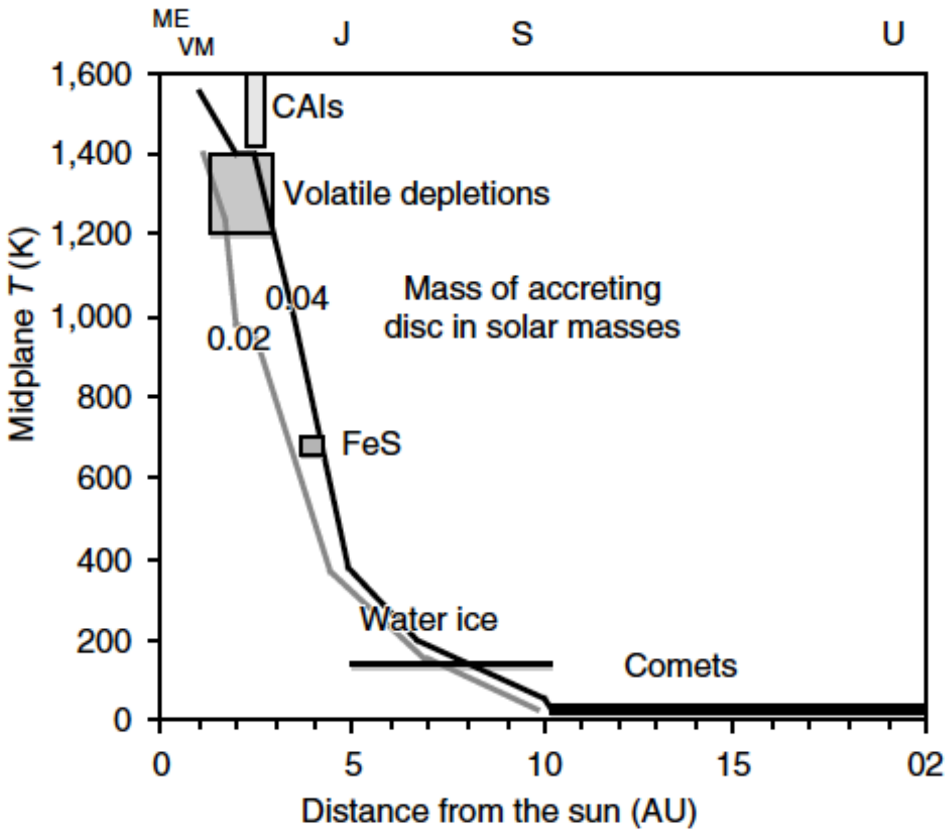
The solar condensation sequence

The processes of vaporization and condensation are of major importance in the solar nebula. In order to systematize this process, **Grossman (1972)** used thermodynamic equilibria to calculate the composition of phases in equilibrium with a gas with cosmic element concentrations, at a pressure of 10^3 atm, and as a function of temperature.

This work has subsequently been developed by others and is systematized in **Lewis (2004)**. It is worth noting that in detail it is likely that the assumption of equilibrium conditions will not always apply to the condensation sequence **(Wood, 1988)**.

Nevertheless, observations of this type are invaluable in providing a first pass at interpreting the processes of planetary formation.

The **solar condensation sequence** may be described as a series of steps which describe the formation of phases, and subsequent reactions between phases, during the condensation of the solar gas (Lewis, 2004). These steps explain the **main sequence of mineral phases** forming in a solar nebula in relation to temperature and distance from the sun:



Midplane solar nebular temperatures (K) calculated for 0.04 and 0.02 solar masses in the accreting disk, and estimated temperatures from meteorites and comets, plotted against distance from the sun, expressed both as astronomical units (1 AU Earth–Sun distance) (bottom) and planetary distance (top).

The temperatures presented here are indicative only, as they are dependent upon the size of the disc and the thermal model used (after Boss, 1998).

The temperatures indicated are taken from the adiabatic curve of Lewis (2004):

1 Formation of the **refractory siderophiles**. (The metals W, Os, Ir, and Re – although in reality concentrations are so low that these phases do not nucleate.)

2 Formation of **refractory oxides** (ca. 1700 K). (Al, Ca, and Ti oxides such as corundum, spinel, perovskite, and some silicates. The phases also include the REEs and U and Th.)

3 Formation of **iron–nickel metal** (ca. 1450 K) (also included are the minor elements Co, Cu, Au, Pt, Ag and may include the nonmetals P, N, C).

4 Formation of **magnesium silicates** (ca. 1420 K) (the principal components are olivine and Mg–pyroxene).

5 Formation of **alkali metal silicates** (ca. 1020 K) (the major component is plagioclase feldspar).

6 Formation of the **moderately volatile chalcophiles** at 670 K (FeS, with Zn, Pb, and As).

7 Formation of **silicates with mineral-bound OH** (ca. 430 K; this group includes the hydrated silicates – the amphibole tremolite, serpentine, and chlorite).

8 Formation of **ice minerals** (ca. 140 K) (to include water ice, solid hydrates of ammonia, methane, and rare gases).

9 A residue made up of **permanent gases** (gases which under natural conditions will not condense are H2, He, and Ne).

This **condensation scheme** provides a valuable framework for understanding the mechanisms behind the formation of the different components found in **primitive meteorites** and a basis for understanding the **differentiation** of the Earth.

Evidence from Meteorites

Meteorites are extremely important to our understanding of solar system evolution, because, in their most primitive form, they are our ***most ancient samples*** of the solar system.

As such they provide valuable information about the **condensation** of the solar nebula from which our solar system formed. Whilst they represent, to date, our most abundant sample of **extraterrestrial material**, we have no idea how representative this is of the solar nebula material as a whole.

Meteorites, as **rocks** produced in a solar nebula, have formed through a range of processes, some of which are quite different from those observed on Earth. Thus while igneous differentiation processes and metamorphism are recognized in meteorites, there also other processes operating which are not observed in terrestrial rocks. These include evaporation and condensation events related to **melting in a gas-rich medium**, **impacting events**, and **metal-silicate fractionation**.

Meteorites and the dramatic fireballs that announce their arrival have long instilled both fear and wonder in the human imagination. Yet scientists did not begin to understand meteorites until fairly recently. It wasn't until the early 1800s—after researchers investigated a series of dramatic meteorite falls in both Europe and the United States—that most scientists accepted that rocks actually fall to Earth from space. Today, better technology allows researchers to study meteorites in new ways and unlock their many secrets.

A 500-year-old fall

Around 11:30 A.M. on November 16, 1492, a young boy saw a large stone plummet from the sky and land in a wheat field near the town of **Ensisheim** in Alsace, France. This fall is the earliest one witnessed in the Western world from which meteorite samples have been preserved.

The Ensisheim meteorite was considered a sign of good luck from God. Immediately after it fell, people began chipping off pieces as sacred souvenirs. Fragments of Ensisheim can be found in museum collections all over the world.

1492

Von dem donnerſtein gefallē jm xcij. iar: vor Enſiſhein.

De fulgetra anni xcij.
Sebaſtianus Brant.

Perlegat antiquis miracula facta ſub annis
Qui volet: et noſtros comparet inde dies.
Viſa licet fuerint portēta / horrēdaq̄ mōſtra
Lucere e celo: flamma / corona / trabes /
Aſtra diurna / faces / tremor et telluris hyatus
Et bolides / Typhon / ſanguineus q̄ polus /
Circulus: et lumē nocturno tpe viſum /
Ardentes clypei et / nubigeneq̄ fere.
Montibus et viſi quondā concurrere montes
Armorū et crepitus / et tuba terribilis.
Lac pluere e celo viſum eſt / fruges q̄ calybſq̄
Ferrū etiam / et lateres / ⁊ caro / lana / cruor /
Et ſexcenta aliis / oſtenta aſcripta / libellis:
Prodigiis auſim vix ſimilare nouis.
Viſio dira quidē Friderici tempore primi:
Et tremor in terris / lunaq̄ / ſol q̄ triplex.
Hinc cruce ſignatus Friderico rege ſecundo
Excidit inſcript⁹ grāmate / ab hymbre lapis.
Auſtria quē genuit ſenior Frideric⁹ / in agros
Terci⁹ hunc pprios. et cadere arua videt.
Anno Dni 1492
Nempe q̄dringētos / p⁹ mille peregerat annos
Sol nouiesq̄ decem ſignifer / atq̄ duos.
Septē preterea dat idus / metuenda Nouēbris:
Ad mediū curſum tenderat illa dies.
Cum tonat horrēdū: crepuitq̄ per aera fulmē
Multiſonū: hic ingens concidit atq̄ lapis.
Cui ſpēs delte eſt / aciesq̄ triangula: obuſtus
Eſt color / et terre forma metalligere.
Miſſus ab obliquo fertur: viſusq̄ ſub auris
Saturni qualem mittere ſydus habet.
Sēſerat hūc Enſhei. Sūtgaudia ſēſit: agros
Illic inſiluit / depopulatus humum.
Qui licet in partes fuerit diſtractus vbiq̄:
Pond⁹ adhuc tamē hoc ꝯtinet / ecce vides.
Qui mirū eſt potuiſſe hyemis cecidiſſe dieb⁹:
Aut fieri in tanto frigore ꝯgeries?
Et niſi anaxagore referant monumēta: molarē
Caſurū lapidē. credere et iſta negem.
Hic tn̄ auditus fragor vndiq̄ littore Rheni:
Audijt hunc Vri prim⁹ alpicola:
Norica vallis eū / Sueui / Rhetiq̄ ſtupebāt:
Allobroges timeant: Francia certe tremit.
Quicq̄d id ē / magnū portēdit (crede) futur⁹
Omen: at id veniat hoſtib⁹ oro malis.

Sych wundert mancher fremder gſchicht.
Der merck vnd leß ouch diß bericht.
Es ſint geſchen wunder vil
Jm lufft / comet vnd füren pfil.
Brinnend fackel / flammē vnd kron.
Wild kreiß vn̄ d zirckel vmb den mon
Am hymel blůt / vnd füren ſchilt /
Regen noch form der thier geſtaldt.
Stoß / bruch des hymels vnd der erd /
Vnd ander vil ſeltzen geberd
Tratzlich zerſtieſſen ſich zwen berg /
Grüßlich trůmett / vnd harneſch werck /
Jſen / milch / regen ſtahel korn
Ziegel / fleiſch / woll / von hymels zorn
Als ouch ander der wunder glich
Dann by dem erſten Friderich
Noch ert bydem vnd finſternuß
Sach man drij ſunn vnd mon gewiß
Vnd vnder keyſer Friderich
Dem andern / fiel ein ſtein grüßlich
Sin form was groß / ein crütz dar jnn
Vnd ander geſchrifft vnd heimlich ſynn
By wil des dritten Friderich
Geboren herr von Oſterich
Begt har jn diß ſin eigen landt /
Der ſtein der hie ligt an der wandt.
Als man zalt viertzehenhundert Jar.
Vff ſant Florentzen tag iſt war
Nüntzig vnd zwei vmb mittentag
Geſchach ein grüſam donnerſchlag /
Drij zentner ſchwer fiel diſer ſtein
Hie in dem feld vor Enſißhein /
Drij eck hat der verſchwertzet gar
Wie ertz geſtalt vnd erdes var
Ouch iſt geſehen in dem lufft
Slymbes fiel er in erdes klufft
Clein ſtück ſint komen hin vnd har
Vnd wit zerfüert ſůſt ſichſt in gar
Tůnow / Necker / Arch / Jll / vnd Rin
Switz / Vri / hort den klapff der Jn /
Och doent er den Burgundern ver
Jn forchten die Frantzoſen ſer
Rechtlich ſprich ich das es bedüt
Ein bſunder plag der ſelben lüt

Von Maximiliano. Romiſchem kuning:

Jch für dich recht o Adler milt.
Erlich ſint wapen in dim ſchilt
Brüch dich noch eren gen dim findt
An dem all truw vnd ere iſt blindt
Schlag redlich vnd mit froüden dran
Triw vmb das rädt Maximilian.
Jn dim geuell das glück jetzt ſtat
Ach ſům dich nit / kum nit zů ſpat
Mit ſorg den vnfal vff diß Jar
Ni. vorcht din findt als vmb ein har
Sig / feld / vnd heyl von Oſterich

Bürgundiſch hertz von dir nit wich
Roniſch ere vnd tütſcher nacion
An dir o höchſter künig ſtan
Nym wa · der ſtein iſt dir geſant
Dich mant gott in dim eigen lant
Das dü dich ſtellen ſolt zů wer
O küning milt für vß din her
Cling harneſch vnd der büchſen werck
Trůmm zerſchöl / franzöſiſch berck
Ouch mach den groſſen hochmůt zam
Bett ſchirm din ere vnd gůtt n nam.

Nüt on vrſach
.J. .B.

The only surviving original of Sebastian Brant's first broadsheet describing the fall of the 'donnerstein' at 'Ensisshein' in 1492.

The Latin and German verses describing the fall are followed by an address to Maximilian, the Roman King. The inked lines and notations are of unknown authorship. (Reprinted by courtesy of Ueli Dill, Keeper of Manuscripts at the Offentliche Bibliothek der Universit/it Basel.)

Sebastianus Brant^s de fulgetra anni 1492

Perlegat antiquis miranda facta sub annis
Qui volet: et nostros comparet inde dies
Visa ~~licet~~ fuerint portenta horrendaque monstra
Luxerit caelo flamma corona trabes
Astra diurna faces tremor et telluris hiatus
Et bolides thiphon sanguineusque polus
Circulus et lumen nocturno tempore visum
Ardentes clypei nubigenaeque ferae
Montibus et visi quondam concurrere montes
Armorum et crepitus et tuba terribilis
Lac pluere caelo visum est frugesque calibsque
Ferrum etiam et lateres et caro lana rudis

A depiction in ink and wash of the fall of the stone at Ensisheim mounted above a handwritten copy of the first 12 lines of Brant's Latin poem in Sigismondo Tizio's History of Sienese. In a strange shift of perspective, Brant’s mountainous skyline in figure is replaced by a meandering river. The inscription above the clouds reads: '*Amsam (Ensisheim) is a city in upper Germany which falls under the Emperor's jurisdiction and is one day's journey above Basel*'. (With thanks to Don Rafaelle Farina Prefect of the Biblioteca Vaticana, for permission to reproduce this illustration from MS Chigi G.II.36.)

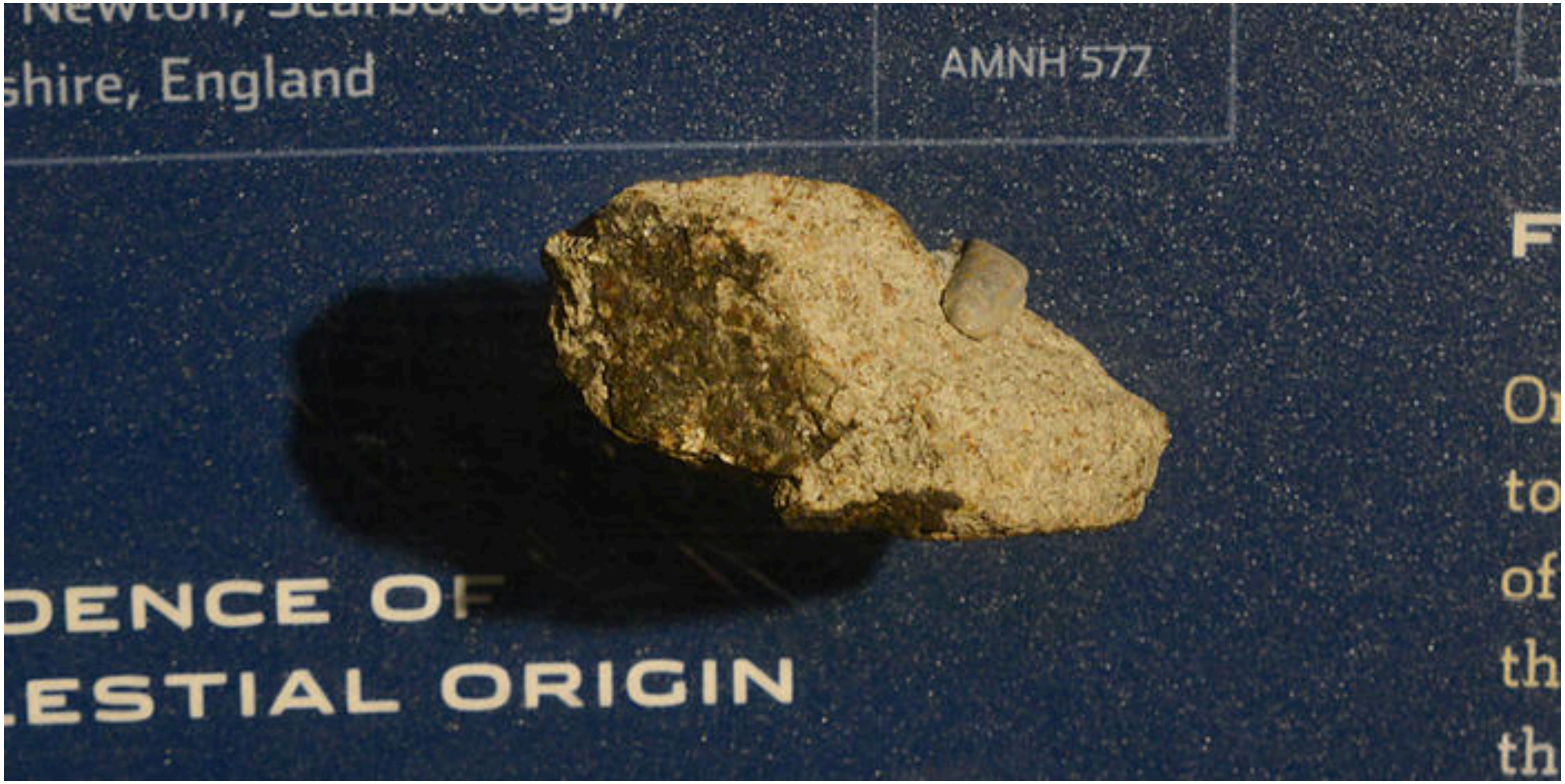
Rocks from space?

When the **Krasnojarsk meteorite** was found in **1749**, no one believed that rocks came from space. But after ***Ernst Chla***dni, a German physicist, analyzed this meteorite's unusual mixture of stone and iron, he began to convince skeptics that meteorites did indeed originate far from Earth. For his innovative work, Chladni became known as the ***father of meteoritics***—the study of meteorites.

Chladni.

Evidences of celestial origin

The **Wold Cottage meteorite** made quite a splash when it landed in Yorkshire, England, on December 13, 1795: a farmhand standing near the impact site was splattered with mud. Many other villagers also watched the fall. Analysis of the stone's composition by scientists at the Royal Society provided additional evidence that meteorites do indeed have ***extraterrestrial*** origins.



Final proof

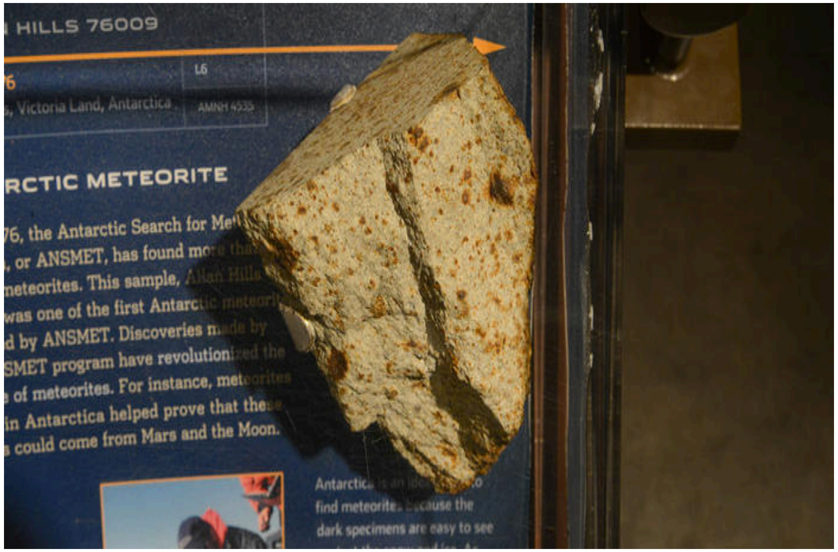
On April 26, 1803, meteorites rained down on the town of **L'Aigle** in Normandy, France. A number of people, including French officials, witnessed this shower of stones, which firmly established that meteorites can and do drop from the sky. After L'Aigle, museums and private collectors began to include meteorites in their collections.

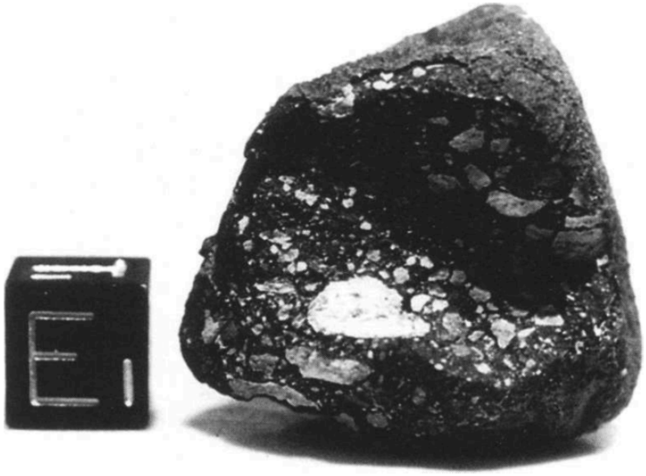
America's first fireball

As scientists in Europe continued to debate the extraterrestrial origins of meteorites, their counterparts in the United States discounted the theory—until a meteorite landed in their backyard. In 1807, astonished residents watched a fireball explode in the skies above Weston, Connecticut.

Antarctic meteorite

Since 1976, the Antarctic Search for Meteorites Program, or ANSMET, has found more than 10,000 meteorites. The sample of Allan Hills 76009, was one of the first Antarctic meteorites collected by ANSMET. Discoveries made by the ANSMET program have revolutionized the science of meteorites. For instance, meteorites found in Antarctica helped prove that these objects could come from **Mars** and the **Moon**.



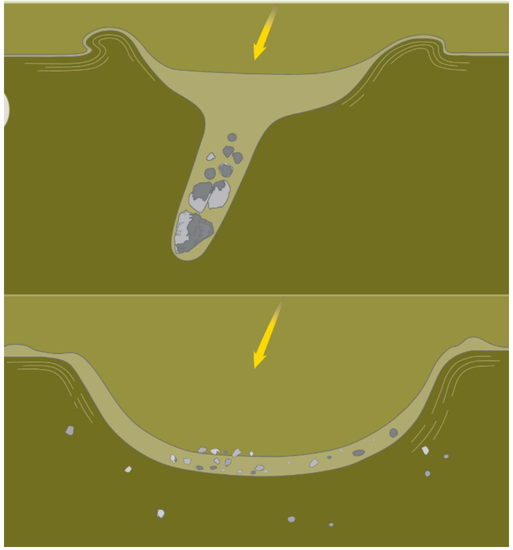


The meteorite ALH 81005 from the Allan Hills, Antarctica, the first lunar-sourced meteorite to be identified. The cube has sides of 1 cm.

Countless impacts continue to shape Earth, other planets and moons in our dynamic Solar System

February 12, 1947, 10:30 a.m.: A woodsman stacking logs in the frozen forest of ***eastern Siberia*** stopped working when he noticed a sudden flash of light, brighter than the Sun, streaking across the sky. Dozens of others in the area saw the flash too, and they described a huge fireball that exploded, bursting into smaller pieces that fell to Earth with cracking and roaring sounds. A huge, red-tinged column of dark dust hung in the sky for several hours, marking the fireball's path.

An **iron meteorite** weighing perhaps 100 tons, more than three times as much as Ahnighito—displayed at the center of this hall—had exploded in the dense lower layer of Earth's atmosphere. It shattered into tens of thousands of fragments that crashed into the thick forest, tearing apart and uprooting trees and digging hundreds of craters in the snowy ground.



Anniversary stamps

When the Sikhote-Alin fireball appeared in the sky, artist P. I. Medvedev was painting at his easel in the nearby town of Iman. He immediately began to paint the image that was later featured on this Russian stamp, issued in 1957 to commemorate the 10th anniversary of the meteorite shower.

Sikhote-Alin crater

The meteorite mass that formed this **crater** weighed roughly 1,300 kilograms (2,870 pounds) before it broke apart upon impact. The crater, one of the larger ones at Sikhote-Alin, measures 11 meters (37 feet) across. Uprooted trees and shattered pieces of rock lie strewn around the crater rim.

DELLA CADUTA
DI UN SASSO
DALL' ARIA
RAGIONAMENTO
DEDICATO
ALLE ALTEZZE SERENISSIME
DI
BENEDETTA,
ED
AMALIA
PRINCIPESSE DI MODENA
DA
DOMENICO TROILI
Della Compagnia di Gesù

IN MODENA MDCCLXVI.
Per gli Eredi di Bartolomeo Soliani Stamp. Ducali.
Con licenza de' Superiori.

The title page of **Domenico Troili's book** of 1766: About the Fail of a Stone From the Air, Explanation.

Dedicated to their most serene highnesses, Benedetta and Amalia, Princesses of Modena, by Domenico Troili of the Company of Jesus. (By permission of the Houghton Library, Harvard University.)

Chladni

Ueber den
Urſprung
der von Pallas gefundenen
und anderer ihr ähnlicher
Eiſenmaſſen,
und über einige damit in Verbindung ſtehende
Naturerſcheinungen.

von

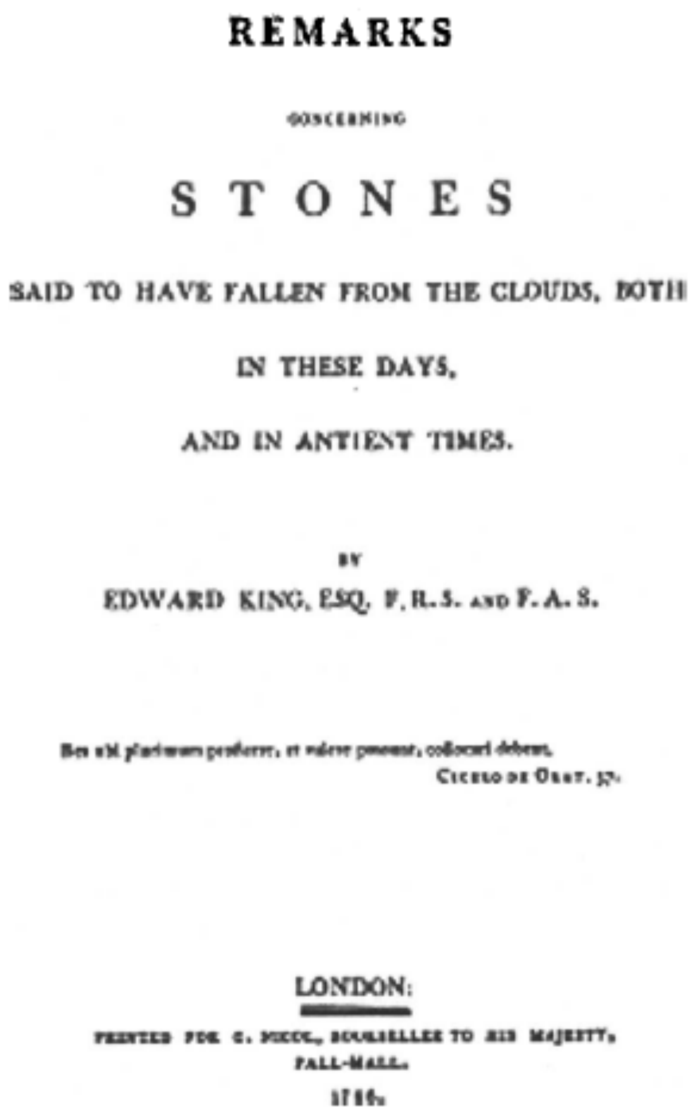
Ernſt Florens Friedrich Chladni,
n Wittenberg, der Phil. und Rechte Doctor, der Berliner Geſellſchaft Naturf. Freunde Mitgliede,
und der königl. Societät der Wiſſenſchaften zu Göttingen Correſpondenten.

Riga,
bey Johann Friedrich Hartknoch.
1794.

In **1794 Ernst F.F. Chladni** (1756-1827) of Wittenberg, a physicist who already was winning fame for himself as the 'Father of Acoustics', published a 63-page book titled *On the Origin of the Mass of Iron found by Pallas and of Other Similar Iron masses, and on a few Natural Phenomena Connected Therewith*. The "few natural phenomena" were meteors, fireballs, and falls of stones and irons.

In his opening paragraph, Chladni declared, forthrightly, that fireballs form around masses of heavy, compact matter, which enter the atmosphere from outer space and fall as meteorites.

Edward King: the first book in English on meteorites, **1796**



REMARKS

CONCERNING

STONES

SAID TO HAVE FALLEN FROM THE CLOUDS, BOTH

IN THESE DAYS,

AND IN ANTIENT TIMES.

BY

EDWARD KING, ESQ. F.R.S. AND F.A.S.

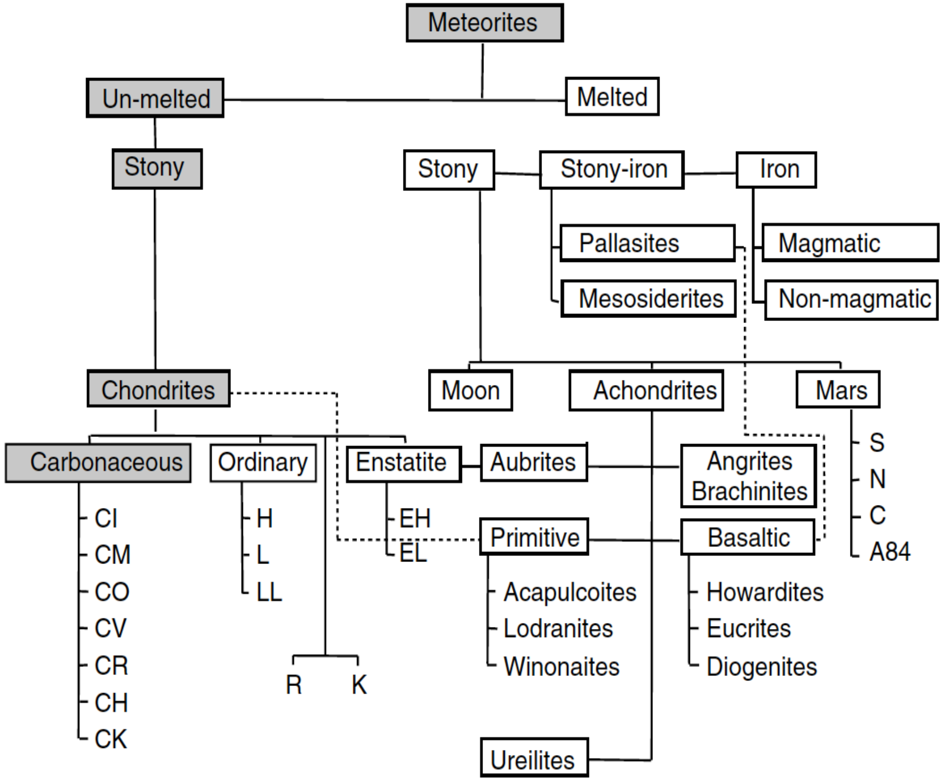
Res ubi plurimum proderunt, et valere possunt, collocari debent.
CICERO DE ORAT. 37.

LONDON:

PRINTED FOR G. NICOL, BOOKSELLER TO HIS MAJESTY,
PALL-MALL.
1796.

REMARKS CONCERNING STONES SAID TO HAVE FALLEN FROM THE CLOUDS, BOTH IN THESE DAYS, AND IN ANTIENT TIMES: An Attempt to account for the Production of a Shower of Stones, that fell in Tuscany, on the 16th of June, 1794; and to shew that there are Traces of similar Events having taken place in the highest Ages of Antiquity. In the course of which detail is also inserted, an Account of an extraordinary Hailstone, that fell, with many others, in Cornwall, on the 20th of October, 1791.

Meteorite classification from the Natural History Museum of London's *Catalog of Meteorites, Fifth Edition* (Grady, 2000).

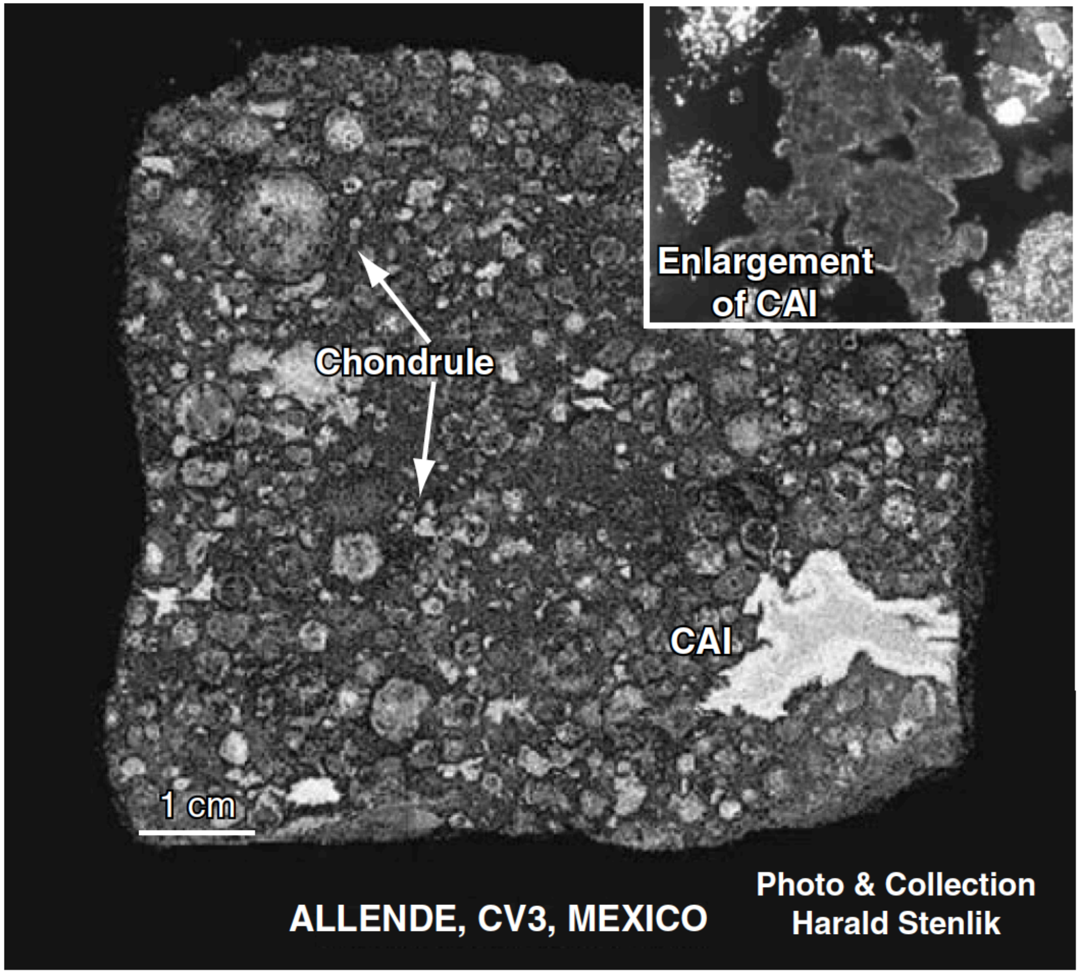


Meteorites may be subdivided into two main categories – **unmelted meteorites**, that is those which come from a parent body which has not been fractionated since its aggregation early in the history of the solar system, and **melted**, or **differentiated meteorites**. Unmelted meteorites are stony meteorites, the chondrites, and are made up of the same silicate minerals that are found on Earth. Melted meteorites are of three types. They include some stony meteorites (the achondrites), the iron meteorites, whose composition is dominated by a metallic iron–nickel alloy, and stony iron meteorites, meteorites which are made up of approximately equal proportions of silicate minerals and iron–nickel metal (Grady, 2000).

Chondrites. Chondrites are stony meteorites and are the most abundant meteorite type (87% of all meteorites). Their radiometric ages are around 4.56 Ga and these ages are thought to define the time when the solar system formed. Chemically their element abundance patterns, apart from the very light and/or volatile elements, are the same as that of the sun and other stars, and for this reason they are thought to represent undifferentiated cosmic matter. Chondrites therefore are thought to represent the most primitive material in the solar system. They are the "stuff" from which all other rocky materials were built.

Chondrites are ultramafic in composition and contain the minerals olivine, pyroxene, and metallic iron. They are composed of three main components, each of which represents a different component of **primitive solar nebula material**.

Chondrites are subdivided into **carbonaceous** (C), **ordinary** (O), and **enstatite** (E) varieties. Carbonaceous chondrites are **volatile rich** and contain abundant carbon in their matrix. Because they have a high volatile content they are thought to be the ***most primitive of all***



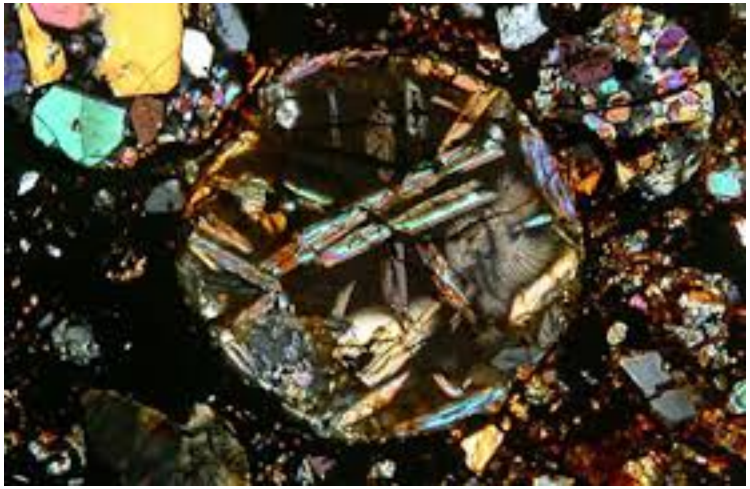
A slice of the ***Allende meteorite*** showing rounded chondrules, a large white CAI and a dark (fine grained) matrix.

- Chondrules – spheroidal ultramafic melt droplets a millimeter or so in diameter, which tend to dominate the texture of their host and from which chondrites take their name.
- CAI's – refractory inclusions, or Ca–Al-Inclusions, up to 2 cm across, enriched in Si-poor, Ca–Al-rich minerals. The most abundant source of CAIs is the Allende meteorite, which fell in 1969.
- Matrix – porous, fine grained mineral matter that fills the space between the chondrules and CAIs.

Chondrules are the principal constituent of many chondritic meteorites and their formation represents a major, pervasive, high-temperature process in early solar system history.

They are made up of **silicate, metal, sulfide, and glass phases** and in detail show a wide variation in chondrule composition, extending from iron-poor to iron-rich and silica-poor to silica-rich varieties. Some chondrules are composite and show high temperature rims on older cores.

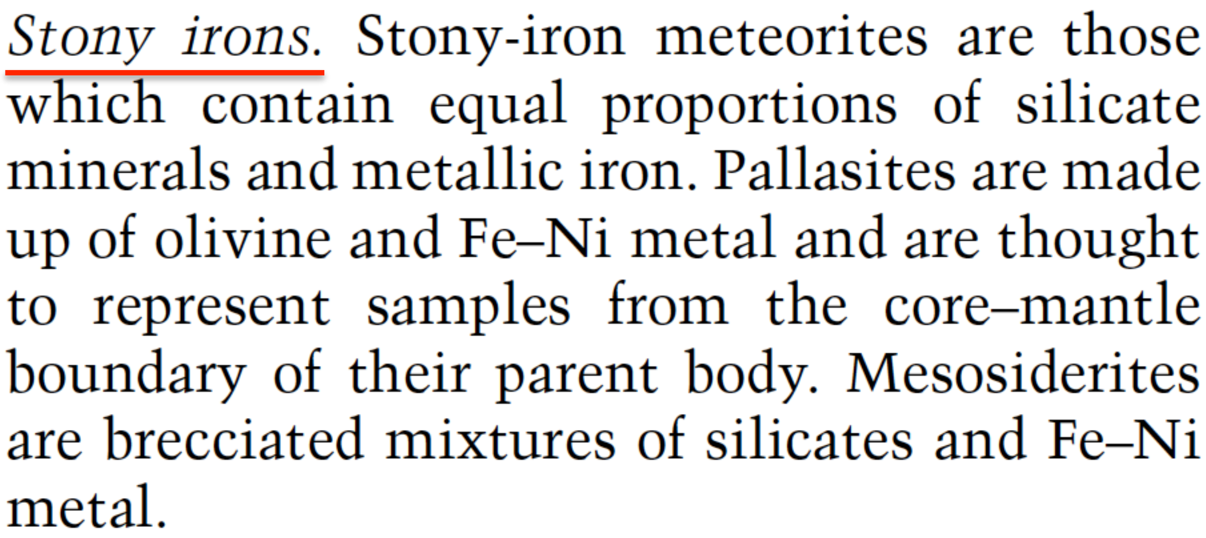
There are two possible explanations for the chemical variability of chondules. One emphasizes variations in the mix of precursor solids. In this model compositionally different chondrules reflect different starting materials.
Alternatively, chondrules vary in composition because of the chondrule-forming process, and record a reaction between chondrules and the ambient gases.



Achondrites. Achondrites are stony meteorites formed by the melting of their parent body. They are differentiated meteorites which have lost their original metal content. Generally they do not contain chondrules. There are a number of different categories of achondrite representing melted chondrites, basaltic igneous rocks, and planetary regolith breccias.

Iron meteorites. Iron meteorites are thought to be derived from the segregated metallic iron cores of small planetary bodies, which were originally a few tens to hundreds of kilometers in diameter. They demonstrate that metal-silicate fractionation was a fundamental process during the evolution of the solar nebula. Mineralogically they are composed of the minerals kamacite (Fe–Ni metal with a low $< 7\%$ Ni content), and taenite (Fe–Ni metal with a high Ni content, 20–50%). Iron meteorites are subdivided into magmatic irons, iron meteorites that have solidified by fractional crystallization from a melt, and nonmagmatic irons, iron meteorites which do not seem to have completely melted. There is also a chemical classification based upon the concentration of Ge and Ga (Wasson, 1985).

Tamentit Iron Meteorite, found in 1864 in the Sahara, weight about 500 kg.

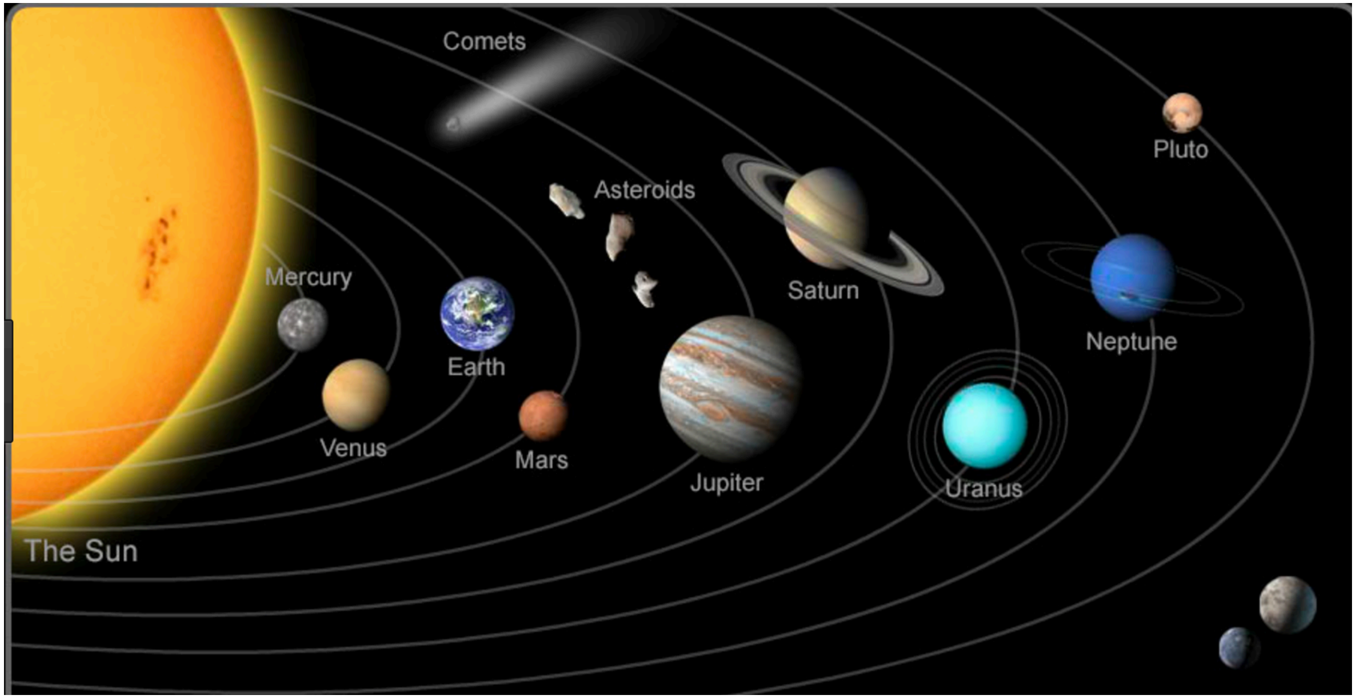


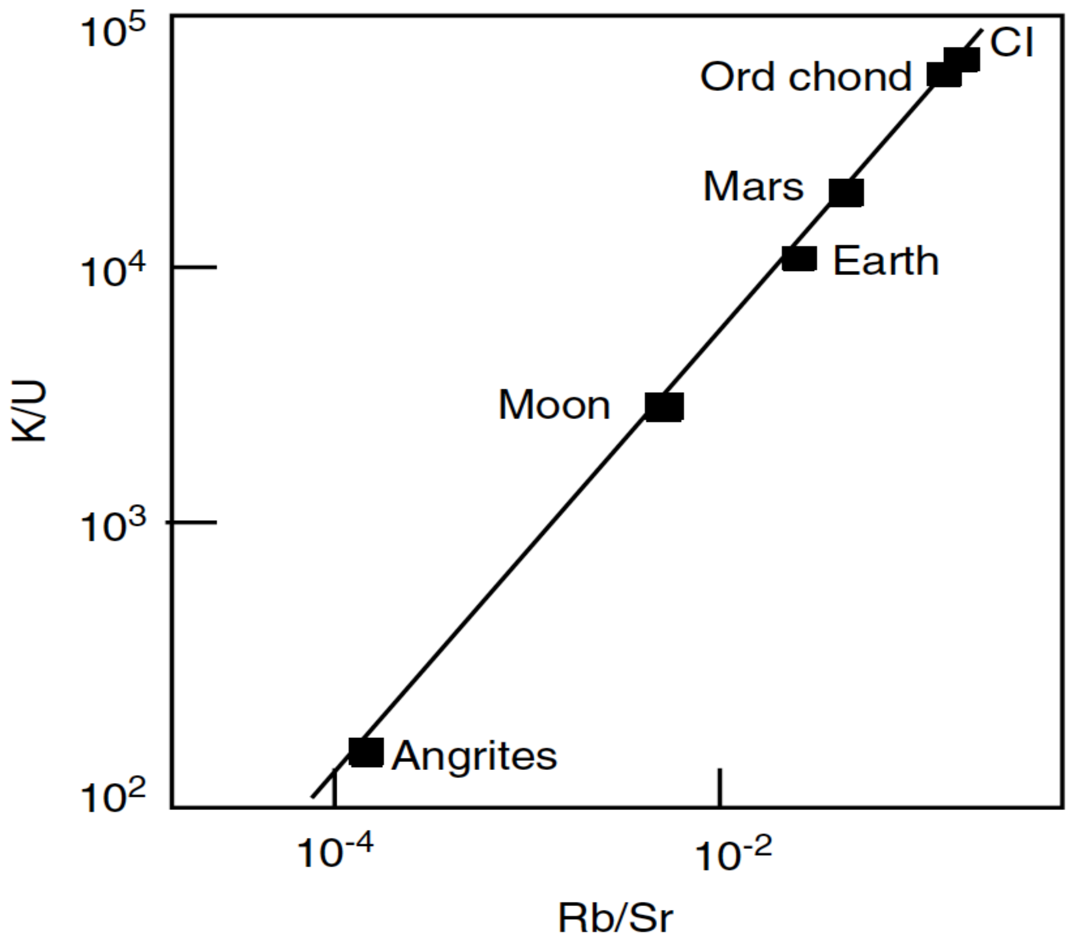
Stony irons. Stony-iron meteorites are those which contain equal proportions of silicate minerals and metallic iron. Pallasites are made up of olivine and Fe–Ni metal and are thought to represent samples from the core–mantle boundary of their parent body. Mesosiderites are brecciated mixtures of silicates and Fe–Ni metal.

A slice of the **Esquel meteorite** showing the mixture of meteoric iron and silicates that is typical of this division.

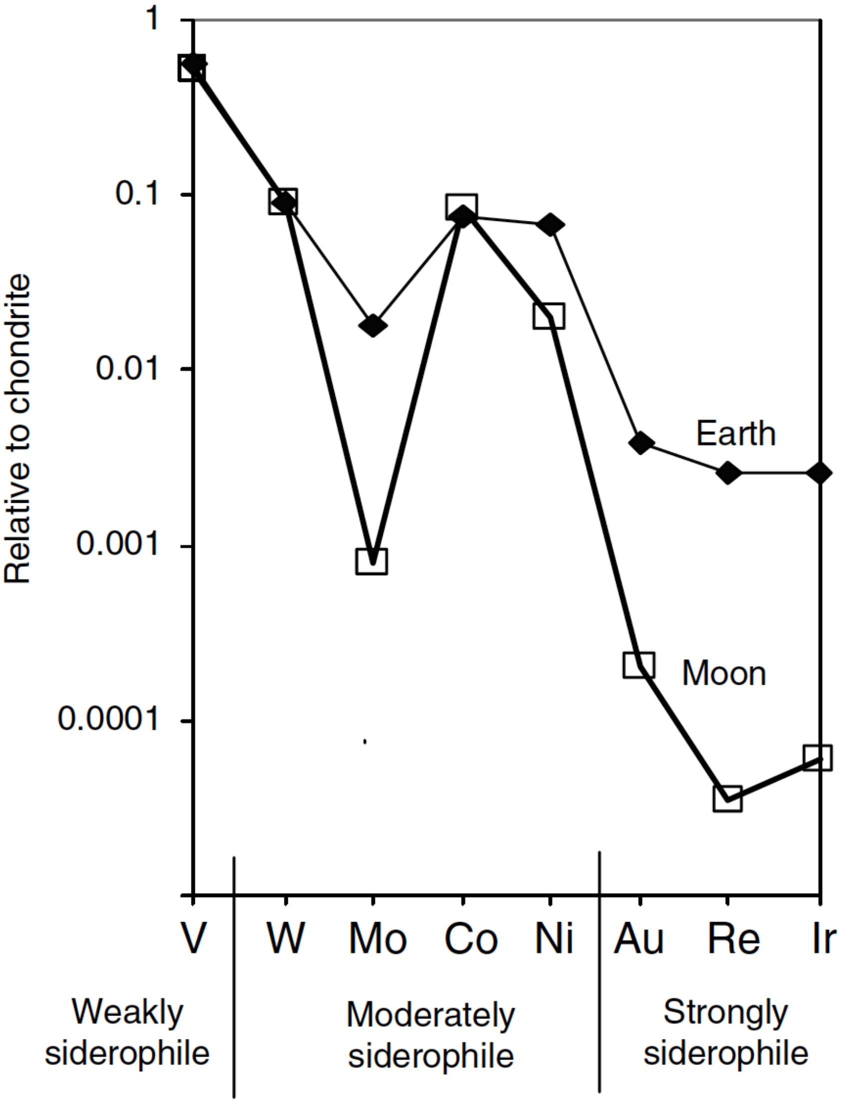
Physical properties of the planets showing the three groups of planets. The Asteroids lie between Mars and Jupiter at 2.7 AU.

		The terrestrial planets				The giant planets		The outer icy planets		
Body	**Sun**	**Mercury**	**Venus**	**Earth**	**Mars**	**Jupiter**	**Saturn**	**Uranus**	**Neptune**	**Pluto**
Increasing mean distance from Sun (Earth to Sun = 1.0 AU)										
Distance from the sun (AU)	0	0.39	0.72	1	1.52	5.2	9.55	19.2	30.1	39.5
Mean density (Terrestrial planets > Jovian planets)										
Actual Density (g cm^{-3})	1.41	5.43	5.25	5.52	3.95	1.33	0.69	1.29	1.64	2.03
Radius (Terrestrial planets < Jovian planets)										
Radius (Earth = 1.0)	109	0.38	0.95	1	0.53	11	9	4	4	0.18

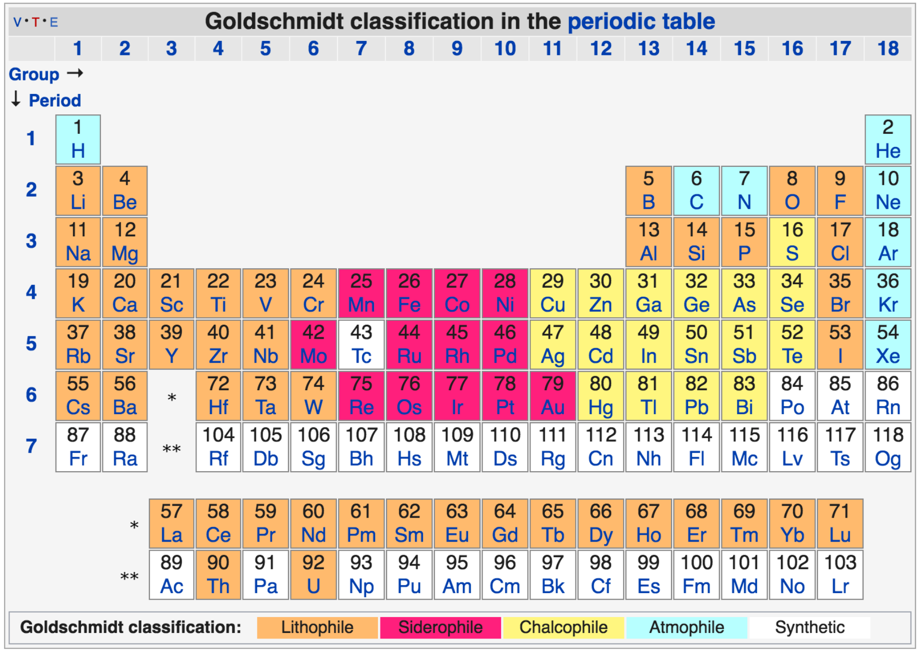




The ratio of volatile (K, Rb) to refractory elements (U, Sr) in planetary and solar system objects (after Halliday & Porcelli, 2001). The relationships show the volatile depleted nature of the Moon relative to the Earth and the Moon and the Earth relative to primitive CI chondrites.



Depletion factors for siderophile elements in the Earth's mantle and the Moon relative to C1 chondrite, using the median Earth and Moon values from the compilation of Kramers (1998) (se

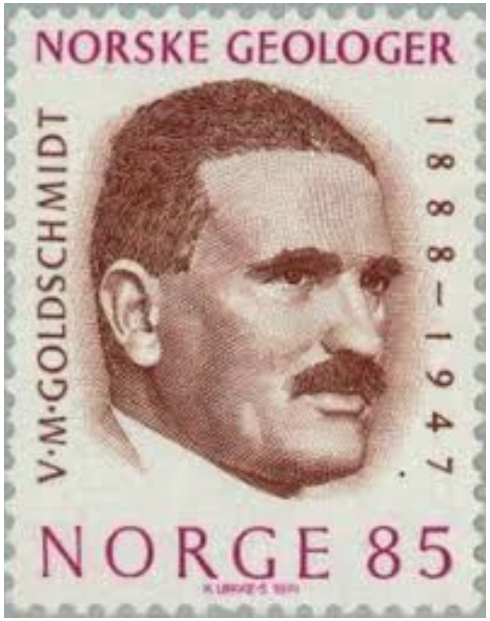


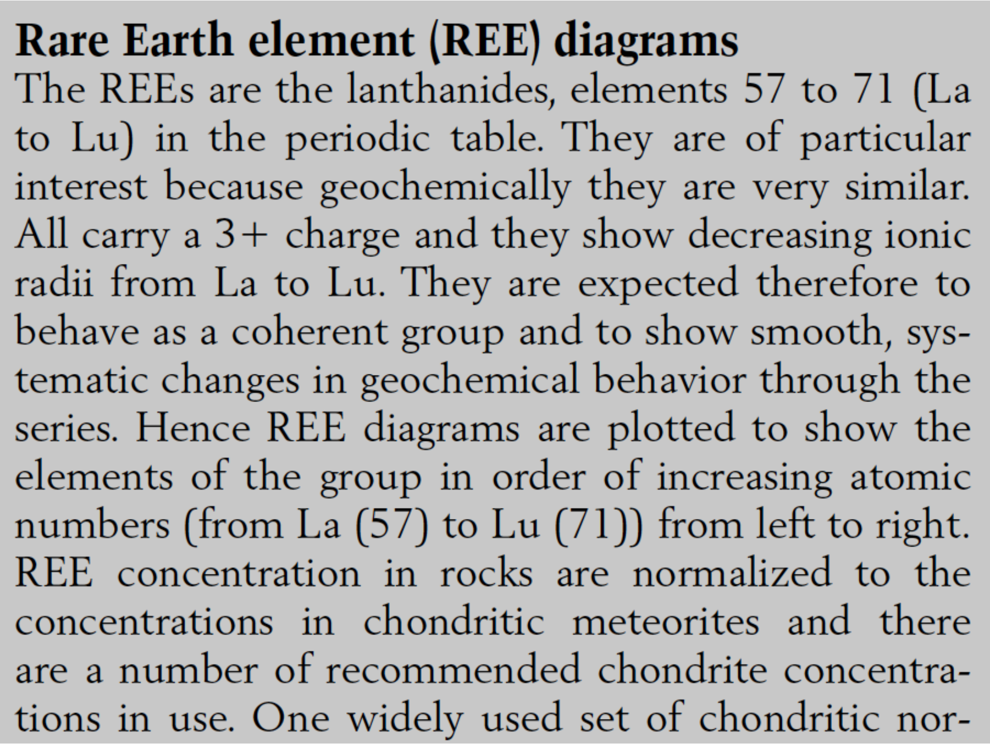
Goldschmidt classification in the periodic table

Group →
↓ Period

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	🟦 1 H																	🟦 2 He
2	🟧 3 Li	🟧 4 Be											🟧 5 B	🟦 6 C	🟦 7 N	🟧 8 O	🟧 9 F	🟦 10 Ne
3	🟧 11 Na	🟧 12 Mg											🟧 13 Al	🟧 14 Si	🟧 15 P	🟨 16 S	🟧 17 Cl	🟦 18 Ar
4	🟧 19 K	🟧 20 Ca	🟧 21 Sc	🟧 22 Ti	🟧 23 V	🟧 24 Cr	🟥 25 Mn	🟥 26 Fe	🟥 27 Co	🟥 28 Ni	🟨 29 Cu	🟨 30 Zn	🟨 31 Ga	🟨 32 Ge	🟨 33 As	🟨 34 Se	🟧 35 Br	🟦 36 Kr
5	🟧 37 Rb	🟧 38 Sr	🟧 39 Y	🟧 40 Zr	🟧 41 Nb	🟥 42 Mo	⬜ 43 Tc	🟥 44 Ru	🟥 45 Rh	🟥 46 Pd	🟨 47 Ag	🟨 48 Cd	🟨 49 In	🟨 50 Sn	🟨 51 Sb	🟨 52 Te	🟧 53 I	🟦 54 Xe
6	🟧 55 Cs	🟧 56 Ba	*	🟧 72 Hf	🟧 73 Ta	🟧 74 W	🟥 75 Re	🟥 76 Os	🟥 77 Ir	🟥 78 Pt	🟥 79 Au	🟨 80 Hg	🟨 81 Tl	🟨 82 Pb	🟨 83 Bi	⬜ 84 Po	⬜ 85 At	⬜ 86 Rn
7	⬜ 87 Fr	⬜ 88 Ra	**	⬜ 104 Rf	⬜ 105 Db	⬜ 106 Sg	⬜ 107 Bh	⬜ 108 Hs	⬜ 109 Mt	⬜ 110 Ds	⬜ 111 Rg	⬜ 112 Cn	⬜ 113 Nh	⬜ 114 Fl	⬜ 115 Mc	⬜ 116 Lv	⬜ 117 Ts	⬜ 118 Og
		*	🟧 57 La	🟧 58 Ce	🟧 59 Pr	🟧 60 Nd	🟧 61 Pm	🟧 62 Sm	🟧 63 Eu	🟧 64 Gd	🟧 65 Tb	🟧 66 Dy	🟧 67 Ho	🟧 68 Er	🟧 69 Tm	🟧 70 Yb	🟧 71 Lu	
		**	⬜ 89 Ac	🟧 90 Th	⬜ 91 Pa	🟧 92 U	⬜ 93 Np	⬜ 94 Pu	⬜ 95 Am	⬜ 96 Cm	⬜ 97 Bk	⬜ 98 Cf	⬜ 99 Es	⬜ 100 Fm	⬜ 101 Md	⬜ 102 No	⬜ 103 Lr	

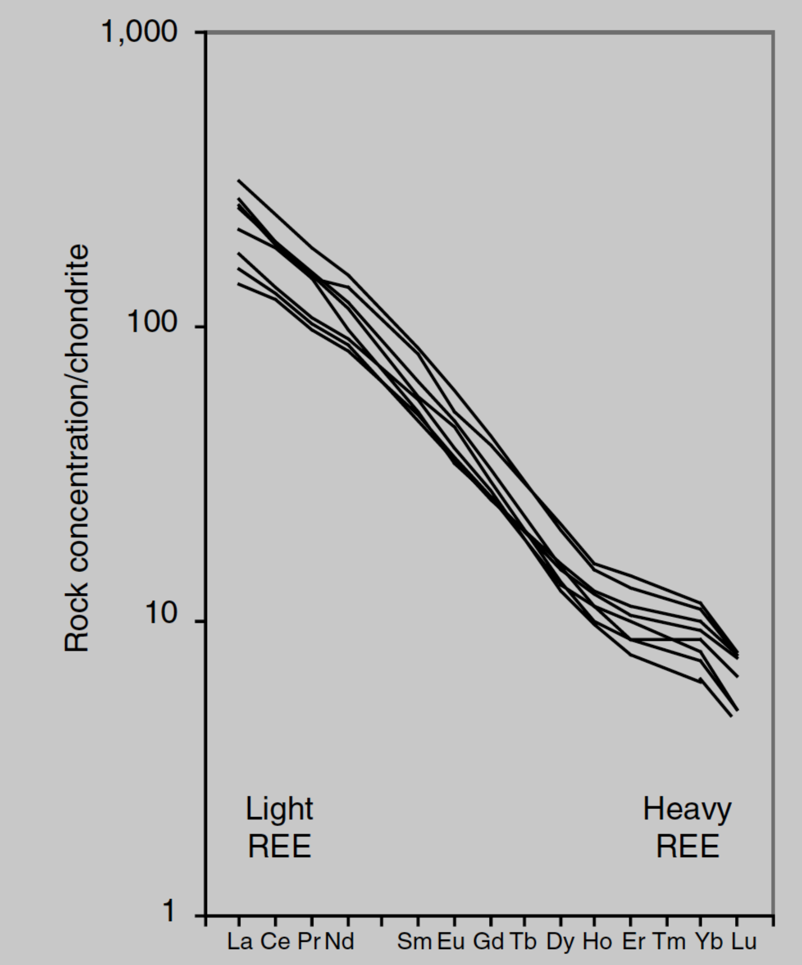
Goldschmidt classification: 🟧 Lithophile 🟥 Siderophile 🟨 Chalcophile 🟦 Atmophile ⬜ Synthetic



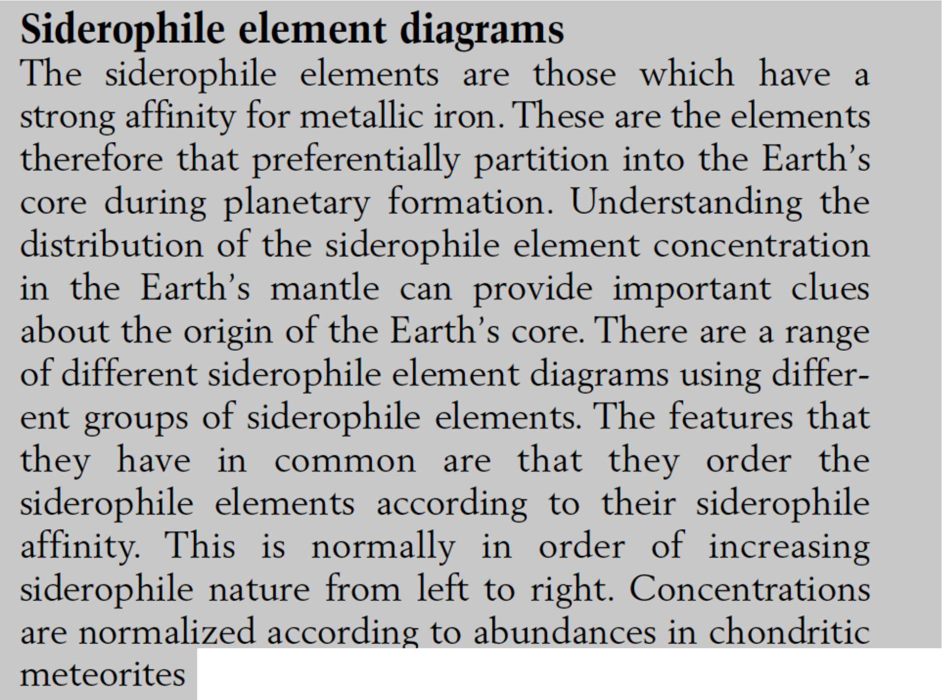


Rare Earth element (REE) diagrams

The REEs are the lanthanides, elements 57 to 71 (La to Lu) in the periodic table. They are of particular interest because geochemically they are very similar. All carry a 3+ charge and they show decreasing ionic radii from La to Lu. They are expected therefore to behave as a coherent group and to show smooth, systematic changes in geochemical behavior through the series. Hence REE diagrams are plotted to show the elements of the group in order of increasing atomic numbers (from La (57) to Lu (71)) from left to right. REE concentration in rocks are normalized to the concentrations in chondritic meteorites and there are a number of recommended chondrite concentrations in use. One widely used set of chondritic nor-

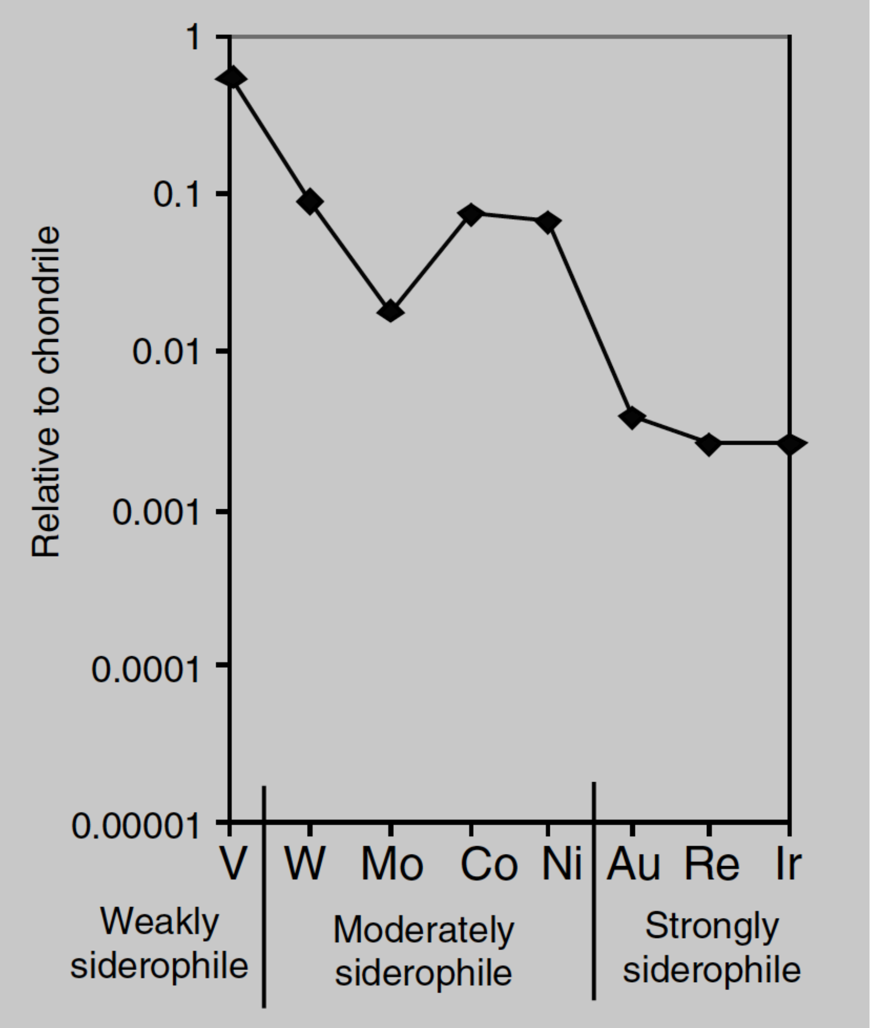


An REE plot for **granitoids** from the **Baltic Shield**, showing the REEs in order of their atomic number on the x-axis and concentrations, normalized relative to abundances in chondritic meteorites, shown on the y-axis, using a log scale. The graph shows that in these rocks all the REE have higher concentrations than in chondritic meteorites (all values 1.0) but that the light REE (low atomic number, at the left) have much higher abundances than the heavy REE (higher atomic number, at the right). The reason for this “fractionation” is important to determine.



Siderophile element diagrams

The siderophile elements are those which have a strong affinity for metallic iron. These are the elements therefore that preferentially partition into the Earth's core during planetary formation. Understanding the distribution of the siderophile element concentration in the Earth's mantle can provide important clues about the origin of the Earth's core. There are a range of different siderophile element diagrams using different groups of siderophile elements. The features that they have in common are that they order the siderophile elements according to their siderophile affinity. This is normally in order of increasing siderophile nature from left to right. Concentrations are normalized according to abundances in chondritic meteorites



A chondrite normalized plot for siderophile elements in the Earth's mantle. The elements are arranged in order of increasing siderophile affinity from left to right and show decreasing element abundances with increasing siderophile character, commensurate with core formation.

Summary of elemental behavior in the silicate Earth relative to chondrites.

Element group	Concentration relative to chondrite	Fractionation process
Light gases – H, He, N, and C	depleted	during planetary accretion
Inert gases	depleted	during planetary accretion
Volatile lithophile elements – Mg, Si, Fe, O, Ni, Na, K, Rb, Cs, S, Cu, and Pb	depleted	during planetary accretion
Silicon	depleted	during differentiation of solar nebula
Refractory lithophile elements – Ca, Al, Ti, Sc, Sr, Ba, Zr, Mo, REE, Hf, Th, U	slightly enriched	or in the core excluded from the core and so ca. 1.6 times chondrite
Weakly siderophile – V	weakly depleted	core formation
Moderately siderophile elements – W, Co, Ni, and Mo	moderately depleted	core formation
Highly siderophile elements – Au, Re, Os, PGE	strongly depleted	core formation

A chronology for the accretion of the Earth.

Event	Time (Ma)	Time from T_0 (Ma)	References
Formation of the solar system (T_0)	4567.2 ± 0.6 (4569.5 ± 0.2)	0	Amelin et al. (2002) Baker et al. (2005)
CAI formation	4567	0	Amelin et al. (2002) Bizzarro et al. (2004) Krot et al. (2005)
Chondrule formation	4567–4563	4	Amelin et al. (2002, 2004) Bizzarro et al. (2004) Haack et al, (2004) Krot et al. (2005)
Core formation (*Earth 64% formed*)	4,556 4,537	11 30	Yin et al. (2002) Jacobsen (2005)
End of core formation			
End of main growth stage	4,557	10	Jacobsen (2005)
End of accretion	4,537	30	
Differentiation of the mantle – predates formation of Moon *(see Chapter 3, Section 3.2.3.1)*	> 4,537	< 30	Boyet and Carlson (2005)
Moon formation	4,537	30	Schoenberg et al. (2002)
?? Late Veneer			Becker et al. (2005)
Oldest terrestrial materials *(see Chapter 1, Section 1.4.3)*	4,404	163	Wilde et al. (2001)
Late Heavy Bombardment *(see Chapter 6, Section 6.3.1)*	3,800–3,900	770–670	Kring and Cohen (2002)