# Understanding the nature of meteorites: the experimental work of Gabriel-Auguste Daubrée

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**Abstract:** The French geologist, mineralogist and experimental petrologist, Gabriel-Auguste Daubrée (1814–1896) was a leading scientist of his generation, possibly best known today for his application of the experimental method to structural geology. During his tenure of the Chair of Geology at the Muséum d'Histoire Naturelle, Paris, to which he was appointed in 1861, he played a leading role in expanding its meteorite collection, developing a classification system for meteorites (1867), and using both petrological (1863–1868) and mechanical (1876–1879) experiments to gain a greater understanding of their chemical composition and how their physical attributes had arisen. This led him to believe in the 'cosmic' importance of peridotites and their hydrated equivalent, 'serpentine' (serpentinite), that the Earth might be unusual in having an oxygen-rich atmosphere and oceans, and that planetary bodies probably had a shell-like structure, increasing in density towards a nickeliferous iron core. (His ideas led to Eduard Seuss's SiAl–SiMa–NiFe model of the Earth.) Following the discovery, by the explorer Nils Nordenskiöld in 1870, of 'native' irons apparently associated with basalts at Disko Island, West Greenland, Daubrée took part in the subsequent investigation and the vigorous debate concerning their terrestrial or meteoritic origin.

Gabriel-Auguste Daubrée (Fig. 1) was appointed to the Chair of Geology at the Muséum d'Histoire Naturelle (Natural History Museum), Paris, known today as the Muséum National d'Histoire Naturelle, in 1861. Its present collection of meteorites numbers over 3300 specimens, representing over 1270 falls and finds, but at that time it contained only 86 specimens, scattered throughout its mineralogical collection, representing 53 falls or finds. As a result of Daubrée's initiation of a vigorous policy of acquistion and encouragment of donations, by November 1867 the collection, now systematically classified (Daubrée 1867*b*), had grown to 525 specimens, representing 205 falls or finds (Daubrée 1867*c*, p. 139) and by 1889 it included specimens from 368 falls, rivalling leading collections elsewhere in the world – at that time, the British Museum, London, only possessed 17 more specimens (de Lapparent 1897). This continued growth provided Daubrée with the material that enabled him, over the following 30 years, to make significant advances in understanding the nature of meteorites.

At the time of his appointment, Daubrée was already acclaimed as a skilled geologist and mineralogist, and one of the leading experimental investigators in the geological sciences. He was therefore in an excellent position to undertake such work. This account begins with an outline of his career and then discusses his work on meteorites.

## Daubrée's career

The study of meteorites formed only one part of Daubrée's scientific output, which included over 300 publications resulting from his own research. This account of his career is based mainly on information in Anon. (1870, 1894), de la Goupillière (1896), Dollfus (1896), Fouqué (1896), Hautefeuille (1896), Linder (1896), Meunier (1896) and de Lapparent (1897).

Daubrée was born in Metz, NE France[1] on 25 June 1814. He entered the École Polytechnique (Polytechnic school) in Paris, the most prestigeous of the 'Grandes Écoles', established by the National Convention in September 1794. After 2 years, he was selected as one of an annual intake of about 10 Éleves ingenieurs (pupil (mining) engineers) to the École des Mines (School of Mines), founded by Louis XVI in 1783, then located in the Hôtel de Vendôme on Boulevard St Michel, Paris, and entered the school in September 1834. This was his first step to eventually becoming a full member of the Imperial Corps of Mining

*From*: McCall, G.J.H., Bowden, A.J. & Howarth, R.J. (eds) 2006. *The History of Meteoritics and Key Meteorite Collections: Fireballs, Falls and Finds*. Geological Society, London, Special Publications, **256**, 101–122.
0305-8719/06/$15.00

Fig. 1. Héliogravure of Gabriel-Auguste Daubrée (1814–1896), attributed to Louis Dujardin (Claudine Billoux pers. comm. 2004), in *de Lapparent* **25** (1897), unnumbered plate opposite p. 245.

Engineers, established by Napoléon I (1810). Between mid-November and mid-April, in each of his first 2 years, Daubrée would have studied the working of mines, assaying, metallurgy, mineralogy, geology, technical drawing, German and English; with laboratory work and visits to mines occupying the rest of each academic year (Smyth 1854; Aguillon 1889). During 1834–1835 he was taught mineralogy and geology by André Jean Marie Brochant de Villiers (1772–1840). On de Villiers' retirement in 1835, mineralogy was taught by Ors Pierre Armand Dufrénoy (1792–1857) and geology by Jean Baptiste Armand Louis Léonce Élie de Beaumont (1798–1874). Daubrée attained the rank of 'pupil first class' in April 1836. His known specialization in mineralogy and geology would have taken place following this (Smyth 1854).

In 1837 Daubrée was sent to England, where he studied tin mineralization in Cornwall. His subsequent report, which recognized the importance of fluorine and boron in the mineralization process, was deemed important enough to be included in the second edition of Dufrénoy and Élie de Beaumont's book on base-metal mineralization in Great Britain (Daubrée 1839, 1841). On his return to France, Daubrée was appointed Aspirant ingenieur (candidate (mining) engineer; Linder 1896). He later studied ore deposits in Germany, Norway and Sweden (Daubrée 1843). During 1838 he wrote two theses (Daubrée 1838) to qualify for the degree of Docteur ès-sciences; these were successfully presented to the Faculty of Sciences of Paris of the University of France in January 1839.

Appointed Mining Engineer in August 1838, Daubrée's first position was in the Département (County) de Haut-Rhin, which forms the southern half of Alsace, an area of NE France adjacent to Germany. The following year, he was invited to become Professor of Mineralogy and Geology in the newly established University of Strasbourg, the principal city of the Département de Bas-Rhin (which forms the northern half of Alsace) and, as a result, Daubrée also took up the joint position of Mining Engineer for the Bas-Rhin. His subsequent investigations in the Rhine valley and the mountains of the Vosges eventually resulted in a geological map (Daubrée 1849*c*), and a noted memoir on the geology and mineralogy of the district (Daubrée 1852). He was appointed Dean of the Faculty of Science at the University in 1852 and Chief Engineer of Mines in 1855.

It was during his period at Strasbourg that Daubrée began the experimental research for which he soon became famous. Having by now studied a variety of tin deposits, he recognized the importance of its association with fluorite. This led to the establishment of an experimental petrology laboratory in 1849 in which he synthesized a variety of minerals in sealed vessels under conditions of high pressure and temperature (up to 500 °C), both dry and in the presence of water vapour (Daubrée 1849*b*, 1851, 1854). In the course of this work he established the important role that water vapour has in bringing about the crystallization of feldspar, quartz and pyroxene well below their fusion temperatures, which in turn led him to important work on the nature of metamorphism (Daubrée 1857, 1859, 1860).

From an initial interest in the hot springs of the district (Daubrée 1849*a*), he also carried out important work on hydrogeology, particularly that of the Roman spa town of Plombières in the Vosges, made fashionable by Napoléon III, and mineralization associated with thermal springs (Daubrée 1858, 1878*d*). Daubrée recognized the difference between what we would now call 'regional' and 'contact' metamorphism, and that the former was associated with foliation, while the latter tended to destroy pre-existing structures. However, his knowledge of the deposition of minerals from solution in Plombières led him to suppose that recrystallization at depth was the result of circulating solutions. In 1860 he was commissioned (jointly with two Belgian engineers) to undertake the geological survey for a new railway line running down the valley of the Moselle, Luxembourg.

By 1861 Daubrée's body of work was judged so important that, on the death of the mineralogist, economic geologist and Inspector-General for Mines, Pierre Louis Antoine Cordier (1777–1861), Daubrée was called to Paris in March 1861 to become Cordier's successor in membership of the Mineralogical Section of the Academy of Sciences and to take up his Chair of Geology at the Museum of Natural History, a post which Daubrée would hold for over 30 years. The following year Daubrée was also appointed Professor of Mineralogy at the School of Mines. He became the School's Director in June 1872, the same year that he was appointed Inspector-General for Mines, first class. Among his innovations as Director was the introduction of courses on statistical graphics, palaeobotany (1878), applied geology (1879) and industrial electricity (1887). From 1875 until his death, Daubrée was also a member of the commission overseeing the geological mapping of France, and from 1877 President of the Commission on Fire-damp in Mines. He was elected Vice-President of the Academy of Sciences in 1878 and its President in 1879. He retired in 1884 with the post of Honorary Director of the School of Mines, which he held until his death, in Paris, on 29 May 1896.

Quite apart from Daubrée's work on the composition and classification of meteorites, discussed in detail below (see also Caillet Komorowski 2006, 178–184), the scope of his research embraced the artificial production of minerals and rocks; the origin of minerals, especially bog iron-ores (Daubrée 1845); the nature of fluorescent minerals; hydrogeology (Daubrée 1849*a*, 1887*a*, *b*); the permeability of rocks to water and its relation to volcanic phenomena; the chemical and mechanical effects of metamorphism (Daubree 1857, 1859, 1867*c*); deformation structures (Daubrée 1878*a*, *c*, 1879*c*); and the occurrence of earthquakes. Overall, he published some 555 works. Thirty-four per cent of these were reports to the Academy of Sciences on the work of other scientists, and from 1869 onwards these tended to dominate his other publications. Of the 366 contributions on his own work, 23% were concerned with meteorites and 15% with applications of what he termed 'experimental geology', that is to say, the laboratory synthesis of minerals, mechanical deformation of rocks and experimental investigation of the nature of meteorites (Fig. 2). These works were brought together in his book *Études synthétiques de Géologie expérimentale* (*Artificial Studies in Experimental Geology*; Daubrée 1879*c*).

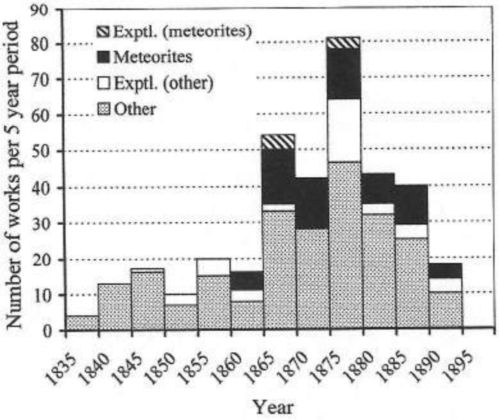


**Fig. 2.** Divided-bar chart showing the distribution with time of Daubrée's 367 publications on meteorites and other research topics, and his experimental studies in these fields. The 188 reports to the Academy of Sciences, Paris, on work undertaken by other scientists are excluded here. Bin-widths are 1836–1840, 1841–1845, etc.

Daubrée's honours included the Gold Medal of the Netherlands Scientific Society of Haarlem (1845) for his studies of iron minerals; the Cross of a Commander of the Crown of Oak, Luxembourg (1860) for his work on the Moselle valley railway; the Wollaston Medal of the Geological Society of London (1880) for his work on mineral formation and metamorphic rocks; election as a Foreign Member of the Royal Society, London (1881); and his election as an Officer of the French 'Legion of Honour' (1858), with promotion to Commander (1869) and Grand-Officer (1881). He also had two minerals named after him: daubréeite, $BiO(OH,Cl)$, first found at the Constancia mine, Bolivia in 1876, and daubréelite $(Fe,Mn,Zn)Cr_2S_4$, first identified in the Coahuila (Mexico) meteorite in 1876.

## Meteorite classification

That meteorites might have their origin in the depths of space was first postulated by the German physicist Ernst Florenz Friedrich Chladni (1756–1827) in 1794 when, following a study of numerous eyewitness accounts, including that of the 1751 Hraschina meteorite (that fell in Croatia in 1751), he postulated (see Marvin 1996, 2006) that there existed small celestial bodies with compositions similar to planets, which were attracted by the Earth's gravitational field and, falling at great speed, the atmospheric friction heated them and made them luminous. Although it is uncertain whether he ever actually saw a fragment of the Pallas iron,[2] composed of olivine and nickeliferous iron metal and reported to have fallen to Earth from a fireball in Siberia in 1749 (Ivanova & Nazarov 2006), he realized from accounts that its mineralogical composition was quite different to that of known terrestrial rocks.

Initially greeted with ridicule (particularly in France), Chladni's ideas were subsequently ignored by the scientific community until the reality of such an occurrence was confirmed by a young French physicist, Jean-Baptiste Biot (1774–1862). Biot, who had hitherto been sympathetic to Laplace's conjecture that meteorites had a lunar volcanic origin, was sent by the National Institute of France to investigate reports of a widely observed meteor and a seemingly related fall of some 3000 stones over a large area at L' Aigle, 140 km NW of Paris, in April 1803. His subsequent account of the investigation to the Institute in July 1803, accompanied by examples of the stones themselves, at last proved wholly convincing to the scientific community (see Poirier 2003; Gounelle 2006).

Although systematic collections of meteorites began to be built up at the Natural History Museum of Vienna (under Carl Franz Anton, Ritter von Schreibers (1775–1852), who published a book on the subject in 1820), at the University of Berlin (Chladni 1825) and elsewhere much of the early investigative work on meteorites was conducted by mineralogists and chemists who were largely content to establish the individual compositions of these objects, rather than obtaining an overall view (Marvin 2006).

On his arrival at the Museum of Natural History, in 1861, Daubrée found that the relatively few meteorites contained in its mineralogical collection were simply recorded as 'native iron with silicate minerals' (de Lapparent 1897). He had the meteorite collection placed under his authority and, as well as initiating an active acquisitions policy, he wrote to his by-now large circle of worldwide scientific contacts, soliciting donations of specimens to enlarge the collection. Much of Daubrée's published work on meteorites (e.g. Daubrée 1864*a*–*d*; 1866*a*, 1867*a*, 1877*c*, *g*) results from studies of material either already in the museum collection or furnished during this period.

Regarding the passage of a meteor (a term that he preferred to the earlier 'bolide' or 'aerolith') through the atmosphere, Daubrée was confident that the existing body of eyewitness accounts of falls showed that: when a meteor arrives in the atmosphere it is travelling at some 20–30 km $s^{-1}$; descending on a long trajectory it becomes luminous, being surrounded by incandescent gas; it may eventually rupture into fragments, often producing an audible explosive sound; and its passage may often leave a visible dust trail in the sky and, rarely, a deposit of dust on the ground. His field investigation following the Orgueil meteorite shower, specimens of which fell over a 5 × 22 km area near Montauban, France, on 14 May 1864 (Daubrée 1864*b*, *c*, 1867*d*), played a large part in formulating these ideas.

Analytical work prior to the 1860s had shown that meteoritic iron was generally characterized by a nickel content of 5–10%, which could occasionally rise as high as 17%, and it was associated with minerals such as troilite (FeS), and schreibersite ($(Fe,Ni)_3P$). In contrast, the rare examples of *in situ* native (i.e. non-meteoritic) iron then known were either associated with volcanic lavas[3] or burning coal seams,[4] and exhibited none of the mineralogical characteristics of their meteoritic equivalent. Daubrée was also particularly struck by the fact that the dominant silicate minerals present within all meteorites (except for the pure irons) were the same as those which compose the basic silicate rocks on Earth, i.e.: (1) what he termed 'péridot', chrysolite olivine ($(Mg,Fe)_2SiO_4$), as typified by its presence in the Pallas iron; (2) the pyroxene minerals, enstatite ($MgSiO_3$) and bronzite ($(Mg,Fe)SiO_3$); and, although rare, (3) plagioclase feldspars, ranging in composition from anorthite ($Ab_0An_{100}$–$Ab_{10}An_{90}$; where $An = CaAl_2Si_2O_8$ and $Ab = NaAlSi_3O_8$) to labradorite ($Ab_{30}An_{70}$–$Ab_{50}An_{50}$). On the other hand, silicate minerals characterisitic of terrestrial rocks such as granite and gneiss (e.g. mica, quartz, the more acid feldspars and tourmaline) were all notably absent from meteorites.

Daubrée decided that the most rational basis for the separation of one meteorite type from another was the proportion of silicate minerals to meteoritic iron, and this underpinned his classification system for the museum's collection (Daubrée 1867*b*, *c*). His scheme (Table 1) was divided into four major classes: I, *holosiderites*, which he named from the Greek (όλος, 'all' and σίδηρος, 'iron'), as they contained no stony (silicate) material (Fig. 3); II, *syssiderites* ('with iron'), containing stony material dispersed through a generally continuous metallic groundmass, rather like a metallic sponge; III, *sporadosiderites* ('dispersed iron'), in which

**Table 1.** *Translation of Daubrée's (1867b, p. 63; 1867c, p. 118; 1879c, p. 506) meteorite classification table*

| | | | Group | | Subgroup | Example | Density ($g\,cm^{-3}$) |
|---|---|---|---|---|---|---|---|
| **Siderites**<br>Meteorites containing iron in the metallic state | Not containing stony material | | **I. Holosiderites**;<br>[Greek: 'all iron'] | | | Charcas[a] | 7.0–8.0 |
| | Containing both iron and stony material at the same time | The iron is in the form of a *continuous mass* | **II. Syssiderites**;<br>[Greek: 'with iron'; stony material in metallic groundmass] | | | Rittersgrünn[b] | 7.1–7.8 |
| | | The iron is in the form of *disseminated grains* | **III. Sporadosiderites**;<br>[Greek: 'dispersed iron'; stony groundmass] | The quantity of iron is *considerable* | ***Polysiderites*** | Sierra de Chaco[c] | 6.5–7.0 |
| | | | | The quantity of iron is *small* | ***Oligosiderites*** | Aumale[d] | 3.1–3.8 |
| | | | | The iron *cannot be discerned* by eye | ***Cryptosiderites*** | Chassigny[e] | 3.5 |
| | | | | | | Juvinas[f] | 3.0–3.2 |
| **Asiderites**<br>Meteorites *not* containing iron in the metallic state | | | **IV. Asiderites**;<br>[Greek: 'without iron'; (carbonaceous meteorites)] | | | Orgeuil[g] | 1.9–3.6 |

*Notes (added by present author)*: [a]Find; Mexico 1804. Daubrée also mentions as examples of this subgroup: Agram (Hraschina), fall, Croatia 1751; Caille, fall, France 1828; Brunau, fall, Bohemia (Czech Republic) 1847. [b]Find, Steinbach, Germany 1724. This has interwoven continuous iron and silicate masses. Also: Pallas, find, Krasnoyrsk, Siberia 1749; Tula (Netschaero), Russia 1846; Atacama, find, Chile (?one of four between 1855 and 1863); all of which contain discontinuous silicate masses. [c]Find, Taltal, Chile 1861. [d]Fall, Algeria 1865; also Château Renard, fall, Loiret, France 1841; Montréjeau, fall, Ausson, France 1858. Daubrée estimated this class (which he also refers to as the 'common type') represents 90% of falls; it includes G. Rose's *chondrites*. [e]Fall, France 1815. Also: Bishopville, fall, USA, 1843; represents Mg silicates and includes Rose's *chassignites*. [f]Fall, France 1821; represents Al–Ca silicates. Also: Stannern, fall, Moravia (Czech Republic) 1808; Jonzac, fall, France 1819; it includes Rose's *eucrites* and *howardites*. [g]Fall, France 1864. Also: Alais, fall, France 1806; Cape of Good Hope (Cold Bokkeveld), fall, South Africa 1838; Kaba, fall, Hungary 1857. Additional information on these falls and finds is from Grady (2000).

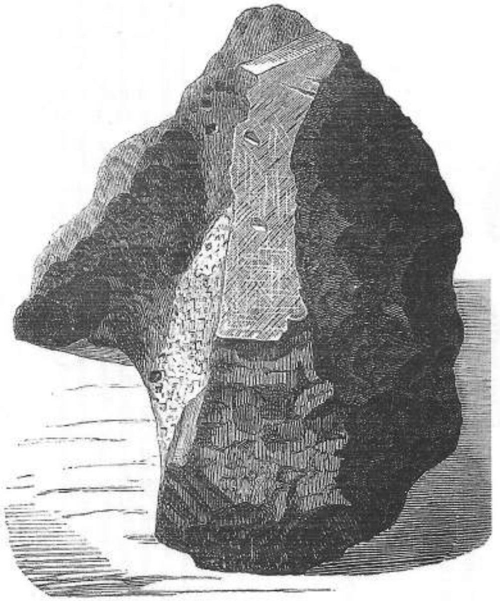


Fig. 3. Characteristic erosion pitting of a holosiderite; Widmanstätten figures visible on cut, etched and polished face (Daubrée 1879*c*, fig. 213, p. 620).

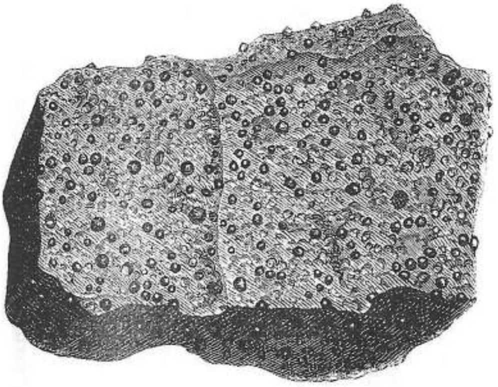


Fig. 4. Characteristic globular structure of a sporadosiderite (chondrite) (Daubrée 1879*c*, fig. 204).

disseminated grains of iron were dispersed throughout a stony groundmass; and IV, *asiderites* ('without iron'), typified by the hydrocarbon-bearing Orgueil meteorite, first investigated by Daubrée (1864*b*, *c*; 1867*d*). Daubrée further divided the sporadosiderites into *polysiderites* ('much iron'), *oligosiderites* ('little iron') and *cryptosiderites* ('hidden iron'), depending on the visible quantity of iron within their silicate groundmass.

As it happened the German chemist, mineralogist, crystallographer and igneous petrologist Gustav Rose (1798–1873), who had been in charge of the mineral collection at the University of Berlin since 1822 (see Greshake 2006), was undertaking a similar study (Rose 1862, 1863) and Daubrée noted the relationship between parts of his own system (Table 1) and meteorite types defined by Rose. For example, the oligosiderites, which Daubrée believed to be the most commonly occurring type, included Rose's *chondrites* (so-called because of their characteristic globular texture, formed of spherical *chondrules* of chrysolite or enstatite, named from the Greek, χόνδρος, a grain, e.g. of salt or sand) (Fig. 4).

Daubrée was inspired by the thought that meteorites represent the only tangible products that arrive on Earth from celestial bodies, hence detailed comparison of their composition with that of terrestrial rocks should not only be of astronomical interest, but would also inform our knowledge of the development of our planetary system: 'It seemed to me that the moment had come to complete by experimental synthesis the numerous notions which [chemical] analysis has furnished about the constitution of meteorites. One might hope that experimental synthesis would render no less a service in this study than in that of terrestrial minerals and rocks' (Daubrée 1866*c*, p. 391).

## Experimental studies (1863–1868): meteorite composition

### *Experimental results*

The long-term aim of Daubrée's experimental programme was twofold. First, to examine the constitution of meteorites by means of their chemical synthesis and comparison with terrestrial rocks (Daubrée 1863, 1866*b*, *c*, 1868). Secondly, to explain what he believed to be mechanically induced phenomena: for example, their often polyhedral shape; the fused outer crust (Fig. 5); the globular texture of the chondrites (Fig. 4); the formation of surface depressions, polished and striated surfaces; and the presence of black veins in their interior (Daubrée 1876*a*, 1877*b*, *d–f*, 1878*b*, 1879*a–c*). He even introduced the term 'piezoglypt' (from Greek, 'to engrave by pressure') to describe the indentations characteristic of the surface of iron meteorites (Fig. 3). For ease of reference, the descriptions that follow are largely based on Daubrée (1866*b*, *c*, 1867*c*) and his well-illustrated account, Part II of his book *Études synthétiques de Géologie expérimentale* (Daubrée 1879*c*): 'Application of the experimental method to the study of divers cosmological phenomena'.

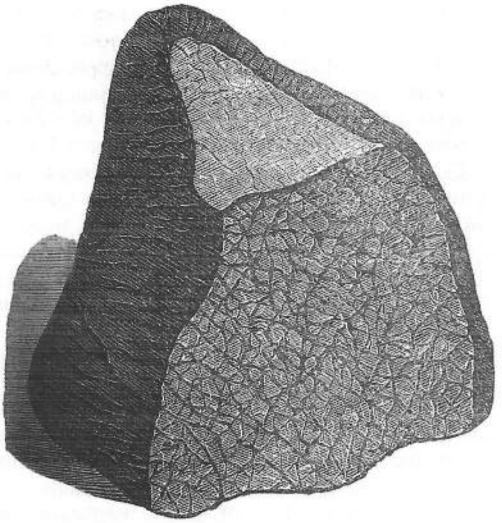


**Fig. 5.** Fusion crust of an aluminous cryptosiderite (Daubrée 1879*c*, fig. 178, p. 481).

Surprisingly, many of his articles describing his experimental results contain no figures at all, presumably because of their cost. A somewhat critical English-language account of Daubrée's presentations of his first experimental results to the Academy of Sciences on 29 January, 19 February and 19 March 1866 (Daubrée 1866*b*) was published by Saemann (1866).

Daubrée suggested that if the meteoritic irons were considered from a purely *compositional* point of view, one could divide them into three types: (1) those essentially without silicates; (2) those containing globules of olivine, e.g. Pallas (cf. Table 1, notes); and (3) those associated with olivine and pyroxene, e.g. Sierra de Chaco. The meteoritic stones were divisible into four types: (1) those containing olivine only, e.g. Chassigny; (2) those with both olivine and enstatite, e.g. Bishopville; (3) those without olivine, but containing augite and anorthite, which meant that they had considerably lower magnesium and higher aluminium contents than the olivine-bearing types (Table 2), e.g. Juvinas, Jonzac and Stannern; and (4) carbonaceous meteorites, e.g. Orgeuil and Alais.

Daubrée's experimental programme began with the fusion of stony meteorites at temperatures approaching the melting point of platinum (*c.* 1770 °C) in a specially constructed coke-fired furnace with a 40 m-high chimney to maintain sufficient draught. He also used a coal-gas/compressed-air torch that could melt several hundred grammes of iron, contained in a platinum crucible, within about 30 min.

Daubrée remarked that since stones are always covered with a thin black, vitreous, crust as a result of their fusion during the passage through the atmosphere, one might expect that on artificial fusion they might simply produce a vitreous mass. However, contrary, he found that whereas the group of stones (Juvinas, Jonzac and Stannern) with higher aluminium content yielded a vitreous amorphous mass ('culot'), the other types tended to produce a crystalline product: The 'common' type of meteorite (i.e. the oligosiderites), yielded well-crystallized olivine and enstatite in variable proportion, together with metallic iron granules (Fig. 6) embedded in the mass. Fusion of the Chassigny meteorite yielded olivine; Bishopsville yielded enstatite with occasional olivine crystals; while the carbonaceous Alais and Orgeuil meteorites produced an olive green mass resembling bronzite. In some cases (e.g. Sierra de Chaco) the iron grains appeared to be associated with what could have been metallic bismuth.

Daubrée next took natural rocks composed of olivine and pyroxenes, such as lherzolite (Table 3) from Lherz in the Pyrenees, and

**Table 2.** *Chemical compositions in wt% (based on terrestrial samples) of the principal silicate minerals present in stony meteorites.* NB. *Arithmetic means have been calculated from pre-1879 analytical data, as quoted in Dana (1899), to indicate the sort of information that would have been available to Daubrée. Few pre-1867 sources are quoted by Dana; Daubrée may well have had access to additional (?unpublished) analytical results when developing his ideas in the 1860s*

| Group | Mineral | *n* | $SiO_2$ (%) | $Al_2O_3$ (%) | MgO (%) | CaO (%) | $\Sigma Fe_2O_3$ (%) | Density (g cm$^{-3}$) |
|---|---|---|---|---|---|---|---|---|
| Olivine | Chrysolite | 15 | 39.64 | 0.40 | 44.41 | 1.26 | 16.59 | 3.35 |
| Pyroxene | Enstatite | 12 | 55.59 | 2.59 | 33.08 | 2.03 | 7.36 | 3.26 |
| | Augite | 6 | 50.44 | 4.78 | 15.63 | 23.42 | 5.58 | 3.28 |
| Feldspar | Anorthite | 9 | 43.68 | 34.36 | 0.89 | 17.12 | 1.36 | 2.77 |
| | Bytownite | 1 | 52.17 | 29.22 | – | 13.11 | 1.90 | 2.71 |
| | Labradorite | 8 | 54.75 | 28.74 | 0.12 | 10.90 | 1.03 | 2.70 |

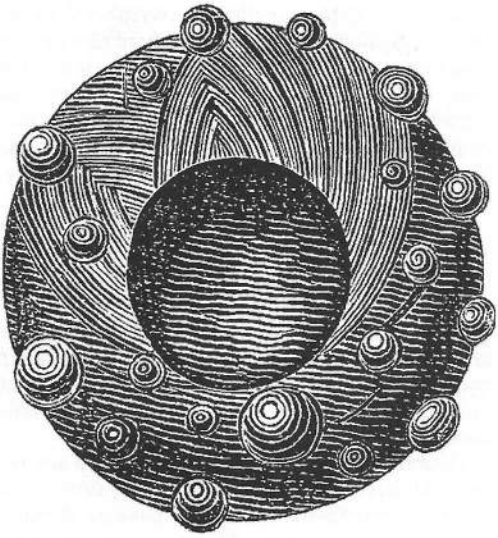


**Fig. 6.** Lower face of 'culot' formed by a fused oligosiderite, showing metallic grains dispersed in a stony matrix; the upper surface is entirely crystalline (Daubrée 1879*c*, fig. 190, p. 514).

fused them in a charcoal-lined clay crucible. The product was very similar to those found with the fused meteorites, even to the extent of it containing spherical silicate globules and grains of nickeliferous iron, as a result of the nickel content of the olivine. A similar result was obtained with hypersthenite (a rock composed almost entirely of the (Fe, Mg)$SiO_3$ pyroxene, hypersthene) from Mt Somma, Vesuvius. He also managed to produce artificial chondrules (Fig. 7) by fusing forsterite (an olivine mineral containing $<5$ wt% FeO, as compared to the 5–30 wt% in chrysolite) with finely divided carbon. Fusion of a mass of olivine crystals from a basalt near Langeac, France, produced an entirely crystalline product in which the crystals had a lamellar structure, like that observed in meteorites of the 'common type' and reminiscent of that found in scoria (volcanic clinker), in contrast to the 'granular' nature of crystals in the usual basaltic rock. From earlier experimental work, Daubrée was aware that olivine differed from most aluminous silicates (particularly the feldspars) in the ease with which it crystallized in anhydrous conditions.

Fusion of a mixture of silica, magnesia, an iron–nickel alloy, iron phosphide and iron sulphide in a magnesia crucible under incompletely oxidizing conditions produced an (unnamed) triple phosphide of iron, nickel and magnesium which Daubrée said Berzelius had reported finding in meteorites. In the presence of sufficient oxygen, the nickel tended to pass into the silicate, yielding iron-rich olivine, as found in terrestrial rocks. Under low-oxygen conditions, the olivine crystals (Fig. 8) contained a low concentration of nickel exactly as found in syssiderites (e.g. Pallas & Atacama).

**Table 3.** *Petrography of terrestrial rocks of basic composition as discussed by Daubrée (1866*b, c, *1879*c*) with additional petrographic data from von Cotta (1866), Cordier (D'Orbigny 1868), Zirkel (1866), etc. M, major component; a, accessory mineral.* NB. *Quantitative petrographic modal analysis only developed following the work of Rosiwal (1898)*

| Group | Mineral | Dunite | Lherzolite | Peridotite | 'Serpentine' | Basalt | Diabase |
|---|---|---|---|---|---|---|---|
| Olivine | | M | M | M | a | M | a |
| Pyroxene | Enstatite/Bronzite | | a | M | M | | a |
| | Hypersthene | | | | | a | a |
| | Diopside | | a | | | | a |
| | Augite | | M | M | a | M | M |
| Feldspar | Labradorite/Bytownite | a | | a | | M | M |
| | Anorthite | | | | | a | M |
| | Ilmenite | a | a | a | | a | a |
| | Chromite | a | a | | a | | a |
| | Magnetite | a | a | | a | a | a |
| | Garnet | | a | | a | | a |
| | Talc | | a | | a | | a |
| | Hornblende | | a | a | a | a | a |
| | Chlorite/Serpentine | | | a | M | a | a |
| | Mica | | | a | a | a | a |
| | Carbonate | | | | a | a | a |
| | Pyrite | | | | a | | a |
| | Zircon | | | | | a | a |
| | Apatite | | | | | a | a |

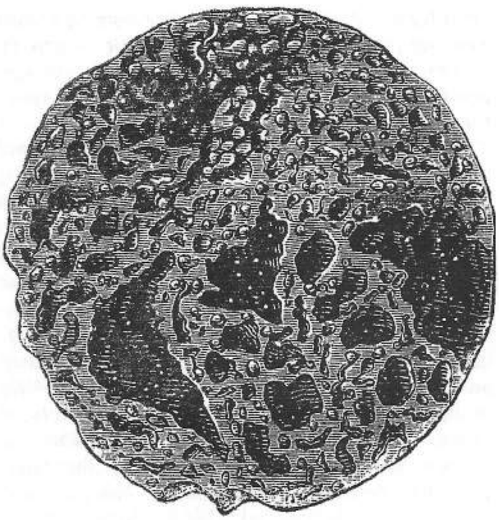


**Fig. 7.** Imitation of condritic structure by solidification of forsterite fused in finely powdered carbon (Daubrée 1879*c*, fig. 205, p. 608).

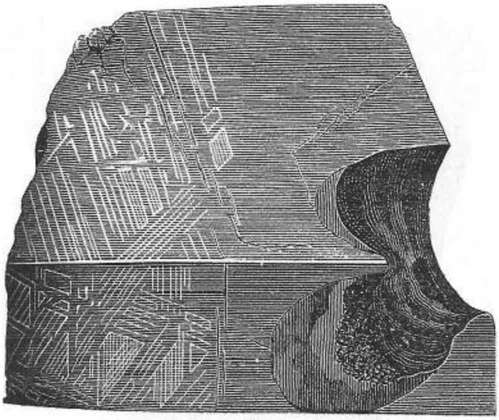


**Fig. 9.** Holosiderite showing Widmanstätten figures on cut, etched and polished faces, and a cavity caused by the erosion of a troilite granule (Daubrée 1879*c*, fig. 179, p. 489).

Turning to the irons, Daubrée was unsuccessful in managing to exactly reproduce the texture of their distinctive 'Widmanstätten figures' (Fig. 9), i.e. exsolution lamellae of kamacite ($\alpha$-iron, which contains 4–7.5 wt% Ni) in taenite ($\gamma$-iron, 27–65 wt% Ni), oriented parallel to the octahedral faces of the taenite. This characteristic structure is named after the Viennese chemist Alois Beck von Widmanstätten (1754–1849), who first revealed them in 1808 in the Hraschina meteorite (Croatia, 1751) by polishing a cut face in the iron and etching it with dilute nitric acid (von Schreibers 1820; see Greshake 2006, fig. 9; Marvin 2006). After considerable experimentation, Daubrée obtained a fair likeness (Fig. 10) by cooling a molten mass of soft iron admixed with 8 wt% nickel, 2% iron sulphide, 2% iron phosphide and less than 1% of silica.

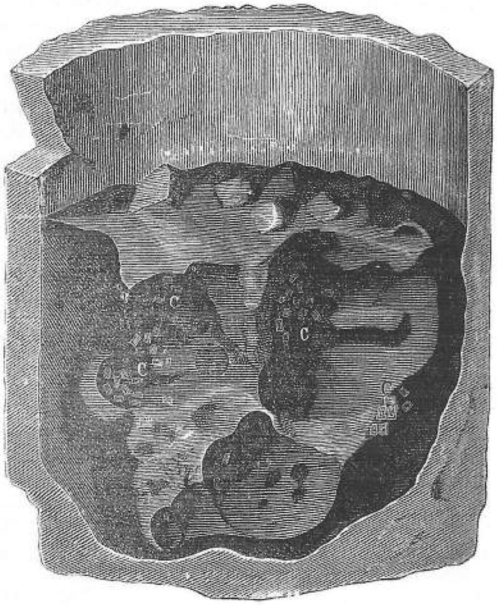


**Fig. 8.** Imitation of meteorites of the 'common type' by partial oxidation of iron silicate in a magnesia lined crucible; (C) olivine crystals (Daubrée 1879*c*, fig. 197, p. 524).

Daubrée believed that the granular texture of the stones, and the very small crystal size, as seen in thin section, resembled an agglomerated crystalline powder, reminiscent of that of frost or flowers of sulphur, which could have been formed by rapid cooling from vapour to the solid state. He was aware that the British geologist, metallurgist and microscopist Henry Clifton Sorby (1826–1908) had reached a similar concusion in his own studies (Daubree 1866*c*, p. 402; cf. Sorby 1864, 1865). This contrasted with the well-crystallized mass encountered in many of the fusion experiments. The fact that the grains of iron disseminated throughout the stony gangue were often irregular in shape, rather than globular (which occurred in fusion experiments), suggested that the original temperature might not have been much above that required to melt solder. The mode of formation of the majority of meteorites must have been under anhydrous conditions, but this was

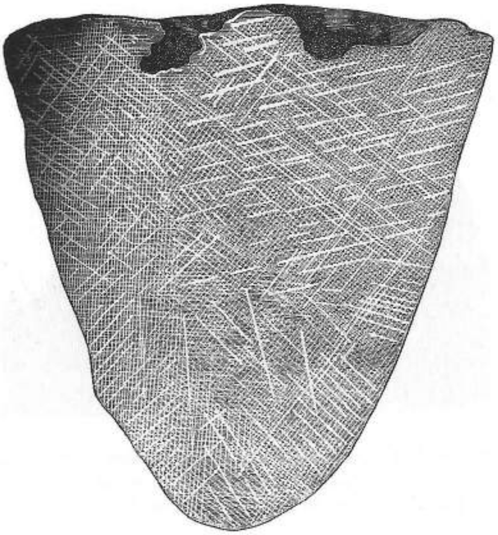


Fig. 10. Imitation of a holosiderite by fusion of iron with 8 wt% nickel, <1% silica, 2% iron sulphide and 2% iron phosphide (Daubrée 1879*c*, fig. 186, p. 511).

not the case with the aluminous meteorites. The fact that hydrocarbons still existed in the Orgeuil type of meteorite showed that these bodies must have been cold when they arrived in the Earth's atmosphere from space.

### *Initial conclusions*

Daubrée suggested that meteorites might have formed under conditions in which oxygen was not yet combined with silicon and the metals, perhaps because the initial temperature was too high to allow such combination. On cooling (or possibly from some other cause), the oxygen would begin to act on the more easily oxidized elements – silicon and magnesium would burn before iron and nickel and if there was insufficient gas to oxidize everything, or insufficient time, then these metals would remain disseminated within a matrix of silicates. Under anhydrous conditions, this would explain the formation of the syssiderites, polysiderites and the 'common type' oligosiderites.

However, in the case of the cryptosiderites, and particularly the aluminous types, this could not be the case, and an alternative model was needed. These could be explained (by analogy with certain Icelandic aluminous lavas containing pyroxene and anorthite) by the presence of superheated water.

The carbonaceous meteorites were clearly formed in a different manner to all the rest, evidently at a relatively low temperature. Although the presence of hydrocarbons might lead one to think of a planet with vegetable matter, it was probable that such compounds could be the last product of a sequence of reactions and were formed in the absence of life.

Turning to the Earth, where iron, silica and oxygen are also the dominant elements, Daubrée argued that one finds that those rocks most similar in mineralogical composition to stony meteorites (Table 3) are rarely exposed at the surface, and undoubtedly become more important at depth. Evidence for this was provided by the frequent presence of angular fragments (xenoliths) of olivine 'torn from a deep and preexisting mass' (Daubrée 1866*c*, p. 406) in the lavas of volcanoes in many districts of France and in dolerites from Montarville, France and Montreal, Canada; in lherzolite from the Pyrenees, the Bahamas, Norway; and the recently discovered (1864) dunite of the Dun Mountains, New Zealand. The lherzolites and dunite were presumed to be eruptive rocks originating at great depth, below the more acid (i.e. silica-rich) rocks, such as granite.

There were also important differences between meteorites and terrestrial rocks: particularly in the oxidation state of iron, rarely found on Earth in its native state, and the presence of phosphides rather than phosphates. From additional experiments, Daubrée satisfied himself that the mineral serpentine represented the hydrated equivalent of olivine, a transition that could be observed in the lherzolites of Sem in the Pyrenees. (His fusion experiments also showed that the final products were essentially identical to those obtained from the melting of olivine-rich meteorites.) As remarked earlier, meteorites also exhibited a complete absence of minerals present in granites and gneisses, nor did they show any evidence of the presence of stratified rocks.

Daubrée was particularly struck by the fact that olivine represents the most basic silicate mineral known, whether present in eruptive rocks or in meteorites, and that olivine-rich rocks have the highest density of any known (Table 4).

**Table 4.** *Daubrée's (1866*c*, p. 408) table of densities (g cm$^{-3}$) of terrestrial rocks*

| | |
|---|---|
| Granite | 2.64–2.76 |
| Trachyte | 2.62–2.88 |
| Porphyrite | 2.76 |
| Diabase | 2.66–2.88 |
| Basalt | 2.9–3.1 |
| Enstatite | 3.30 |
| Lherzolite | 3.25–3.33 |
| Peridotite | 3.33–3.35 |

He believed this was responsible for their 'normal position' in the Earth's crust 'beneath' granites and aluminous basic rocks.

He proposed that one should regard peridotites (a general term for rocks without feldspar, mainly consisting of olivine), together with their hydrated equivalent, 'serpentine' (serpentinite),[5] as of such fundamental importance that they should be considered as '*cosmic rocks*'. Recalling the long-held idea of the genesis of the Earth's crust by oxidation of metals in the Earth's core, a process which Élie de Beaumont (1847, p. 1326) had termed 'natural cupellation', Daubrée (1866*c*, p. 413) proposed that the chrysolite olivine represented a 'universal scoria' (akin to the slag remaining after the smelting out of a metal from its ore). He drew an analogy (Daubrée 1866*c*, p. 414) with what happens when a mass of impure cast iron is in contact with the air: the iron oxidizes as well as the silica with which it is associated. This gives rise to a ferruginous silicate that floats on top of the molten metal; a 'liquid scoria', which on cooling becomes first pasty then solid, with a compact crystalline structure quite unlike the 'spongy and puffy' texture of volcanic scoria. Finally, to explain the general absence of native iron in terrestrial rocks, he proposed that the excess of oxygen in our atmosphere was able to render such complete oxidation that little iron remained in the crust in the metallic state. He suggested (Daubrée 1866*c*, p. 415) that beneath the aluminium-rich lavas of Iceland (which resembled the Juvinas type of meteorite), or the peridotitic rocks similar in composition to the Chassigny type of meteorite, one might find lherzolites in which metallic iron begins to appear, thus (compositionally) resembling the 'common' meteorites. Furthermore, continuing lower in the Earth's crust, one might expect to find progressively increasing quantities of iron. Rose (1842, p. 390) had reported the occurrence of native platinum associated with 'serpentine' in the Urals, and Daubrée knew that in some cases it was alloyed with iron in sufficient quantity so as to become magnetic, a fact which he later (Daubrée 1875, 1876*b*) investigated. Daubrée felt that because of the very high specific gravity of platinum (13.5–17.7 g $\mathrm{cm}^{-3}$) its presence supported his idea of high-density metals associated with peridotites at depth.

He concluded (Daubrée 1867*c*, pp. 137–138) that, except for the carbonaceous meteorites, one might imagine the rest to be derived from a hypothetical celestial body less evolved than the Earth (in the sense of lacking an excess of oxygen in the atmosphere and without water) in which a series of concentric shells of different lithologies increased in density towards its centre, and that one might perhaps draw some analogy with the structure of the earth (Table 5), but he did not, at this stage, go further.

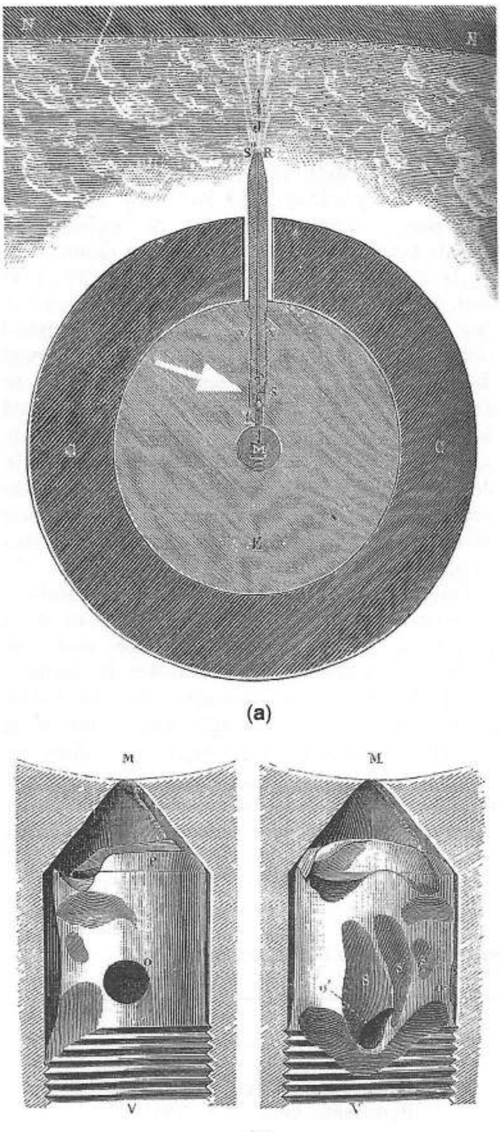
Daubrée was obviously aware of Sorby's microscopical studies of meteorites, so it is surprising that he did not make more of Sorby's conclusions (made known in lectures in 1864), that in a meteorite like the Pallas iron, 'iron and olivine might remain mixed in a state of fusion long enough to allow of gradual crystallization' either on the surface of a small planetary body with weak gravitation or 'towards the interior of a larger' (Sorby 1865,

**Table 5.** *Daubrée's (1867c, p. 138) comparative table of densities (g* $\mathit{cm}^{-3}$*) of (I) meteorites and (II) terrestrial rocks*

| I | | II | |
|---|---|---|---|
| ″ | | Stratified terrains | ″ |
| ″ | | Granite and Gneiss | 2.7 |
| ″ | | Pyroxenitic lavas | 2.9 |
| Aluminous meteorites | 3.0–3.2 | ″ | |
| ″ | | Peridotite | 3.3 |
| Peridotitic meteorites | 3.5 | ″ | |
| ″ | | Lherzolite | 3.5 |
| Common type of meteorites | 3.5–3.8 | ″ | |
| Polysiderites (Sierra de Chaco) | 6.5–7.0 | ″ | |
| Syssiderites (Pallas) | 7.1–7.8 | ″ | |
| Holosiderites (Charcas) | 7.0–8.0 | ″ | |

*Notes:* the meaning of his '″' symbol is not explained; his use of it elsewhere seems to imply 'not determined'. A later version of the table in Daubrée (1897*c*, p. 545), otherwise unchanged, gives the density for 'Stratified terrains' as 2.6 g $\mathrm{cm}^{-3}$.

p. 334); and that the 'round grains met with in meteorites' (i.e. chondrules) resulted by cooling from molten detached globules (Sorby 1864).



(a)

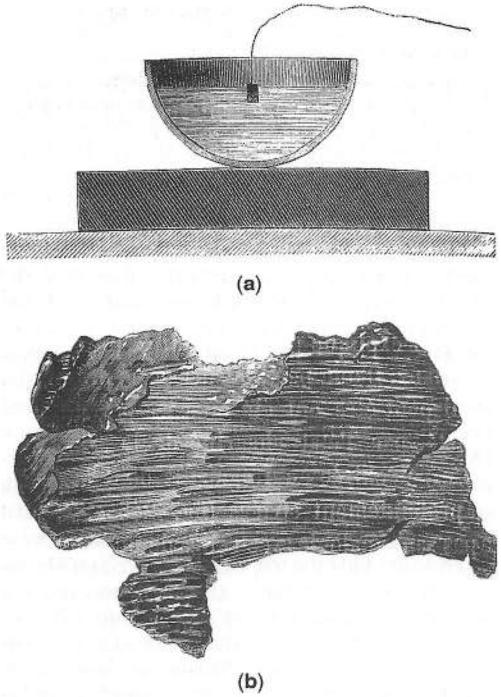
(b)

**Fig. 11.** (**a**) Apparatus to study erosion of steel plate (N–N) by hot gas from gunpowder explosion: central explosion chamber (M) surrounded by soft iron (E) and bronze (G) jacketing (Daubrée 1879*c*, fig. 223, p. 640); (**b**) examples of erosion of steel valve adjacent to the combustion chamber (Daubrée 1879c, figs 226 and 227, p. 642). The valves are shown inverted, as in original; the white arrow showing location of the valve in (a) has been added.

## Experimental studies (1876–1879): physical appearance

Daubrée now turned to a careful experimental programme (Daubrée 1876*a*, 1877*b*, *d–f*, 1878*b*, 1879*a*, *b*) to explain the physical features of meteorites that he attributed principally to the result of the erosive effect of hot, highly compressed, gas. One clue that the polyhedral shape of meteorites was attributable to mechanical rupture came from the fact that a cryptosiderite which fell in Le Teilleul, France in 1815 could be pieced together from three fragments which fortuitously turned up in the collections of the Muséum d'Histoire Naturelle and the École des Mines. The gradual erosion of the bore of cannons from the effect of the hot gases from gunpowder explosions had long been known. Microscopic examination revealed that partially combusted grains of gunpowder resembled the surface form of irons in minature, and in his initial experiments Daubrée was able to replicate this to some extent in metal by directing the hot gases from a contained gunpowder explosion (Fig. 11a) through a steel valve (Fig. 11b) or onto millimetre-sized zinc pellets. Later experiments involved the use of more powerful explosives: dynamite (Fig. 12), nitroglycerine (Fig. 13a, b) and gun-cotton (Fig. 14a, b). It was

**Fig. 12.** Detail of portion of steel bar, broken and eroded by dynamite explosion (Daubrée 1879*c*, fig. 234, p. 651).

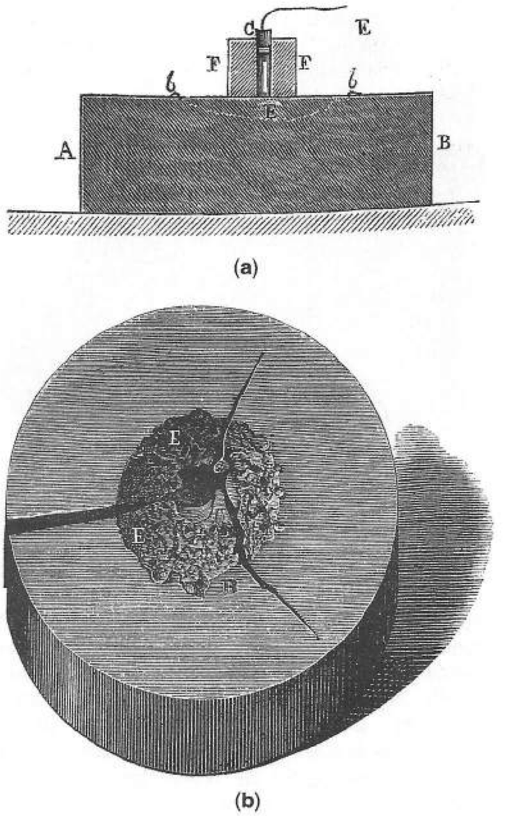

(a)

(b)

**Fig. 13.** (**a**) Nitroglycerine in lead container (4 mm thick, 20 cm diameter) with central electrically operated detonator above an iron slab (Daubrée 1879*c*, fig. 246, p. 662); (**b**) a fragment of the container, flattened and striated after the explosion (Daubrée 1879*c*, fig. 248).

ironic that one of the best examples of erosion, produced by an air-blast at white heat, was a piece of hydraulic cement from Hauenschid's Portland Cement works in Vienna (Fig. 15), sent to Daubrée by the Austrian geologist, Eduard Suess (1831–1914), who was at that time Professor of Geology at the University of Vienna.

Daubrée concluded from his experimental programme that the surface depressions, polish and striations were produced by rotation under the erosive action of a very hot turbulent gas under high pressure, together with the combustion of the Fe–Ni sulphide and phosphide minerals (these factors also contributed to the formation of the dust clouds that often accompanied the passage of a meteorite through the atmosphere); the rapid heating and expansion during its passage through the Earth's atmosphere caused its fragmentation into polyhedral shapes; and the superficial black crust and internal veining was caused by fracture, penetrative oxidation and in-fill with surface melt.



(a)

(b)

**Fig. 14.** (**a**) Arrangement for electrically detonating a 50 mm-diameter cylinder (15–18 g) of gun-cotton against an iron slab (Daubrée 1879*c*, fig. 250, p. 664); (**b**) eroded surface of the slab following the explosion (Daubrée 1879*c*, fig. 251, p. 665).

## The problem of 'native' irons

As has been seen, in the years prior to 1867, when Daubrée was drawing his first conclusions regarding the implications of meteorite compositions, there was little evidence that 'native' iron could occur in more than trace quantities on Earth. This view changed following an expedition to Greenland in May 1870, led by the Finnish geologist, mineralogist and Arctic explorer, Baron Nils Adolf Erik Nordenskjöld (1832–1901).

Since 1818 previous explorers of Greenland had noted that the indigenous population used knives and other instruments reputedly manufactured from large isolated boulders of iron, and specimens of some of these boulders had been retrieved (see Ebel 2006, 270–271).

On 30 August 1870, following a brief, unsuccessful, search for the site of a previously

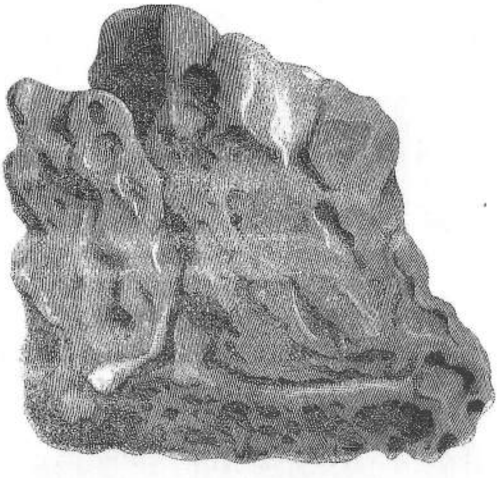


**Fig. 15.** Block of hydraulic cement eroded by hot furnace gas (Daubrée 1879*c*, fig. 253, p. 682).

reported find at Fortune Bay on Disko Island (located off the west coast of Greenland at approximately latitude 69°30′N, longitude 53°W), Nordenskiöld and his colleagues were taken by one of the Greenlanders along the coast to the NW, to 'one of the shores most difficult of access in the whole coast' beneath Ovifak Mountain. Here, on the shoreline, below a talus slope abutting 2000 ft (610 m) cliffs of horizontal basalt flows, the party came across 15 large, apparently isolated, ovoid boulders of iron, the largest of which was 2 m in diameter and estimated to weigh 21tonnes (t).

> The meteorites ... lay between high and low water, among rounded gneiss and granite blocks. ... Sixteen metres from the largest iron block a basalt ridge of a foot high rose from the detritus on the strand, and could be followed for a distance of four metres, and was probably part of the rock. Parallel with this and nearer to the strand ran another similar ridge, also about four meters long. *The former contained lenticular and disk-shaped blocks* of nickel iron, in external appearance, chemical nature, and relation to the atmosphere (weathering), like meteoritic iron. On being polished and etched this iron exhibited fine Widmanstädt's figures. The native iron lay imbedded immediately in the basalt, separated from it at the most by a thin coating of rust. Moreover, in that basalt, in the neighbourhood of the blocks of native iron, nodules were found of Hisingerite [a hydrated iron silicate of uncertain composition; Dana 1899], evidently formed by the oxidation of the iron, as also small imbedded particles of nickel iron. The meteorites themselves were of various colours ... Here and there one could discover upon their surface and in the iron nearest the surface pieces of basalt or fragments of a crust of basalt perfectly similar to the basalt in the above-described ridge. (Nordenskiöld 1872, p. 461, italics as in original; a map of the site is given opposite p. 355; see also Lawrence Smith 1879, plate II, fig. 5, after Steenstrup.)

Nothing of this kind had ever been seen before. Immensely excited by the discovery, the smaller blocks were retrieved, and over the following 2 years successive expeditions under the Danish geologist, Knud Johannes Vogelius Steenstrup (1842–1913), brought back even the largest ones. Additional finds came from Fortune Bay (1852), Mellemfjord and Assuk (Asuk, 1872) on Disko Island; and from Niakornaok (1847) on the mainland coastline. Although some of the specimens remained in their original condition, unless very careful precautions were taken to exclude the air, others showed an alarming tendancy to undergo alteration and disintegrate (Story-Maskelyne 1871; Daubrée 1872*b*).

Nordenskiöld's initial discovery was reported at a meetings of the Geological Society of London on 8 November 1871 (Forbes 1871) and of the Geological Society of Paris on 5 February 1872 (Hébert 1872). However, Daubrée probably first learnt of the finds in his role as rapporteur to the Academy of Sciences in 1871. Following a request to Nordenskiöld to send him some specimens, Daubrée (among others) was soon involved in their study (Daubrée 1872*a*, *b*, 1876*c*, 1877*a*).

Quite apart from the huge metallic blocks and much smaller specimens of malleable iron (found within the basalt), some specimens gave the appearance of a 'sort of metallic sponge composed of small grains'or 'a mass of iron grains welded together'; others showed a mixture of stony matter with delicate filaments of iron. In Daubrée's terminology, the forms ranged from what could be syssiderite to sporadosiderite (Fig. 16a–c). Other sites revealed rocks that appeared to the unaided eye to be of normal basalt, but which in thin section clearly showed the presence of iron grains (Lawrence Smith 1879, p. 470). In 1872 Steenstrup found a 28-t block of nickeliferous pyrite in a basalt dyke at Igdlokungoak, on the north coast of Disko (Lawrence Smith 1879, p. 487).

As seen in the quotation above, Nordenskiöld's immediate reaction was to characterize the suite as of meteoritic origin, the fall of the fragments into the basalt having taken place 'during the latter part of the Cretaceous and the beginning of the Tertiary'

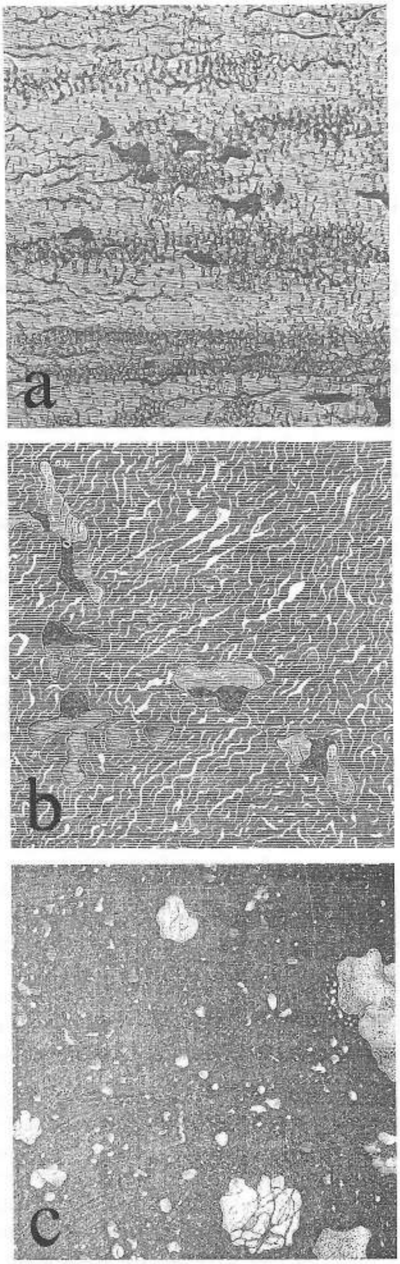


**Fig. 16.** Polished surfaces of cut slabs of Ovifak 'irons': (**a**) light grey metallic 'syssiderite' with 'worm-like' carbonaceous fragments and darker angular silicate fragments (Daubrée 1879*c*, fig. 201, p. 558); (**b**) deep grey metallic 'syssiderite' with lighter lamellae of 'schreibersite' and iron sulphate; darkest particles are silicates (Daubrée 1879*c*, fig. 202, p. 561);
(**c**) 'sporadosiderite', dark silicate groundmass containing light-coloured grains of 'iron carbide', nickeliferous cast iron or iron sulphide (Daubrée 1879*c*, fig. 203, p. 564).

(Nordenskjöld 1872, p. 520). He realized that 'as considerable masses of iron, of a composition very similar to that of meteoritic iron, without a doubt occur in the interior of the Earth', the iron could have been brought to the surface during the eruption of the basalt, but he felt that the presence of the hydrocarbons militated against that. He also felt it unlikely that the iron could have originated 'from the reduction by gases developed in connection with basalt eruptions of a ferruginous material' (Nordenskiöld 1872, p. 520).

Needless to say, Nordenskiöld's conclusion proved extremely contentious. Some geologists and mineralogists, for example Story-Maskelyne (1871) and Daubrée (quoted in Hébert 1872, p. 172; Daubrée 1872*a*, *b*) supported him; others, such as the Scottish geologist, Sir Andrew Crombie Ramsay (1814–1891) and the French geologist and mineralogist, Alexandre Émile Béguyer de Chancourtois (1820–1886), who had been on an expedition to Greenland in 1856, argued for a terrestrial origin (Ramsay 1871; de Chancourtois 1872*a*, *b*).

Initial mineralogical and chemical examination of the 'iron' specimens by a number of scientists had revealed several unusual features: the presence of troilite and perhaps schreibersite (hitherto known only from meteorites); up to 5 wt% Ni (lower than found in irons hitherto) plus small quantities of cobalt, chromium and copper; 1–2 wt% 'free' C; and the presence of soluble salts (particularly calcium sulphate), combined water and hydrocarbons (Forbes 1871; Hébert 1872; Nordenskiöld 1872).

In his first study of the samples sent to him by Nordenskiöld, Daubrée (1872*a*, p. 1546) also pointed out that the sharpness and size of the silicate crystals, which appeared to be of labradorite, contrasted with the 'confused' state of the small crystals usually found in meteorites. Furthermore, using a method developed by the French chemist Jean Baptiste Joseph Dieudonne Boussingault (1802–1887) for measuring the amount of combined carbon in cast iron, Daubrée showed that an additional 3 wt% of carbon was 'combined' with iron. It was only later (Daubrée 1877*a*, 1879*c*, p. 564) that he specifically mentions 'iron carbide', but he knew (Daubrée 1872*b*, p. 246) that 'one sees daily in metallurgical workshops the ease with which carbon associates with iron to form steel and cast iron'. Cohenite ($(\mathrm{(Fe,Ni,Co)_3C})$) now known to be present in the Ovifak specimens (Goodrich & Bird, 1985), was not formally described from meteoritic irons, and stated to be analogous with the $Fe_3C$ 'which separates from cast iron in crystals', until 1889 (cf. Dana 1899).

Daubrée (1872*a*) pointed out that the presence of both combined and free carbon in the specimens was remarkable: in this, their composition resembled that of carbonaceous meteorites, but the presence of so much metallic iron as well as silicates suggested a new class of meteorite. However, he also noted that the vast eruptions of doleritic lavas in Greenland, known to contain *c.* 20 wt% FeO, could be subject to partial reduction as a result of the presence of numerous beds of lignite 'particularly on Disko Island' and graphite, which could have been encountered by the dolerites on their way to the surface. It was even possible that such eruptions could have carried masses of nickeliferous iron up from the depths of the earth (Daubrée 1872*a*, p. 1548). Aware that recent experiments had shown that carbon monoxide in the presence of iron oxide, or even metallic iron, could produce 'a deposit of carbon partly combined with iron, partly mixed with the oxide' at temperatures around 400 °C (Daubrée 1872*a*, p. 1549), he suggested that carbonaceous meteorites might have been exposed, either simultaneously or alternately, to oxidation and reduction by exposure to water vapour or carbon monoxide. He hoped that further experimental work might throw more light on the origin of both the Ovifak rocks and carbonaceous meteorites in general. Nevertheless, in Daubrée (1872*b*, p. 245) he was still inclined towards a meteoritic origin.

Apart from Daubrée, the Ovifak material had also been examined in the years 1872–1875 by the Danish geologist Johannes Frederik Johnstrup (1818–1894), Swedish geologist Jonas Gustaf Oscar Lindström (1829–1901), Austrian mineralogist, petrologist and chemist, Gustav Tschermak von Seysenegg (1836–1927) and the German chemist Friedrich Wöhler (1800–1883) (see Lawrence Smith 1879, p. 454 for references), all of whom supported the hypothesis of a meteoritic origin. Nevertheless, in France, Daubrée's debate with de Chancourtois (1876*a*–*c*) continued (Daubrée 1876*c*), but by the following year Daubrée (1877*a*, pp. 69–70) was beginning to sound less certain as to whether a 'cosmic' or 'telluric' origin for the Ovifak iron was the more probable.

Matters were finally resolved in April 1879, when the American chemist and geologist, John Lawrence Smith (1818–1882), published the results of an exhaustive chemical and mineralogical study. As a young man, he had trained to be a doctor, but had then studied chemistry, physics and mineralogy in France and Germany before taking up an academic career, largely as a skilled chemist, in the United States (see Clarke *et al.* 2006). An advantageous marriage in the 1850s enabled him thereafter to travel frequently to Europe (Silliman 1883). Fluent in French, he frequently published in French-language journals. Having analysed many meteorite specimens from the Americas, it is not unsurprising that he made contact with Daubrée. It was Lawrence Smith (1876, 1878) who first identified and named 'daubréelite', and when Daubrée found crystals of ferrous chloride in some of the Ovifak specimens, he named the mineral 'lawrencite' (Daubrée 1877*a*, p. 69) after his colleague, who had first described this mineral in the Tazewell iron, USA, in 1855. So it is ironic that it was Lawrence Smith's (1879) study of the Greenland specimens that finally dashed all hopes for their meteoritic origin: he showed that, both petrologically and chemically, there was no difference between dolerites that contained iron and those which did not, and that there was evidence that the feldspar (labradorite) had often crystallized in direct contact with the iron, penetrating into its texture, although sometimes it was enclosed by a rim of what was probably magnetite. Some altered olivine and chlorite were also present. Associated minerals were nickeliferous pyrrhotite ($Fe_{5-16}S_{6-17}$) or pentlandite ((Fe,Ni)S) (which had been previously misidentified as troilite); graphite, hisingerite, spinel and corundum.

Other than the association of nickel and cobalt with metallic iron, he concluded that there were many points of dissimilarity between the Ovifak 'irons' and meteorites: the hardened crust of iron oxide was unlike that on any known meteorites; the metal slugs were much more fragile than was normally the case with meteoritic iron; the blocks of iron were in immediate contact with the basalt; silicates resembling eucrites in composition were far more common in dolerites on Earth than in meteorites; and the occurrence of magnetitie and graphite was quite unlike what was found in eucrites. The most telling point was that in the basalt specimens from Assuk, microscopic inclusions of iron were found within crystals of labradorite and oligoclase. No specimens of meteoritic iron had ever shown such quantities of combined carbon; what had been described as 'Widmanstätten figures' exhibited very different patterns and were formed by a quite different mechanism. Finally, the composition of the iron bore a striking resemblance to that obtained experimentally by Daubrée in the 1860s by fusion of olivine from the Langeac basalts. To be certain, Lawrence Smith had had his microscopic results confirmed by the leading French mineralogists and petrologists Alfred Louis

Olivier Legrand Des Cloizeau (1817–1897), Ferdinand André Fouqué (1828–1904) and Auguste Michel-Lévy (1844–1911). He concluded that the most likely mechanism for production of the Ovifak iron was that molten basalt had been reduced on its passage through the beds of lignite by the presence of carbon, and the iron consequently separated from ferruginous silicates.

Observational astronomical spectroscopy had become well advanced since the 1860s, and a crucial understanding of the nature of the solar absorption spectrum – that the dark lines of the solar spectrum could be correlated with the bright lines of flame-spectra, and that each chemical element has its corresponding spectrum (Kirchhoff 1861–1862) – was provided through the collaboration of the German chemist Robert Wilhelm Bunsen (1811–1899) and the theoretical physicist Gustav Robert Kirchhoff (1824–1887). Spectroscopic evidence led Daubrée to comment that elements present in both meteorites and terrestrial rocks (Daubrée 1867*c*, pp. 119–120) were also present in the sun and the stars (Daubrée 1879*c*, pp. 593). He listed in order of approximately decreasing importance: iron, magnesium, silicon, oxygen, nickel, cobalt, chromium, managanese, titanium, tin, copper, aluminium, arsenic, phosphorous, nitrogen, sulphur, chlorine, carbon and hydrogen. He particularly emphasized the importance of iron, silicon, oxygen and magnesium in both meteorites and rocks from the deep Earth. In Daubrée's (1879*c*, p.555–576) discussion of the 'native' iron of Ovifak, he accepted the conclusion of its terrestrial origin, but believed that meteoritic density stratification (Table 5) still implied that metallic iron could exist within the Earth at a depth of 'many kilometres'; an idea that he believed was supported by the existence of the terrestrial magnetic field (Daubrée 1879*c*, p.546).

In 1883 Lawrence Smith's results were confirmed by the Danish mineralogist Johannes Theodor Lorenzen (1855–1884). In addition to studying previously known specimens, Lorenzen also analysed fine particles of metallic iron that had been found *in situ* in a basalt at Assuk by Steenstrup in 1880 (Daubrée 1885). Although Lorenzen (1884) believed that Lawrence Smith's identification of labradorite and corundum were erroneous (and that it was anorthite and spinel that were present), he endorsed his overall results and added that Daubrée's hypothesis of transport of iron from the deep Earth seemed untenable because it could not account for the close association of the iron with the presence of graphitic feldspar. Nevertheless, in Daubrée's (1885) final contribution on the subject, he reiterated his argument that a deep-Earth origin for the iron was possible, and that it could have been 'uprooted' from large masses during eruption of the basalt, on the assumption that both would be present at the depth from which an eruption began.

A popular summary of the whole range of Daubrée's scientific work appeared soon after (Daubrée 1888*a*). Reports to the Academy of Sciences of the discovery of diamonds and natural silicon carbide (named 'moissanite' in 1905) in meteorites (Daubrée 1888*b*, 1893) were his last contributions on meteoritics.

Despite the controversy over the terrestrial origin of 'native' iron, Daubrée must have been well satisfied that his work on meteorites of proven cosmic origin had done much to advance understanding of their nature and probable origins. His classification remained popular until the end of the century and his ideas led to the SiAl–SiMa–NiFe model of the Earth put forward by Suess in *Das Antlitz der Erde* (The Face of the Earth; Suess 1883–1909).

### *Modern views on the 'native iron' question*

Puskarev & Anikina (2002) describe the origin of the Nizhny–Tagil dunite–(serpentinite)-hosted chromite–platinum ores of the central Urals as forming at the latest stage of the recrystallization of the dunite, following plastic deformation. The ore bodies formed at temperatures below 750 °C, with the platinum-group metals precipitating after chromite, together with chromium-rich silicates enriched in alkalis and calcium. Native iron, copper and nickel, together with nickel sulphides and magnetite, formed in the last stages of ore formation.

However, even today, the issue of 'native' iron is subject to some controversy. Treiman *et al.* (2002) discussed a pseudo-meteorite that they suggest is actually from the iron-bearing basalts of the Siberian Trap. Modern reanalysis of historical specimens from Disko Island has been undertaken, together with new fieldwork (Goodrich & Bird 1985; Klöck *et al.* 1986). Goodrich & Bird (1985) suggested that iron, nickel, cobalt, copper and phosphorous oxides in basaltic magma were reduced at a depth of less than 1.2 km by carbon assimilated from the Tertiary shales and coals through which the magma passed. The metal formed as immiscible droplets of carbon-saturated liquid. Subsequent separation of iron from the graphite caused exothermic decarburation, and FeO and $P_2O_5$ were concentrated into silicate liquids trapped as inclusions within the metal. As the metallic grains and possibly still-liquid droplets were carried upwards in the magma, they accumulated to form large masses of iron in a subvolcanic intrusive body. However, Klöck *et al.* (1986) suggest that the larger metal particles sank in the silicate liquid of a magma chamber and, as they aggregated, they concentrated nickel, cobalt, copper, chromium and other siderophile elements, forming large massive iron cumulates containing FeO- and $P_2O_5$-rich silicate inclusions, at the base of the magma chambers.

Although Fundal (1975) and Bird & Weathers (1977) argued in favour of a mantle origin for the metallic iron, Klöck *et al.* (1986) rejected this on the basis of the low nickel content of the metals.

Recently, Jones *et al.* (2002) have shown that the effects of decompression melting mean that an impact by a 20 km-diameter iron hitting the Earth at 10 km $s^{-1}$ could produce a transient, almost spherical, crater of approximately 100 km in diameter. Of the resulting $3 \times 10^6$ $km^3$ of melt, around $1 \times 10^6$ $km^3$ would be delivered to the surface; the initial crater becoming obliterated by the subsequent vulcanism. They suggest that similar events could account for the occurrence of platinum-rich nickel–iron metal within both the Siberian Platform and the Disko Island lavas (Jones 2000).

## Notes

[1] In 1871, the town was swept up in the annexation of Lorraine by the Prussian army; becoming part of German-Lorraine, it did not return to France until 1918 (and, unfortunately, suffered a similar fate in 1940–1945).

[2] This meteorite fell in Kranoyarsk (Krasnojarsk), Siberia; it is named after the German-born Russian geologist and naturalist, Peter (Pyotr) Simon Pallas (1741–1811), who brought it to St Petersberg in 1772. See Ivanova & Nazarov (2006) for further discussion.

[3] Dana (1899, p. 29) notes that a thin coating of iron on lava was recorded following the eruption of Etna in August 1874; Daubrée was evidently aware of an earlier example.

[4] Alder Wright (1880) mentions that masses of iron weighing up to several kilograms were found near Nery, France, at a spot where a coal seam had been burning for some time; it was presumed that the iron must have been formed by the 'reducing action of the burning coal on ferruginous matter in the soil and rock'. He does not give a date, but this may have been the example Daubrée knew of. Dana (1899, p. 29) quotes a similar example from Canada.

[5] The modern term 'serpentinite' had not been introduced at the time Daubrée was writing. In geological dictionaries such as Page (1859), Hatch (1892), Holmes (1928), etc., 'serpentine' refers to both the mineral and the (serpentinite) rock.

I thank the librarians at the Geological Society of London, Science Museum Library, Royal Astronomical Society, Royal Society of Chemistry and Institute of Materials, Mining and Metallurgy, London, for their help – without which this work would have been impossible to contemplate; J. McCall for alerting me to the Treiman *et al.* (2002) publication; M. Gounelle, and referees J. Grattan and I. Sanders all made useful comments on the manuscript and M. Gounelle kindly sent me a copy of Daubrée (1867*d*). The assistance of M.J. Barande and Mlle. C. Billoux of the Bibliothèque de l'Ecole Polytechnique, Paris, and Mlle. S. Roulleau of the Musée de la photographie, Paris, is also much appreciated.

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