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Iron meteorites and controversies over the origin of erratic boulders

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ABSTRACT

In the 1770s and 1780s reports circulated through Europe that two large masses of metallic iron had been discovered in remote regions on opposite sides of the Earth: one in Siberia, the other in the chacos of northern Argentina. Located far from any known volcanoes or sites of primitive smelting operations, the irons initially were classed with the huge erratic boulders of granite, basalt, and other common rocks that were scattered over much of Europe. Acrimonious debates arose over whether the exotic blocks had been dispersed early in the Earth's history by violent explosions or by torrential waters. The first naturalist to envision a separate mode of origin for the irons was Ernst F. F. Chladni of Wittenberg, who proposed, in 1794, that masses of iron and stones fall to the Earth from space. At first, this "infamous" hypothesis was roundly criticized, but, within the next five years, four witnessed falls of stones occurred and were widely publicized. By 1802, chemical analyses had shown that, unlike granites and other common rocks, the erratic irons and metal grains found in the fallen stones all consisted of nickel-iron – a previously unknown alloy. These observations quickly led to the acceptance of meteorites as valid natural phenomena. Another four decades would pass before the concept of continental ice sheets would provide a satisfactory explanation of the distribution of large crustal erratics. In recent years we have learned that, under certain conditions, the Antarctic ice sheet concentrates frozen-in meteorites, of many different varieties and dates of fall, in virtual placer deposits on so-called stranding surfaces. This new linking of meteorites with ice sheets has provided the international research community with an abundance of valuable samples from other bodies in the solar system.

ZUSAMMENFASSUNG

In den 1770er und 1780er Jahren zirkulierten in Europa Berichte über zwei grosse Körper reinen Eisens, die in entgegengesetzten Teilen der Welt entdeckt worden waren: in Sibirien und im Chaco des nördlichen Argentinien. Weit entfernt von allen bekannten Vulkanen und Stätten einer primitiven Eisenindustrie, wurden diese Eisenfunde in einen Topf geworfen mit den riesigen erratischen Blöcken von Granit und Basalt und anderen Gesteinsarten, die weit über grosse Teile Europas verstreut waren. Es wurden erbitterte Diskussionen darüber geführt, ob diese Blöcke früh in der Erdgeschichte durch heftige Explosionen oder Sturzfluten an den Ort ihrer Ablagerung gelangten. Der erste Naturforscher, der einen besonderen Ursprung für diese Eisenmassen annahm, war Ernst F. F. Chladni aus Wittenberg, der 1794 die Ansicht vertrat, dass die eisernen Blöcke aus dem Weltraum auf die Erde herabgefallen seien. Diese «infame» Hypothese wurde zuerst rundweg abgelehnt, aber in den folgenden fünf Jahren wurden eindeutig bezeugte Beispiele von vom Himmel gefallenen Steinen weit bekannt. Um 1802 zeigten chemische Analysen, dass die erratischen Eisenblöcke und Metallkörner, die sich in den vom Himmel gefallenen Steinen fanden, ganz anders als Granite und andere gängige Gesteine aus Nickeleisen bestanden, einer damals unbekannten Legierung. Diese Beobachtungen führten bald dazu, dass Meteoriten als ein natürliches Phänomen anerkannt wurden. Weitere vier Jahrzehnte vergingen, ehe das Konzept kontinentweiter Vereisungen zu einer befriedigenden Erklärung für die Verteilung grosser erratischer Blöcke aus dem Grundgebirge führte. In neueren Jahren hat sich gezeigt, dass unter bestimmten Bedingungen das antarktische Inlandseis eingefrorene Meteoriten sehr verschiedener Art und verschiedenen Alters konzentriert, in Form von echten Placern. Diese neue Verbindung von Meteoriten und Gletschern hat der internationalen Forschung eine grosse Menge wertvoller Proben von anderen Körpern des Sonnensystems geliefert.

Introduction

In 1776, a large, isolated mass of iron, found near a mountain top in central Siberia, was described by Peter Simon Pallas (1741–1811), the German natural historian, in his book of travels through the Russian Empire: *Reisen durch verschiedene Provinzen des Russischen Reichs, 1771–1773.* Twelve years later, a much larger mass of iron lying in the flat, porous soils of the northern Argentine chaco was described by Don Rubín de Celis in the *Philosophical Transactions of the Royal Society* (de Celis, 1788). De Celis's expedition had dug around the mass, tilted it up and over, and found no extensions in depth, thus demonstrating that it was an isolated mass rather than, as previously claimed, the surface exposure of an iron mine.

Naturalists in Europe were inclined to class these two iron masses with the large, erratic boulders of granite and other common rocks that were scattered, far from outcrops of similar bedrock, over much of Europe. At least two different explanations, both catastrophic, were put forward to account for the erratics. In 1776, Jean-André Deluc (1727–1817) wrote that the collapse of great subterranean caverns in an early epoch of the Earth's history had triggered violent outbursts of expansible fluids at depth that projected high into the air huge blocks of granite, primordial rocks, and volcanics which came to rest on mountains and plains where they are found today. In response, Horace-Bénédict de Saussure (1740–1799) point-

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ed out that the great flying blocks should have made impact craters (enfoncements considérables) where they plunged back to Earth – but that, in fact, they often perch delicately on two or three points (de Saussure, 1779: 168). These blocks, he wrote, bear silent testimony to one of the greatest catastrophes that has effected our globe: when the waters of the ocean in which our mountains had formed still covered a part of them, a violent earthquake suddenly opened all the great empty cavities at depth, and the waters rushed toward them with extreme violence, cutting deep valleys and sweeping along immense quantities of earth, sand, and rock fragments of all sizes. This semi-liquid heap piled up to the heights where we still see many of the scattered fragments today (de Saussure, 1779: 151).

At that time, the idea that stones and masses of iron sometimes fall from the sky, which had been accepted from ancient times through the Renaissance, had not been reintroduced since the advent of the Enlightenment, and the concept of continental ice sheets, which could transport boulders far and wide, still lay decades in the future. The first advance toward understanding that the irons were of a different origin from the crustal erratics took place over the turn of the 19th century when meteorites became accepted as valid natural phenomena. The events leading to this development will be the main topic of this paper.

The Pallas Iron

The Siberian iron was discovered in 1749 when Yakov Medvedev, a blacksmith and prospector, guided a mining engineer from the provincial government at Krasnojarsk to a site near the top of Mt. Bolshoi Emir to show him bands of magnetite in the schistose bedrock. The magnetite proved to be too sparse for mining, but as the two rounded a high ridge they came upon an isolated mass of metal about 70 cm across. A careful search yielded no additional fragments of metal, so the engineer dismissed the mass as having no value.

Medvedev, was so intrigued with the metallic iron that he returned the next winter, most likely with a horse and sledge, and personally wrestled it down the mountain and across 20 kilometers of frozen bogs to his village of Obeisk on the upper Yenesei River. After all his efforts, he found that the metal was too malleable when hot and too brittle when cold to be worked at his smithy so he placed the mass in his courtyard. The local shamans, however, viewed the exotic metal as a very special gift from the sky and led public mountaintop ceremonies of thanks for it (Gallant, 1998: 8).

Twenty years later, Pallas heard of the mass of iron when he arrived in Krasnojarsk. Whether or not he travelled to Obeisk or climbed to the find-site is in dispute. In any case, he arranged for the mass to be shipped the 230 km down the Yenisei to Krasnojarsk, where he estimated its weight at nearly 700 kg. He found it to be a meshwork of metal enclosing an abundance of yellowish, glassy-looking inclusions, 0.5–2 cm across. Some of these had broken away leaving cavities with thin, sharply-pointed metal walls. Pallas described the texture as porous as a rough sea sponge.

As a man of the Enlightenment, Pallas rejected the local belief that the mass had fallen from the sky. He knew of no volcanic activity or ancient smelting operations near the find-site, so he concluded that the metallic mass had formed in the pocket of a large vein the rest of which had eroded away. Pallas had the mass transported to St. Petersburg, where it was exhibited in the Czar's Kunstkammer (Curiosity Room) and pieces were sent to the principal scientific societies and mineral collectors of Europe. For nearly 90 years, from 1778 to 1866, the Russian Academy published nothing on the "Pallas Iron". By then it long-since had been acknowledged to be a meteorite and named Krasnojarsk (although traditionally meteorites are named for their place of fall). It consists of olivine crystals embedded in nickel-iron metal and is the type specimen for a rare class of stony-iron meteorites called pallasites, of which only 46 are known today.

The Méson de Fierro

The mass of iron in South America lay in the remote chacos of northern Argentina, a vast region of flat, powdery soils without rocks or watercourses. The lack of water precluded permanent settlements, but the territory was frequented by nomadic bands of Indians.

In 1553, Spanish conquistadores crossed the Andes and reached the western margins of the chacos where they built Santiago del Estero, the region's first garrison. There, they encountered Indians with metal tips on their arrows and spears (Turone, 1995: 20). The Indians told them of a huge mass of iron that had fallen from the sky at a place they called *Piguem Nonraltá*, where great fires had nearly wiped out their ancestors. Like most 16th-century Europeans, the Spanish readily accepted tales of odd things, including stones and fragments of iron, falling from the sky, so they translated the name as Campo del Cielo (Field of the Sky).

In 1576 the Governor of Santiago del Estero commissioned Capitán Hernán Mexía de Miraval to search out the source of the metal. De Miraval led eight soldiers eastward into the chaco, where, after constant harrassment by the Chiriguano "cannibals", they came upon a huge mass of metal projecting out of the ground. Don Hernán collected small pieces of similar metal from around the mass and reported finding an iron mine. At Santiago del Estero a blacksmith fashioned nails, spikes, and rings from the metal, which he declared to be iron of the very finest quality (Alvarez, 1926: 23). In 1589 don Hernán and two of his soldiers described their expedition in a notarized document which we recognize today as the earliest record of a meteorite in the Americas.

In 1591, de Miraval returned to Spain and a document describing his many accomplishments, including his discovery of the iron mine, were deposited in the *Archivo General de Indias* in Seville. Within only two or three decades, however, all local memory of his expedition to the iron mine appears to have been lost, and, once again, chroniclers of the region were repeating the native story of a mass of iron fallen from the sky. Not until the early 20th century was the document retrieved and a copy sent to Santiago del Estero thus restoring de Miraval's expedition to its place in history (Alvarez, 1926: 20).

Nearly 200 years passed before the next expedition entered the chaco in search of metal. In 1774, Bartolomé Francisco de Maguna, a leading official of Santiago del Estero, led a band of men eastward out of the city in search of a rumored silver mine. At a distance of some 450 km they found an object that de Maguna called a "gran barra o planchon" (large bar or plate) of metal (Alvarez, 1926: 26). Smooth on top and almost level with the ground, it was thereafter referred to as *"el Mesón de Fierro"* (the Table of Iron). De Maguna estimated the weight of the visible mass at ~ 23,000 kg and took off a few samples, wearing out several chisels in the process.

It generally has been assumed that de Miraval and de Maguna discovered the same large iron meteorite (e.g. Alvarez, 1926: 21). However, de Miraval spoke of a huge mass that "... rose above the surface like strange monument" (Turone, 1995: 20) with small pieces lying around it; de Maguna described a large plate of metal nearly level with the ground and made no mention of small pieces. In any case, from what we know today of the large numbers of iron meteorite fragments at Campo del Cielo, it seems unlikely that these two expeditions, 200 years apart, would have chanced upon the same mass of iron.

De Maguna's samples were sent to chemists in Lima and Madrid. A few months later, a report from Madrid announced that the metal was 80% iron and 20% silver! Tremendous excitement ensued; rumors spread that the chaco must be richer in silver than all of Peru. Three more expeditions to *el Mesón* followed in 1778 and 1779 although chemists in Buenos Aires and at Uspallata, a mining town in the Andes, had declared that the metal was iron of unusual purity containing no silver at all.

Finally, in 1783, the Viceroy of Buenos Aires ordered Lieutenant Rubín de Celis, of the Royal Spanish Navy, to determine the extent of the iron ore and, if he found it to be a workable deposit, to found a colony at the site. Don Rubín entered the chaco with 200 men who opened a road to the Mesón de Fierro. Don Rubín's route map shows them passing close by six "pozos" (shallow circular depressions we now recognize as meteorite craters). When they arrived at the Mesón de Fierro, they dug around the mass, tilted it up on spikes and tipped it over. They deepened its hole and exploded gunpowder in it, but found no extension in depth or in holes they dug on either side of it. They wore out 70 chisels taking 12 kg of samples – a common experience with meteoritic iron, which is malleable but very hard. Don Rubín sketched the mass from two sides and estimated its weight as only about 15,000 kg.

Like Pallas, Don Rubín, rejected the native fable that the mass had fallen from the sky. He wrote that it was astonishing to find such a mass in a country where there are no mountains, nor even the smallest stone within a circumference of 100 leagues, although "... we know there are mines of pure iron in Europe" (de Celis, 1788: 369). Don Rubín concluded that since it showed signs of melting, the metal must be volcanic, and presently, about two leagues east of where the Mesón de Fierro lay, he found a mineral spring at the crest of a gentle rise four to six feet high. He speculated that since: "Volcanoes frequently leave behind them, after explosion, pits of water, either hot or cold ... I will suppose that the volcanic explosion happened in the spot where I found the brackish spring" (de Celís, 1788: 371).

While finishing his investigation, Don Rubín received warnings of an imminent Indian attack and left the area on short notice. He abandoned the Mesón de Fierro in its deepened hole and there it lies – never to be seen again to this day. Don Rubín sent an account of his expedition, along with samples of the metal, to the Royal Society in London, which published his report in English and Spanish in 1788 and forwarded his samples to the British Museum.

We may well ask how a 15-ton mass of metallic iron could become lost in the flat, porous soils of the chaco. Presumably, the hole filled with windblown dust and mud from seasonal floods; eventually it must have been overgrown with the thorny bushes that abound in the region. Even so, the iron should respond to airborne magnetometers but it has not done so, despite repeated searches (Marvin, 1994: 161).

Today, Campo del Cielo ranks as one of the greatest meteorite strewn fields of the world. Some 60 metric tons of iron fragments have been recovered and 32 meteorite craters identified along a strip 18 km wide that extends N60°E for at least 75 km across the chaco. Rubín de Celis reported the latitude of the Mesón de Fierro as 27°28'S. On modern maps latitude 27°28'S intersects the strewn field close to its northeastern end at about 61°25'W (Cassidy, 1967). To arrive there, the Spaniards, particularly Don Rubín with his road builders, marched directly through the heart of Campo del Cielo and its wealth of large and small iron meteorites without encountering a single one until they reached the Mesón de Fierro. This circumstance testifies to the wide spaces of the region and the burial of many of the meteorite fragments.

Carbon dating on carbonized wood in crater walls and rims indicates that the fall occurred about 4,000 years ago, when ancestors of the Indians who met the first Spaniards may well have witnessed the event and suffered from the shock-produced fires it set. Since then, the surface of the chaco has aggraded by an estimated six inches (Cassidy, 1997). This would have buried the smaller meteorite fragments and added covering to the larger ones, many of which plunged deeply into the soil when they landed.

Stones and Irons from Space: E. F. F. Chladni, 1794

Although scientists in Russia paid scant attention to the Pallas Iron, Ernst F. F. Chladni (1756–1827) of Wittenberg featured it in the title of a small book he published in 1794: *On the Origin of the Mass of Iron Found by Pallas and on Other Similar Iron Masses and on a few Natural Phenomena Connected Therewith.*

Chladni had not seen the Pallas Iron, or even a sample of it, at that time, but he had a radical new theory to propose, namely, that: 1) masses of iron and stone do fall from the sky; 2) they form exploding fireballs as they decelerate in the Earth's atmosphere, and 3) they originate in space. Chladni cited the Pallas Iron as a prime example of a body that, for lack of any other reasonable explanation, must have fallen from the sky.

While pursing library research in Göttingen, Chladni had discovered that observers in several different countries had given virtually identical descriptions of falls of stones and irons from fireballs dating from the year 1 to 1785. Chladni also presented arguments from physics. Meteors and fireballs streak down the skies from every direction at velocities far exceeding those of bodies originating in the atmosphere. Chladni concluded that they must be small masses of solid material that either originated in interstellar space where they never had accreted into planets, or originated within the solar system as fragments of planetary bodies disrupted by explosions or collisions.

Chladni also made some erroneous deductions, but he was basically correct about so many things that today we take his book as a landmark in the founding of meteoritics. When it appeared, however, the book was roundly denounced in Germany, where critics ranked Chladni's eyewitness reports with folk tales, protested that he flouted the Aristotelian-Newtonian dictum that no small bodies exist in space beyond the Moon, and accused him of basing his hypothesis on materials not known to exist. In October, 1794, Alexander von Humboldt (1769–1859) wrote to his friend, Carl Freiesleben (1774–1846) in Freiberg, that he "Must read Chladni's infamous book on iron masses", (Hoppe, 1979: 26). But, Chladni's reputation was saved when stones began falling from the skies.

Four Witnessed Meteorite Falls: 1794–1798

Between June, 1794 and December, 1798, four witnessed falls of stones took place: at Siena in Tuscany, Wold Cottage in Yorkshire, Evora in Portugal, and Benares in India. All four falls were widely publicized and samples from all of them were described as grainy gray stones with shiny black crusts.

The fall at Siena was the first and most consequential. At 7:00 o'clock in the evening of June 16th, 1794, about 60 days after Chladni's book appeared in Germany (but two years before it would reach Italy or England), a high gray cloud, laced with flashes of red lightning, rapidly approached Siena from the north. Suddenly, amid thunderous explosions it emitted a shower of stones that fell amidst men, women and children near Cosona, about 14 km southeast of Siena. Siena was a university town, and this was the first instance in which educated people – not just ignorant country folk – witnessed a meteorite fall. Within three months, the Abbé Ambrogio Soldani (1736–1808), a professor of mathematics, had collected eyewitness reports and described the physical characteristics of the stones in a 290-page dissertation: *On a Shower of Stones that Fell on the 16th of June at Siena.* This was the first report to raise the subject of fallen stones to the level of scholarly discourse.

In Naples, Sir William Hamilton (1730–1803), the British ambassador to the two Sicilies, inserted a paragraph on the fall in his 74-page report to the Royal Society on the activity of Mt. Vesuvius, which had sprung into eruption 18 hours before the fall at Siena. Although Siena lies some 375 km northwest of Mt. Vesuvius, this coincidence in timing confused the issue of meteorite origins for decades to come. Soldani and Hamilton both believed that the stones formed within the atmosphere. Soldani supposed they had accreted in the high, lightning-filled cloud. Hamilton thought that they formed from vesuvian ash, which had risen to a very high altitude and drifted northwestward past Siena until it met an opposite draft and turned back; it then mixed with a storm cloud and compacted into stones (somewhat analogous to hailstones) that were vitrified on the outside by the action of the electric fluid on them (Hamilton, 1795: 105). Hamilton's report, published in February, 1795, was widely read in England and Germany.

Later that year, at 3:00 p.m. on December 13, 1795, a huge, 56-pound stone plunged out of an overcast sky at Wold Cottage in Yorkshire. The landowner, one Captain Edward Topham (1751–1820), exhibited the stone in Piccadilly, London, where it was examined by Sir Joseph Banks, the president of the Royal Society. Banks obtained a sample, most likely from Topham himself. Two months later a small stone fell amid loud explosions from a clear sky at Evora, Portugal, and in December, 1795, a dazzling fireball coursed across the evening sky and showered stones over several villages near Benares in India. When news of the fall in India reached London, Sir Joseph Banks decided it was time to address the issue of fallen stones with a serious scientific inquiry. Banks gave his samples from the Siena and Yorkshire falls to the distinguished young chemist, Edward C. Howard (1774–1816), and asked him analyze them. Banks called them generations in the air by fiery meteors, and predicted that they would open up a new line of inquiry (Sears, 1975: 218).

Chemistry and Controversy

As Howard was setting to work, the chemist, Joséf-Louis Proust (1754–1826) in Madrid, analyzed a sliver of the Mesón de Fierro and found it to consist of 90% iron and 10% nickel – a previously unknown compound. Proust (1799: 149) wrote that "... it would seem premature to judge whether the precious alloy were a product of nature or of artifice."

In preparing for his analyses, Howard obtained two additional "fallen" stones and samples of four erratic irons, including the Pallas Iron and the Mesón de Fierro plus an iron from Siratik in Senegal and one, with silicate inclusions, from Steinbach in Germany. He collaborated with the French emigré mineralogist, Jacques-Louis de Bournon (1751–1825), who observed that tiny grains of metallic iron were scattered through all of the four stones. De Bournon separated out the metal grains with a magnet, and, used a loup to carry out the daunting task of separating the three other main components for Howard to analyze individually.

Meanwhile, in 1796 at Geneva a group of savants founded the *Bibliothèque Britannique* to provide readers on the continent with French translations of articles in English journals, at a time when France, itself, was in revolutionary uproar. From the first, Marc-Auguste Pictet (1752–1835), editor of the Arts and Sciences Series, published articles on fallen stones – often with favorable editorial commentary. Soon, the pages of *Bibliothèque Britannique* were humming with debates on falls.

In 1801, Pictet published a translation of an English extract of Chladni's book in *Bibliothèque Britannique*. In tones of excitement, he urged his readers to hold off from unfavorable prejudgements while reading Professor Chladni's hypotheses that samples have arrived on the Earth from other planets. Pictet (1801a: 74) wrote: "They seem to us to be the most plausible of all previous attempts to explain the singular facts of falling stones, which are difficult to doubt when we consider the great number of such events attested to by authorities who are, for the most part, respectable."

One reader, Guillaume-Antoine Deluc (1729–1812) of Geneva, did not agree. He denounced Pictet for publishing Chladni's ideas and defending them editorially. Deluc argued that bodies simply do not fall from the sky – persons only imagine such things when lightning bolts strike too close to them. Referring to Pallas' description of the Siberian iron as "porous as a rough sponge", Deluc concluded that the Pallas iron was volcanic scoria of a ferruginous variety found at many active and extinct volcanoes. "We must look for such a source", wrote Deluc (1801a: 316), "instead of one that is solely imaginary".

Deluc remained totally unimpressed with the large size and isolated position of the Pallas Iron. He wrote (1801a: 318): "Huge blocks of granite are found equally isolated lying on wide plains and rugged highlands at enormous distances from granite mountains – as are scorias from the vents of volcanoes. But, nobody yet has informed us that the isolated blocks of granite fell out of the sky!" In fact, however, Deluc himself thought that the blocks fell out of the sky, albeit without originating there. He cited the hypothesis of his older brother, Jean-André Deluc (1776), that the great blocks had been blasted through the air to their present resting places in one great cataclysm during the Earth's creation.

Pictet published Deluc's objections, but in the same issue of *Bibliothèque Britannique* he described a visit to Howard's laboratory in London where he was astonished by the similarities of the four stones Howard and de Bournon were working on. They all had disseminated pyrite and grains of malleable iron which he thought were unique to them. "No longer can I doubt", wrote Pictet (1801b: 416), "the fact of their falls from the sky – whatever might be their origin".

At this, Louis Bertrand (1731–1812) of Geneva entered the fray. Bertrand could not abide Chladni's hypothesis that fragments of other planets ever fall on the Earth. But he was equally opposed to Deluc's idea of the great flying blocks. "One can scarcely understand", wrote Bertrand (1801: 433), "how subterranean fluids capable by their expansion of breaking up rocks and projecting their fragments everywhere, have traversed so many beds without disturbing them ... However, most of the superficial beds of the globe are intact and in a state where the sea left them." Bertrand attributed the erratics to transport by powerful ocean currents as they washed over the lands during periodic exchanges between land and sea. There ensued bitter exchanges on these points between Deluc and Bertrand that we need not pursue here.

A second critic, the French mineralogist Eugène M. L. Patrin (1742–1815), also opposed both Chladni and Deluc. Patrin had seen the Pallas Iron in St. Petersburg and read Pallas' report that the magnetite bands in the country rock assayed 70% iron. Patrin (1801: 205) concluded that quite obviously a bolt of lightning had melted some of the ore and reduced it to the mass of metal. Possibly, he said, the bolt may have been observed by the tartars, and this made them think the block fell from the sky.

Presently, Deluc announced a change of mind about the Pallas Iron. He now believed that it was an artifact. Deluc (1801b: 215) wrote: "I regard, at present, the question as perfectly settled. This mass that has given rise to so many hypotheses ... is very simply, without any doubt, a product of abandoned exploitations of the mine near the site where it was found." Although Pallas had said there was no local knowledge of such things near the find-site, Deluc observed that: "... certain scorias of iron at the summit of Mont Salève near Geneva give positive indications that ancient foundaries existed there, although no traces have been discovered and all memory of them are lost." He added that if no sign of such workings ever are found on the mountain in Siberia, he would return to his earlier theory that the iron mass is volcanic.

While the critics fulminated, Howard and de Bournon analyzed their stones and irons. By the close of 1801 Howard had confirmed Proust's analysis of Ni in the Mesón de Fierro and measured several percent of Ni in the three other irons and the metal grains of the four stones. This decisively linked the stones with the irons and set both apart from known terrestrial rocks. Howard concluded that fallen stones and irons both originate as the bodies of fiery meteors. However, as noted by Sears (1976: 138) the editors of the *Philosophical Transactions of the Royal Society* recast Howard's final statements as questions: "Have not all fallen stones, and what are called native irons, the same origin? Are all, or any, the produce or the bodies of meteors?" (Howard, 1802: 212).

Extracts of Howard's paper immediately began to appear in English, French, and German journals. In September, 1802, Pierre-Simon Laplace (1749–1827) wrote to Franz Xavier von Zach (1754–1832) at Gotha asking if he supposed the fallen bodies might have been ejected by volcanoes of the Moon. In October, 1802, Pictet read Howard's results to the French National Institute of Sciences in Paris, prompting a decisive shift of opinion among leading members who ceased asking how bodies could possibly fall from the sky and began to ask: Where do they come from? By December, 1802, the astronomer Wilhelm Olbers (1758–1840) in Bremen was calling for a second edition of Chladni's book.

But strong opposition continued. In June, 1802, Eugène Patrin published seventeen pages of biting criticism of Howard and de Bournon in the *Journal de Physique*. He upbraided them for allowing themselves to be duped by the testimony of ignorant laborers and women, and for publishing analyses of ordinary ores and masses of pyrite that had been struck by lightning. In conclusion, he scoffed "... the love of the marvelous is the most dangerous adversary of science" (Patrin, 1802: 393).

De Bournon responded in high dudgeon – demolishing Patrin's objections one by one. Lightning bolts, he exclaimed! "What bolts they would be – that metallize iron masses the size of those in Siberia and South America ... Do they change part of the iron into nickel, or do the bolts strike only those minerals into which they can introduce nickel? ... It is beyond the laws of chance to find, time after time, the same unusual type of stone where people have seen them fall – whatever the social rank of the witnesses" (de Bournon, 1802: 298).

In the next issue of the *Journal de Physique*, Patrin (1803: 392) conceded all points, with apologies to Howard and de Bournon. He said that he had pressed his argument not out of disrespect for two such eminent scientists but because he wished to see fully confirmed his own theory that stones and irons originate in volcanic emanations and fall from the sky accompanied by burning meteors. In February of 1803 the National Institute heard a paper on analyses of fallen stones by the Parisian chemist, Louis-Nicolas Vauquelin (1762–1829), whose results confirmed those of Howard. In France, that pretty much established the authenticity of fallen stones.

Then came the spectacular fall of stones at L'Aigle in Normandy. On 26 April, 1803, a high, gray cloud exploded in a clear sky and showered nearly 3,000 stones in full view of many witnesses. The young Jean-Baptiste Biot (1774–1862), sent to examine the evidence, returned with compelling eyewitness testimony, specimens of gray stones with black crusts, and a map of a meteorite strewn field – the first to show that meteorite showers distribute fragments over elliptical areas. "I shall consider myself happy", wrote Biot (1803: 405) "if philosophers find that I have succeeded in placing beyond a doubt the most astonishing phenomenon ever observed by man." Later that year, in a review of a widely read book on stones forming within the atmosphere, Guillaume Deluc very reluctantly accepted the actuality of the fall at L'Aigle (Deluc, 1803: 39).

Chladni became celebrated in his day for his hypothesis that stones and erratic irons fall from the sky – but not for his theory of their cosmic origin. Until about 1860, arguments for their compaction in the atmosphere vied chiefly with those of an ejection by lunar volcanoes. Then theories of their origin in interstellar space competed with those of an origin within the solar system, with some scientists convinced that meteorites come from both realms. Not until the 1950s did meteorites became universally accepted as the impact debris of asteroids and rocky planets and satellites (Marvin, 1996: 581).

Meteorites and Ice Sheets

Once meteorites were established as genuine natural phenomena, there seemed no need to relate them in any way to the erratic boulders of common rocks. These remained puzzling until the 1840s when the concept of continental ice sheets provided an explanation for their transport and distribution. However, since the early 1970s we have learned that there is a vitally important link between meteorites and ice sheets. The Antarctic ice sheet, for example, carries cargos of frozen-in meteorites of many classes and dates of fall. Wherever the shoreward-creeping ice becomes temporarily stagnated behind mountain barriers, the winds coursing down the polar plateau sweep away the snow and ablate the ice itself to deeper and deeper levels, slowly exposing meteorites in virtual placer deposits on so-called "standing surfaces", (Cassidy *et al.*, 1992). Since 1973, more than 17,000 meteorite fragments have been collected on the Antarctic ice sheet by teams of scientists from the United States, Japan, and Germany. Most of them are samples of asteroids, but since 1982 fragments from the Moon and Mars also have been collected in Antarctica. Analyses of ice motion and of the recovered meteorites have yielded a wealth of information on the dynamics of ice sheets and on the composition of other planetary bodies. Collecting meteorites on the Antarctic ice sheet is an elegant way of acquiring planetary research materials while we await further missions into space.

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