meteoroid that has passed through the atmosphere to arrive on the Earth's surface intact. *Meteoritics* is the study of meteorites and the origin of the solar system, and *meteoriticists* are metallurgists, chemists, or mineralogists who study meteorites.

Millions of meteoroids, mostly dust-sized to pea-sized particles, enter the Earth's atmosphere each year at speeds of 10 to 26 miles per second (36,000 to 94,000 miles per hour) to become meteors. Upon entering the atmosphere, friction with air molecules converts their kinetic energy to heat, light, and

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sound. Meteors become luminous at an altitude of about 60 miles, where the air has sufficient density to resist their motion. As temperatures approach 3,000° F., their outer sections melt, become incandescent, and fragment. Simultaneously, the surrounding air ionizes and also become incandescent. The solid body of a meteor just one foot in diameter can produce a glowing mass of air hundreds of feet across—the “fireball” commonly known as a “shooting star.” Fireball colors vary with both the composition of the atmosphere and the meteor, with individual metals, minerals, and gases emitting specific, characteristic incandescent colors. The vaporized material quickly condenses in the cooler air behind the fireball to form the smoke train. Virtually all meteoroids less than 1/8 inch in size vaporize completely after entering the atmosphere. Each year, an estimated average of 24,000 meteorites, most ranging in weight from four ounces to 20 pounds, survive atmospheric entry to land on Earth. Nearly three-quarters of these are lost in the oceans, leaving about 7,500 to fall on land.

Meteorites consist primarily of two basic components— iron-nickel alloys and stone. They are classified into three groups according to the relative amounts of stone and metal present— *iron*, comprising 33 percent of all meteorites; *stony*, making up 60 percent of all meteorites; and *stony-iron*, accounting for 4 percent of all meteorites. The remaining three percent are unclassified.

Iron meteorites, fragments of the cores of asteroids or planets, are almost entirely metal with little stony material. Very dense and heavy in the hand, they have a bright, metallic luster when scratched or when cut and polished. Iron meteorites are structurally divided into three categories: hexahedrites, octahedrites, and ataxites. Hexahedrites are essentially kamacite, with a low nickel content and a six-sided crystal structure. Octahedrites, which represent 70 percent of all iron meteorites, are an intergrowth of kamacite and taenite with intermediate nickel content and an eight-sided crystal structure. Ataxites are primarily taenite with a high nickel content of 12 percent or more and no discernible crystal structure.

Stony meteorites, fragments of the crusts of asteroids or planets, consist mainly of silicate minerals (stone) with less than 25 percent iron-nickel. They are classified into two major groups, chondrites and achondrites, depending upon the presence or absence of small, rounded pockets of minerals called chondrules. Chondrites make up 94 percent of all stony meteorites and are subdivided according to the silicate mineral(s) present. Carbonaceous chondrites contain 10-20 percent water and as much as 4 percent carbon. The much rarer achondrites are divided into two groups, calcium-poor and calcium-rich, depending upon the amount of calcium oxide (CaO) present.

Stony-iron meteorites, fragments of the mantles of planetary bodies, contain significant amounts of both silicate minerals and iron-nickel and are classified as pallasites or mesosiderites. Pallasites typically contain grains of olivine embedded in iron-nickel, while the very rare mesosiderites contain roughly equal amounts of metal and stone and have few consistent structural features.

### *COMPOSITION*

The chemical formula of kamacite,  $\alpha\text{-(Fe,Ni)}$ , indicates that it is an alloy consisting primarily of the metals iron (Fe) and nickel (Ni). On average, kamacite contains about 93 percent iron, 6.5 percent nickel, as much as 0.5 percent cobalt, and small amounts of carbon (C), phosphorus (P), copper (Cu), and sulfur (S). Meteoritic kamacite also contain relatively high (but still trace) amounts of such elements as germanium (Ge), osmium (Os), and iridium (Ir). These elements are called “siderophile” (literally “iron-loving”) metals because of their affinity for iron. On Earth, most siderophile metals are bound to the iron deep in the core, and hence are much rarer in the Earth’s crust than they are in iron meteorites.

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Kamacite, an iron-nickel alloy found almost exclusively in meteorites, is the primary component of the hexahedrite and octahedrite types of iron meteorites, as described above. Kamacite is always associated with another iron-nickel meteorite mineral called taenite. Kamacite and taenite differ in relative iron-nickel composition and in crystal structure. Kamacite contains about 6.5 percent nickel, while taenite contains at least twice that amount. The iron and nickel in both minerals are joined by strong metallic bonding in which the two outer electrons of the metals are shared. Kamacite and taenite originate from solidification of the molten, metallic core material of planetary bodies, and both crystallize in the isometric system as cubic, six-sided crystals. Kamacite forms body-centered crystals with nine iron or nickel atoms in the crystal lattice—one atom each at the eight corners and one in the center. Taenite forms face-centered crystals consisting of 14 iron or nickel atoms—one at each of the eight corners and one in the middle of each of the six faces. Nickel atoms readily substitute for iron atoms in both crystal lattices. Because there are more atomic positions in the taenite lattice, it contains more nickel atoms, and thus a higher percentage of nickel.

Kamacite and taenite are temperature phases of the same basic alloy. Kamacite, chemical formula  $\alpha\text{-(Fe,Ni)}$ , is the “alpha phase” of the iron-nickel alloy, while taenite, chemical formula  $\gamma\text{-(Fe,Ni)}$ , is the “gamma phase.” Both form from the same iron-nickel melt, with different phases forming at different temperatures. As the molten material cools, taenite crystals form first at higher temperatures, while kamacite crystals form at lower temperatures.

At high temperatures, iron and nickel atoms freely diffuse through both the kamacite and taenite crystal lattices. But as the newly formed solid alloy continues to cool below a temperature of 932° F., diffusion of iron and nickel atoms stops and the taenite loses some of its iron atoms, thus converting to kamacite. This enables kamacite and taenite to form complex intergrowths, producing crystals that combine the features of kamacite’s body-centered crystals with those of taenite’s face-centered crystals. As cooling taenite loses some iron atoms, kamacite grows within the taenite structure, much in the manner of a mineral pseudomorph. The resulting crystal shape is an octahedron with an eight-sided dipyramidal shape and eight equilateral triangles as faces. In meteoritic occurrence, this form is known as an *octahedrite*.

The intergrowth of kamacite and taenite produces geometric structures within the alloy. To display this internal structure, sections of iron meteorites are cut and polished, then treated with nitric acid ( $\text{HNO}_3$ ). A bit of the kamacite surface dissolves away, leaving the more acid-resistant taenite structures in highly visible relief as patterns of crisscrossed lines called lamellae or Widmanstätten patterns (named for Austrian physicist Alois von Widmanstätten, 1753-1849).

The Sikhote-Alin (pronounced seh-kah-tay-AY-lin) iron octahedrite meteorite consists primarily of kamacite with only a small amount of taenite. The composition of the Sikhote-Alin meteorite is 93.32 percent iron, 5.71 percent nickel, 0.48 percent cobalt, and traces of copper and phosphorus.

### *METEORITE COLLECTING*

Although meteorites occur everywhere, they are most likely to be found near impact craters or known fall areas. In the past one million years, an estimated 100 meteorites have landed on every square mile of land on Earth. While some meteorites can be identified visually by their dark color and unusual surface textures, older specimens accumulate a mineral patina and appear much like adjacent rocks. Experienced collectors use magnets and metal detectors in their searches. The most productive places to look for meteorites are those with little vegetation and few dark rocks. Ideal searching areas are desert floors, dry lake beds, regularly plowed farmlands, and permanent ice sheets, such as those in the Antarctic, where meteorites are the only “rocks” present.

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The meteorites most available through the specimen market include ours, as well as the octahedrites found in Namibia, commonly called Gibeon meteorites. Researchers place its fall about twelve thousand years ago, with a strewn field about 70 miles by 230 miles, making it one of the largest on Earth. The largest meteorite yet discovered weighs about 60 metric tons, and was discovered at Hoba West, near Grootfontein, Namibia. Another large supply was caused by the meteor that fell to Earth in May 1516, in Lihu and Yaozhai, Nandan County, Guangxi, China. A witness wrote of this awesome event: "During summertime in May of Jiajing 11<sup>th</sup> year [sic], stars fell from the northwest direction, five to six fold long, waving like snakes and dragons. They were as bright as lightning and disappeared in seconds." This fall, estimated at about 19,000 pounds, went largely ignored until 1958, when meteorites were collected as a source of iron for steel manufacturing—fortunately, their melting point proved too high, and they were spared destruction! Smaller quantities of meteoric kamacite are found in many other places.

Terrestrial kamacite, on the other hand, is extremely rare, and the only large source is on Disko Island, Greenland, where huge masses up to twenty tons are present in basalts that have broken through coal seams. Here, native iron was reduced by the assimilation of carbonaceous material and recrystallized as kamacite. It is also found at Bühl, Kassel, Germany, and Putorana plateau, Taimyr Peninsula, Russia.

### *JEWELRY & DECORATIVE USES*

Iron and stony-iron meteorites are cut into "slices" and polished for use in jewelry, usually to be mounted as pendants, as are small, complete specimens. The most attractive and valuable meteorite "gems" are the stony-irons, usually pallasites, that display both transparent green olivine (see our December 2003 write-up for more on olivine and its gem form, peridot) and silvery iron-nickel. Diamonds are occasionally found in pallasites! Also popular are iron meteorites that are sliced, polished, and treated with acid to reveal Widmanstätten patterns. Natural meteorite specimens, marketed by a worldwide network of dealers, are highly valued by collectors for mineralogical and display purposes, as well as for display and use as paperweights.

### *HISTORY & LORE*

Prior to the early 1800s, the origin of meteorites was unknown. References to meteorite falls appear often in ancient writings. Some biblical scholars believe that Joshua 10:11, which tells of "stones from heaven" killing the enemies of the Israelites some 3,000 years ago, is the earliest record of a meteoritic fall, though the scripture specifically mentions hailstones. Ancient Chinese, Greek, and Roman literature tells of dozens of falls that occurred as early as 687 B.C. Accompanied as they are by thunderous noises, bright lights, and smoke trails, meteoritic falls obviously intrigued the ancients, who often made meteorites into objects of superstition or religious reverence. In 204 B.C., a meteorite worshiped in Asia Minor was brought to Rome amid great public celebration. Later, Muslims kept a sacred meteorite in the Kaaba at Mecca. In the New World, archaeologists have found meteorites in Aztec temples and among the sacred relics of several Native American cultures.

The earliest meteorite with a known date and place of fall came to Earth in the Alsace region of France on November 7, 1492. The first documented meteoritic investigation took place in 1576, when a Spanish military expedition tracked down a 23-ton mass of metal that had been reported by natives in Argentina's Chaco region and assumed it to be the outcrop of a rich iron deposit. After further investigation in 1774, the Spanish named the mass of metal *Mesón de Fierro*, literally "great table of iron," and concluded this time that it was volcanic ejecta. Samples of *Mesón de Fierro* eventually reached European scientists, including the German physicist Ernst Chladni (1756-1827). Chladni had compiled many reports of

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fireballs which fell to Earth as fragments of stone or iron. In 1794, Chladni proposed that meteors were actually small bodies of iron and stone from space that became visible because of atmospheric friction. He was also the first to identify the *Mesón de Fierro* as a meteorite.

In 1799, French chemist Joseph-Louis Proust (1754-1826), studied a *Mesón de Fierro* sample and noted its shiny fracture surfaces, lack of rust, and ductility. He correctly determined that it contained approximately 90 percent iron and 10 percent nickel, and predicted that the proper proportions of iron and nickel could produce rustproof alloys, the first hint of the concept of future stainless steels. In 1803, spectacular, well-witnessed falls in France and Norway yielded hundreds of meteorite samples for study by scientists, including the eminent French physicist Jean Baptiste Biot (1774-1862). Biot's reports finally convinced most other scientists that meteorites did indeed originate in interplanetary space. In 1861, German scientist Baron Karl von Reichenbach (1788-1869), identified the alpha-iron-nickel alloy kamacite as a separate mineral species after studying it from the type locality at Disko Island, Uivfaq, Blaafjeld, Greenland.

Metaphysicists believe that meteorites symbolize, and provide access to, the energy of other worlds, bring aid from higher dimensions, and balance one's physical, mental, and spiritual energies. Meteorites, impact craters, and meteors have appeared on the postage stamps of 26 nations. The most celebrated issue is the 1957 10-kopeck stamp which the Soviet Union issued on the 10<sup>th</sup> anniversary of the Sikhote-Alin fall. The stamp reproduces the eyewitness painting by artist P. J. Medvedev of the fireball and smoke train as it appeared beyond the village of Iman.

### ***TECHNOLOGICAL & SCIENTIFIC USES***

Early cultures worldwide fashioned tools and weapons from iron meteorites. Iron and stony-iron meteorites have also occasionally served as iron ore, but the greatest value of all meteorites is to science. Still the only tangible source of interplanetary knowledge, meteorites provide clues to the formation and evolution of our solar system.

One example of the scientific significance of meteorites is the specimen designated ALH84001, which was recovered in Antarctica and is one of only 12 meteorites known to have originated on Mars. In ALH84001, National Aeronautics and Space Agency researchers identified possible bacterial fossils, certain organic molecules, and troilite (a meteoritic form of iron sulfide, FeS<sub>2</sub>) and magnetite (iron oxide, Fe<sub>3</sub>O<sub>4</sub>), two minerals which can have biological origins. Some researchers consider ALH84001 strong evidence that life at one time existed on Mars, while others are opposed, such as UCLA researcher William Schopf, who said, "I think it's very unlikely they have remnants of biological activity."

Furthermore, knowledge that iridium is much more common in meteorites than in the Earth's crust is the foundation of the theory that a huge meteoritic impact on Mexico's Yucatan Peninsula some 65 million years ago caused the extinction of the dinosaurs. A worldwide iridium-rich sediment layer corresponding to the time of the impact is believed to have originated as fallout from the great clouds of dust and debris generated by the huge meteoritic impact.

### ***ABOUT OUR SPECIMENS***

The Sikhote-Alin meteorite fell to Earth in the Sikhote-Alin Mountains of the Maritime Territory of eastern Siberia, Russia, on the morning of February 12, 1947, at a site 250 miles north-northeast of the port city of Vladivostok and near the towns of Iman, Burlit and Novopokrovka.

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Artist P. J. Medvedev was one of the hundreds of people who witnessed the fall. Medvedev was painting a scene at Iman when, at 10:38 a.m., a fireball “as large as the sun” traveled north to south across the sky. The fireball was bright enough to cast shadows even in daylight. It was trailed by a multi-colored smoke train and changed color, becoming more reddish near the end of its brief flight. After the fireball disappeared behind the ridges, Medvedev began sketching the stunning image that remained in his mind.

Witnesses recalled seeing the fireball break up into several pieces before impact and hearing an enormous explosion followed by the sound of prolonged thunder. Those nearest the impact point felt a shock wave radiating outwards, a wave that shattered windows for a distance of more than 50 miles. Researchers later calculated that the main meteoritic mass broke up at the unusually low altitude of 19,000 feet, explaining the very small, 1.2-square-mile area over which the fragments fell. The next day, aircraft pilots discovered the craters and shattered trees that marked the remote impact site.

On February 21, a search party which included three geologists flew to a clearing seven miles from the impact center, then trekked into the subarctic forest of spruce and fir. On the fourth day of their search, they encountered snapped tree branches, pieces of newly displaced and fragmented bedrock, heavily crusted snow that had been melted and refrozen, and finally, craters. They discovered many iron-meteor fragments along with 122 craters and pits, the largest measuring 87 feet across and 20 feet deep.

The Sikhote-Alin fall was the largest iron-meteorite fall ever observed and provided an exceptional opportunity to study new impact craters. By 1951, three expeditions had investigated the site and recovered thousands of meteorite fragments, the largest weighing nearly two tons. By screening soil with powerful magnets, they also recovered a large quantity of meteoritic dust in three distinct forms. The first type was irregularly shaped with sharp, angular edges and had been torn from larger masses at impact. A second type had fragmented when the main mass broke apart in the atmosphere. The third type consisted of tiny, rounded, near-spherical globules that had separated from the fireball and which had probably formed the dense smoke train. Today, searchers have recovered more than 8,000 pieces of the Sikhote-Alin meteorite weighing a total of 28 tons.

After taking reports from 240 eyewitnesses, researchers calculated the orbit of the original meteoroid before it had entered the atmosphere. The orbit’s aphelion, or farthest distance from the Sun, was 2.16 Astronomical Units (a standard distance unit in solar-system astronomy equal to the average distance between the Earth and the Sun, or about 92,900,000 miles). This placed the original Sikhote-Alin meteoroid within the asteroid belt between the orbits of Mars and Jupiter. Its perihelion point, or the closest distance to the Sun, fell just inside the Earth’s orbit. Because these orbits crossed, collision had been just a matter of time. How many more such collisions might occur on our lifetimes? How fortunate we are to hold in our hand a fragment of the core of a small planetary body!

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