Meteorite in picture
隕石淺談

VWONG2019

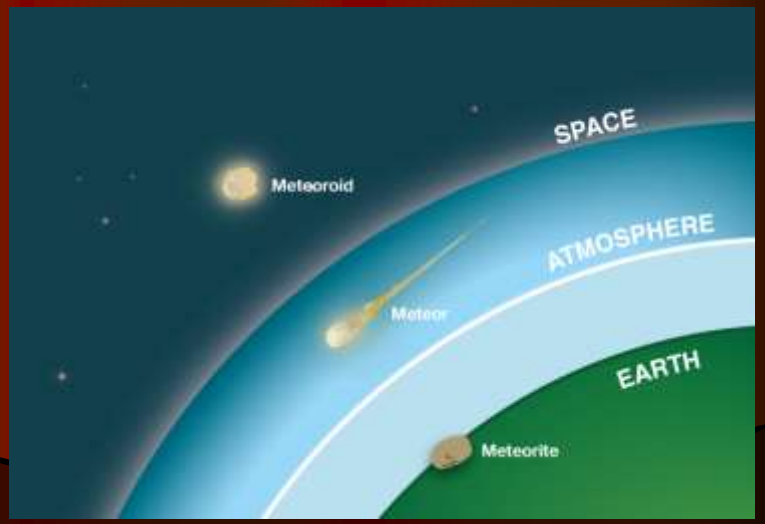
Content

- Origin 來源
- Classification 分類
- Other evidence of Impact 其它撞擊證據
- Major Historical Impact 過去重要撞擊
- Interesting Objects 趣味隕石文物
- Protection from future Impact 未來撞擊預防

Origin

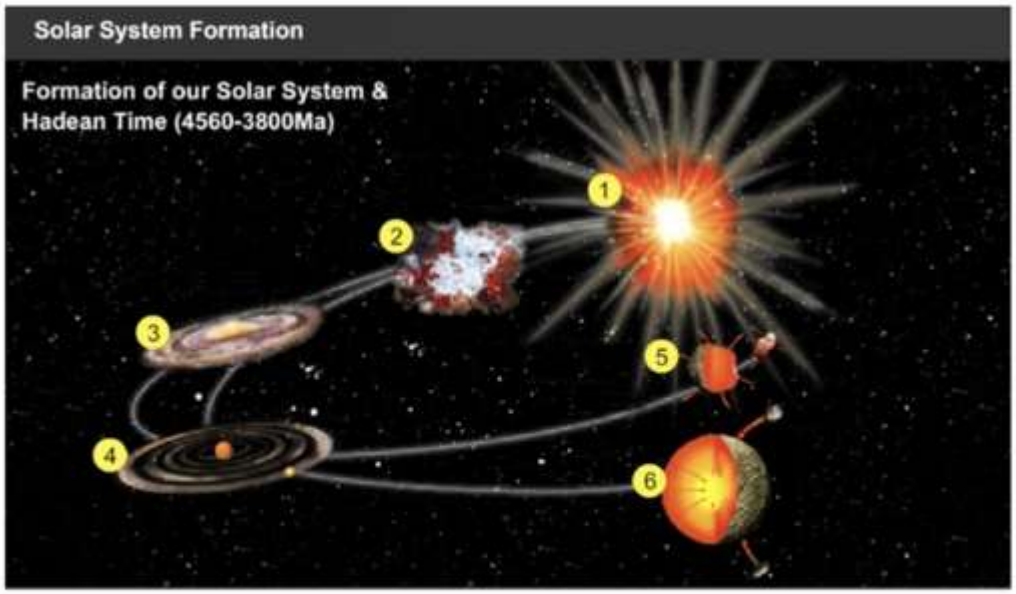
- A Meteorite 隕石 is a solid piece of debris from an object that originates from outer space and survive its passage through the earth's atmosphere as well as the impact with the ground. Studying meteorites can help us to understand the origin of our Solar System; how past meteorite strikes had shaped our planet's behavior; how life evolved on Earth and get better prepared for future impacts. Charged by the gram, Meteorite is also a very valuable collectible making meteorite hunting quite a lucrative hobby ! Every year thousands of meteorites land on Earth but so far only about 61,000 have been collected and with some being analyzed. In terms of origin

99.37% of the meteorites come from Asteroids 小行星
0.4% from the Moon 月球
0.2% come from Mars 火星
0.03% come from Comets 彗星

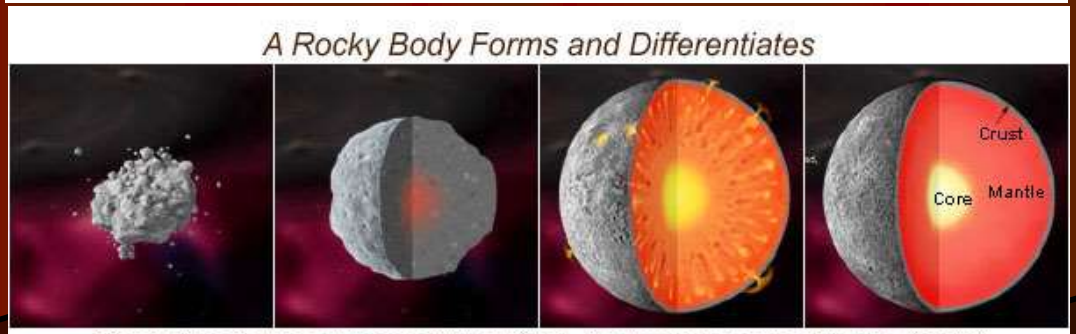


Asteroid
小行星

- Asteroids 小行星 in Greek means "star-like". They are minor planets or planetoids which orbit the Sun in the inner Solar System. Over a billion strong they are believed to be the leftovers of the "Big Bang" when our solar system was formed 4.6 billion ya



1. Big Bang Singularity 15 billion years ago
2. Nebulae of first matter condensed after ca 300000 years
3. Formation of galaxies after ca. 2 billion years
4. Generation of protoplane
5. Formation of homogenous asteroids
6. Planetary differentiation



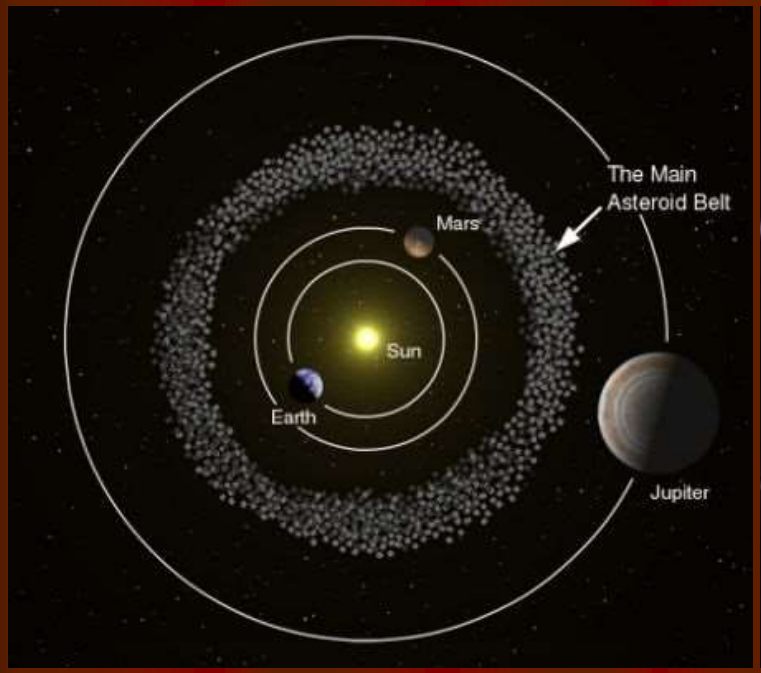
Some scientist suggested that asteroids were formed by a planet which was broken up billions of years ago but their total mass which is less than 4% of the mass of the moon and only 0.005% that of the Earth is too small to support this hypothesis.

Of the 750,000 asteroids identified about 100 are larger than 200 km and several hundred thousands in the 10 km to 100 km size range. There may be millions more of about 1 km in size. As of today over 504,000 asteroids have been given numbers of which 21,000 also were given names by IAU (International Astronomical Union)

Where are Asteroids located ?

1.Asteroid Belt, 2.Trojan Asteroid, 3.Near Earth Objects/Inner Earth Objects

1. Asteroid Belt 小行星帶: About 90% of asteroids are concentrated in a 1 Astronomical Unit or AU (150 million km) wide belt located between Mars 火星 and Jupiter 木星 with an inner edge around 2.1 AU and outer edge 3.3 AU from the Sun. Jupiter's gravity stirs up the asteroids orbits and prevents their planet formation. Collisions between asteroids in the belt are very frequent producing more asteroids

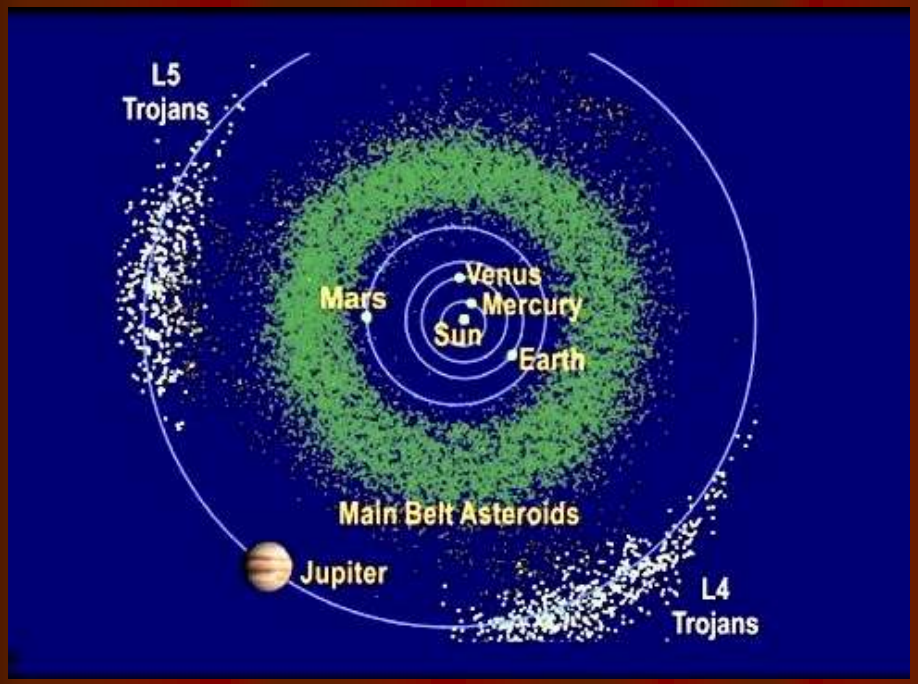


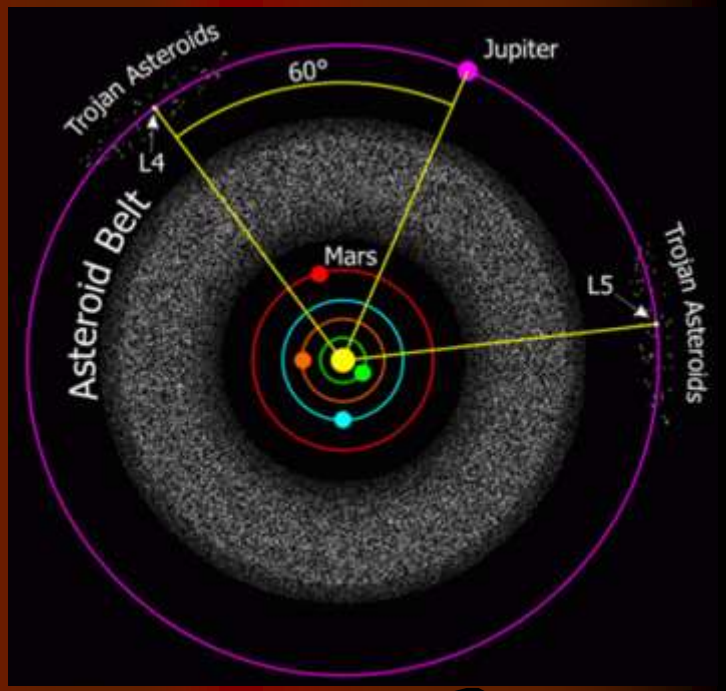
An artist's concept showing how families of asteroids are created through collision inside the asteroid belt and sending some of them Earth bound

2. Trojan Asteroids 特洛伊小行星：these asteroids share orbit with a planet. More than 1 million Trojans share the orbit of Jupiter. There are also 9 Mars Trojans, 22 Neptune Trojans, 2 Uranus Trojans and so far only 1 Earth Trojan has been identified

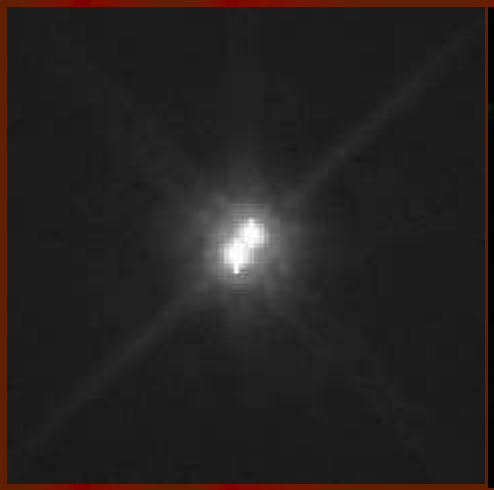
Jupiter Trojans

Two large groups totalling 7,040 were identified to share the planet Jupiter's orbit around the sun at the two Lagrange points with L4 lying 60 degree ahead and L5 lying 60 degree behind. Jupiter trojans larger than 1 km are forming into families





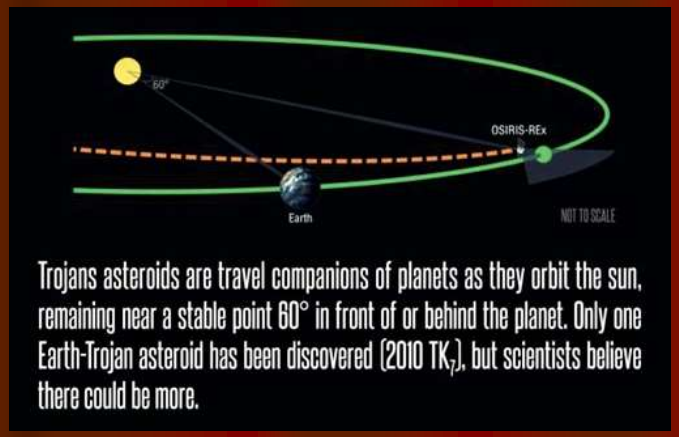
- Jupiter Trojan 617 Patroclus, a L5 is a binary asteroid 140 km in diameter

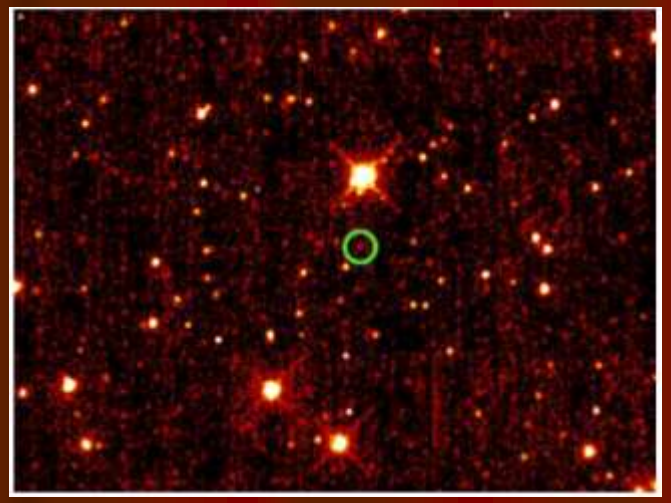


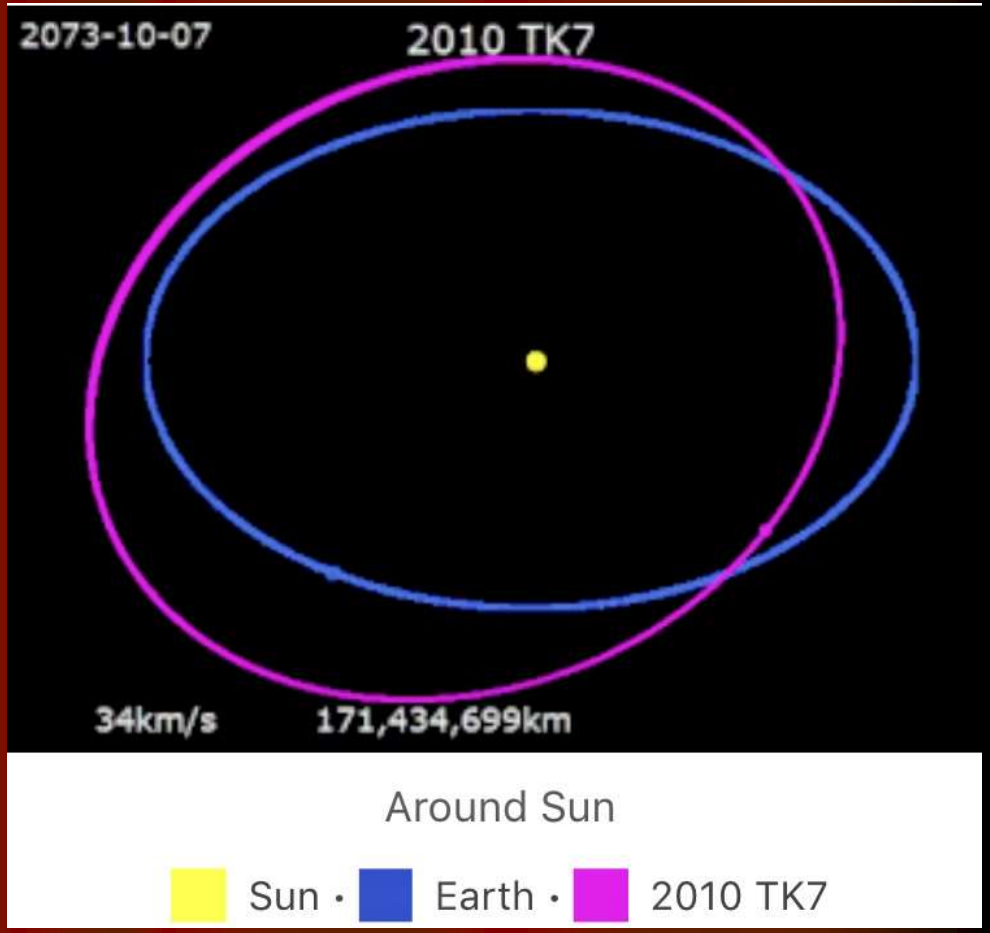
- Jupiter Trojan 624 Hektor, a L4 it is the largest Jupiter Trojan with diameter between 225 to 250 km shaped like a peanut and it has one small satellite Skamandrios

Earth Trojan 2010 TK7

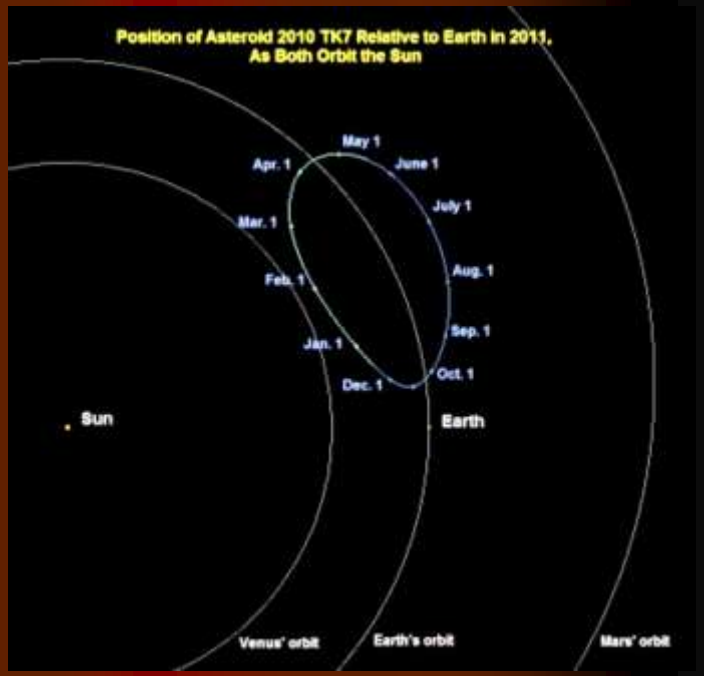
Asteroid 2010 TK7 is circled in green in image from the WISE spacecraft shown in the lower left picture. The single Earth Trojan has a diameter of about 300 meters





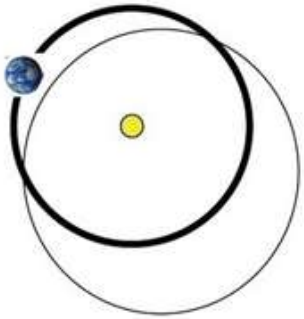


- 2010 TK7 trojan was discovered only in October 2010. It does not orbit at the Sun-Earth L4 Lagrangian point (60 degrees ahead of Earth) but oscillates along a spiral path (green) relative to Earth

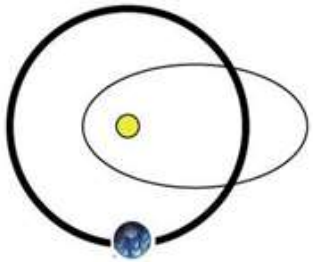


3. Near Earth Asteroid (NEAs) 近地小行星: NEAs are asteroids which cross or very close to the Earth's orbit and raise concern of a possible collision. 20,000 were discovered and grouped under Apollo, Aten, Amor and Apohele (aka Inner Earth Objects IEOs)

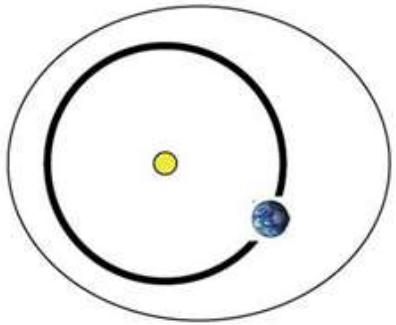
Apollo
Semimajor Axis ≥ 1.0 AU
Perihelion ≤ 1.02 AU
Earth Crossing



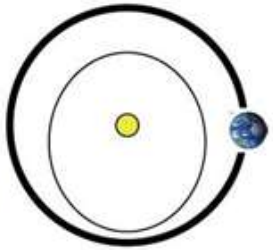
Aten
Semimajor Axis < 1.0 AU
Aphelion ≤ 1.0167 AU
Earth Crossing



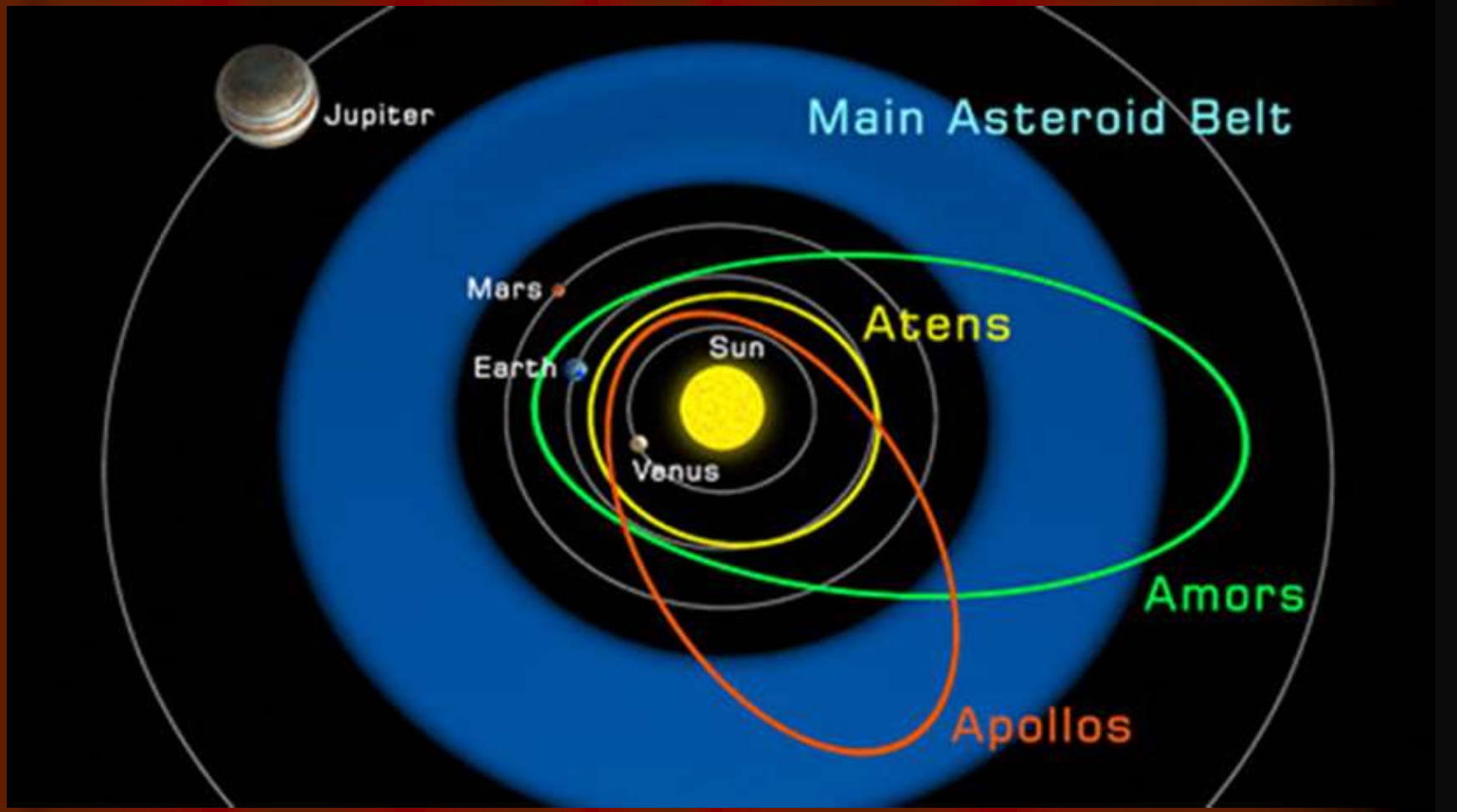
Amor
1.02 AU < Perihelion ≤ 1.3 AU



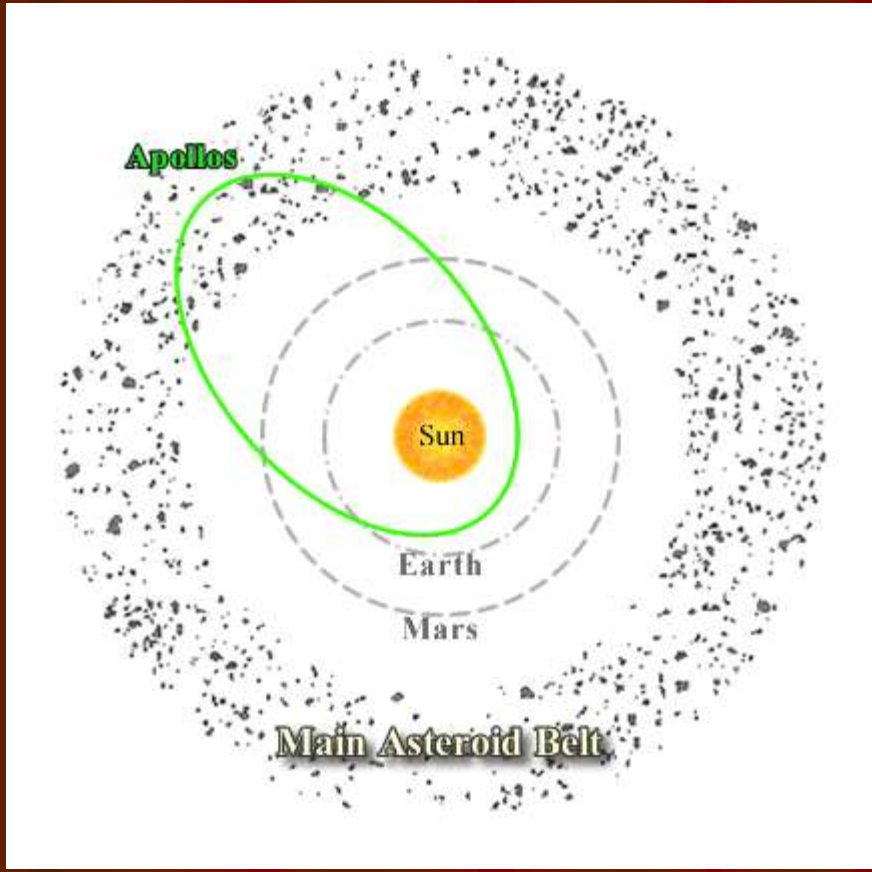
Inner Earth Objects (IEOs)
Aphelion < 0.983 AU
Always inside Earth's orbit
(aka Apohele)



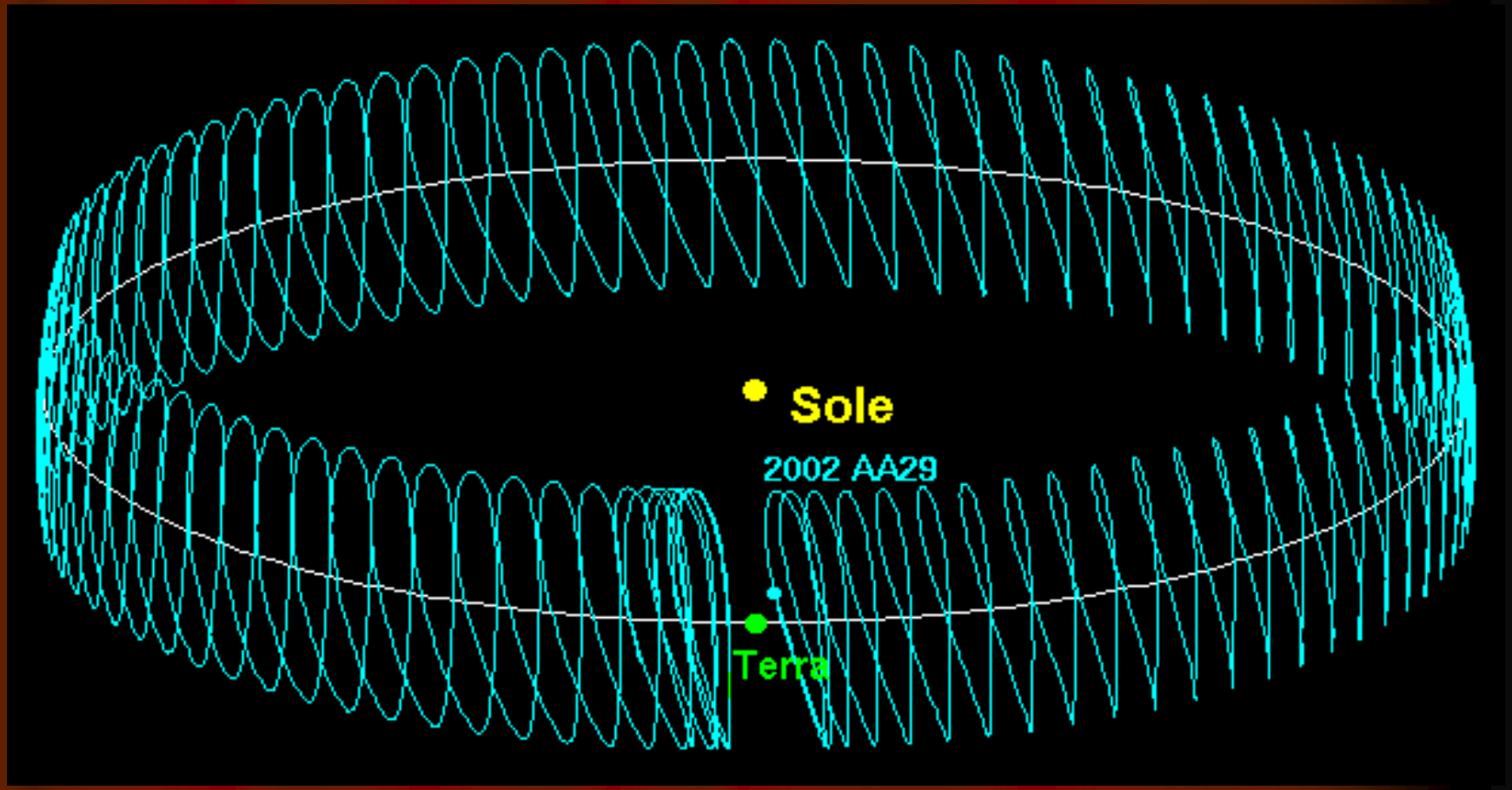
Type	Near-Earth Population
Apollo	62% of known asteroids
Aten	6% of known asteroids
Amor	32% of known asteroids
IEO	6 known asteroids


Jupiter
Main Asteroid Belt
Mars
Atens
Sun
Earth
Venus
Amors
Apollos

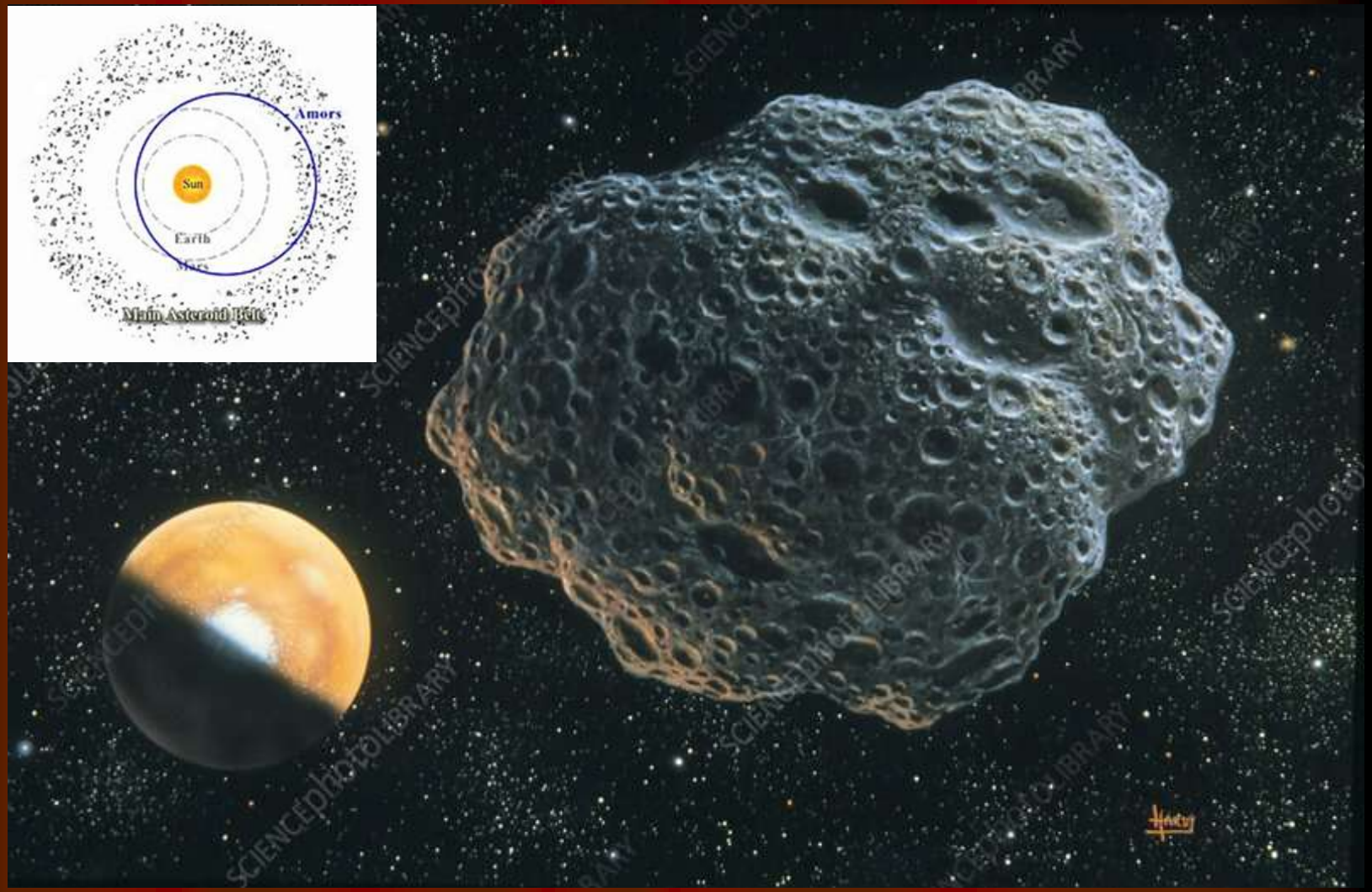
Apollo : Named after 1862 Apollo, they are Earth-crossing asteroids have sizes less than 10 km. A total of 2,600 asteroids under this group have been discovered so far of which 600 are potentially hazardous due to their size



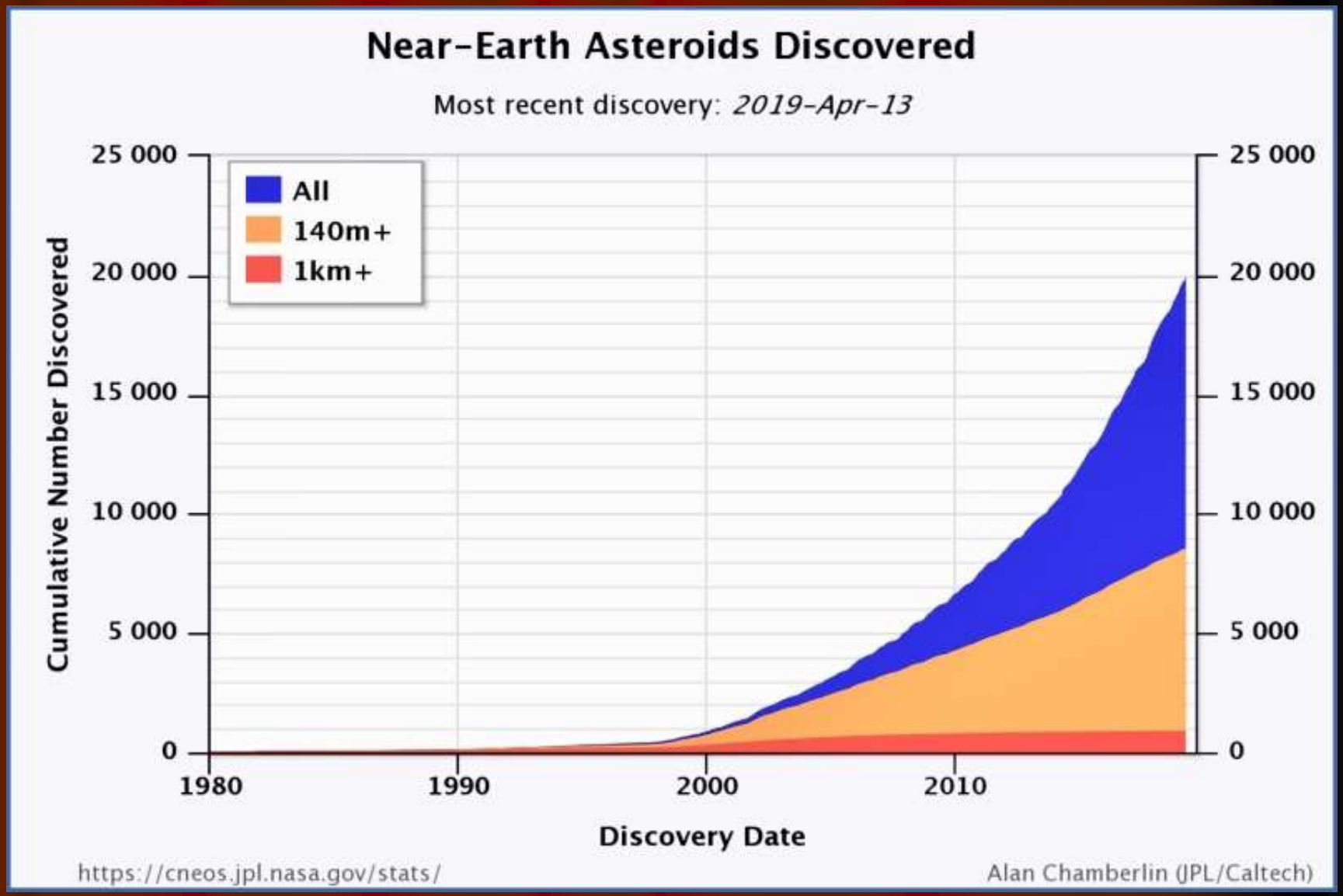
- Aten : 2002 AA29 is a 60 m wide NEA classified as an Aten. Some scientists believed it might be a left over from the "Big Splash" which created the moon at 4.527 Ba !



- Amor : Named after 1221 Amor. The group crosses both the orbits of Earth and Mars. Below is artist impression of 1221 Amor passing Mars

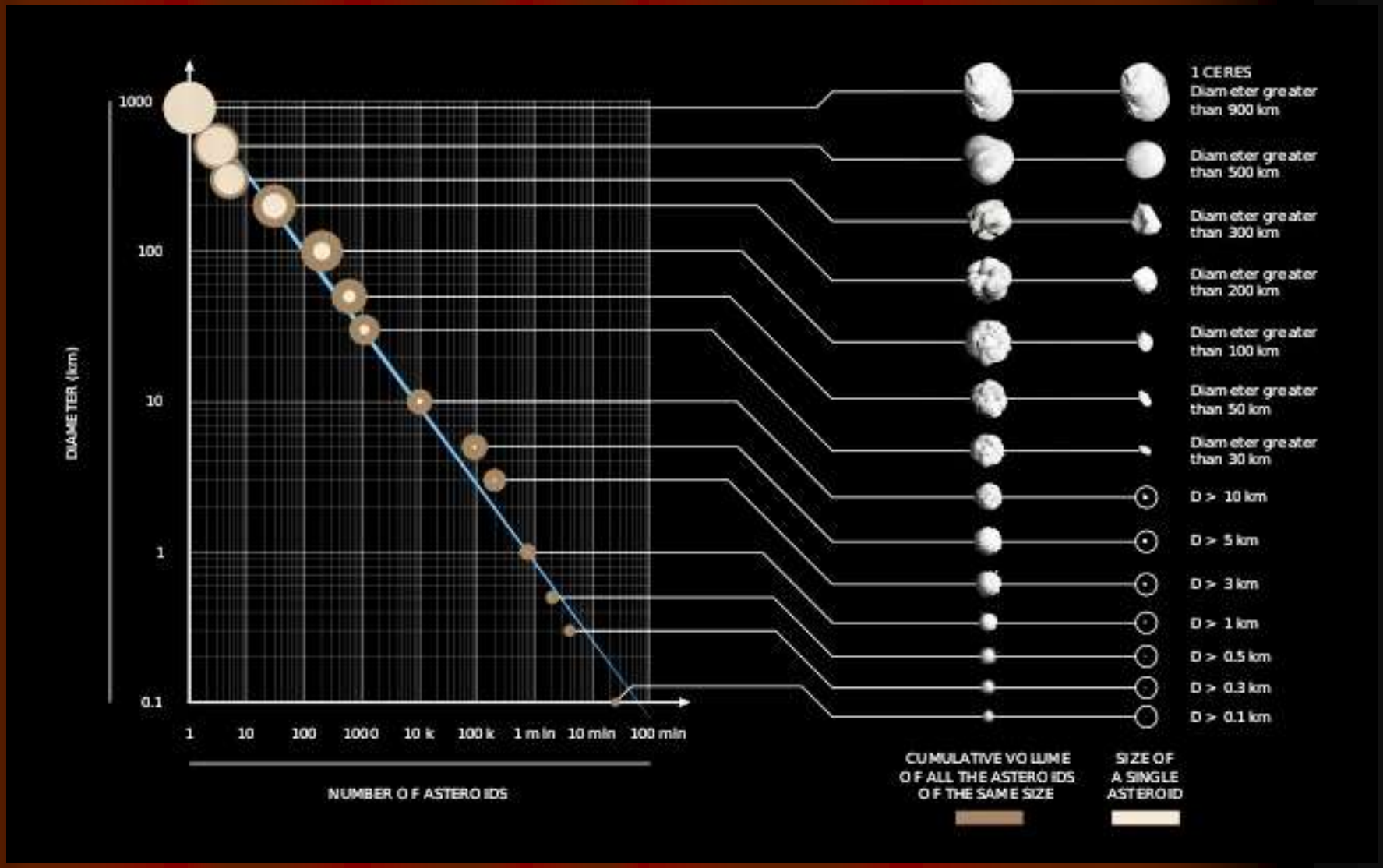


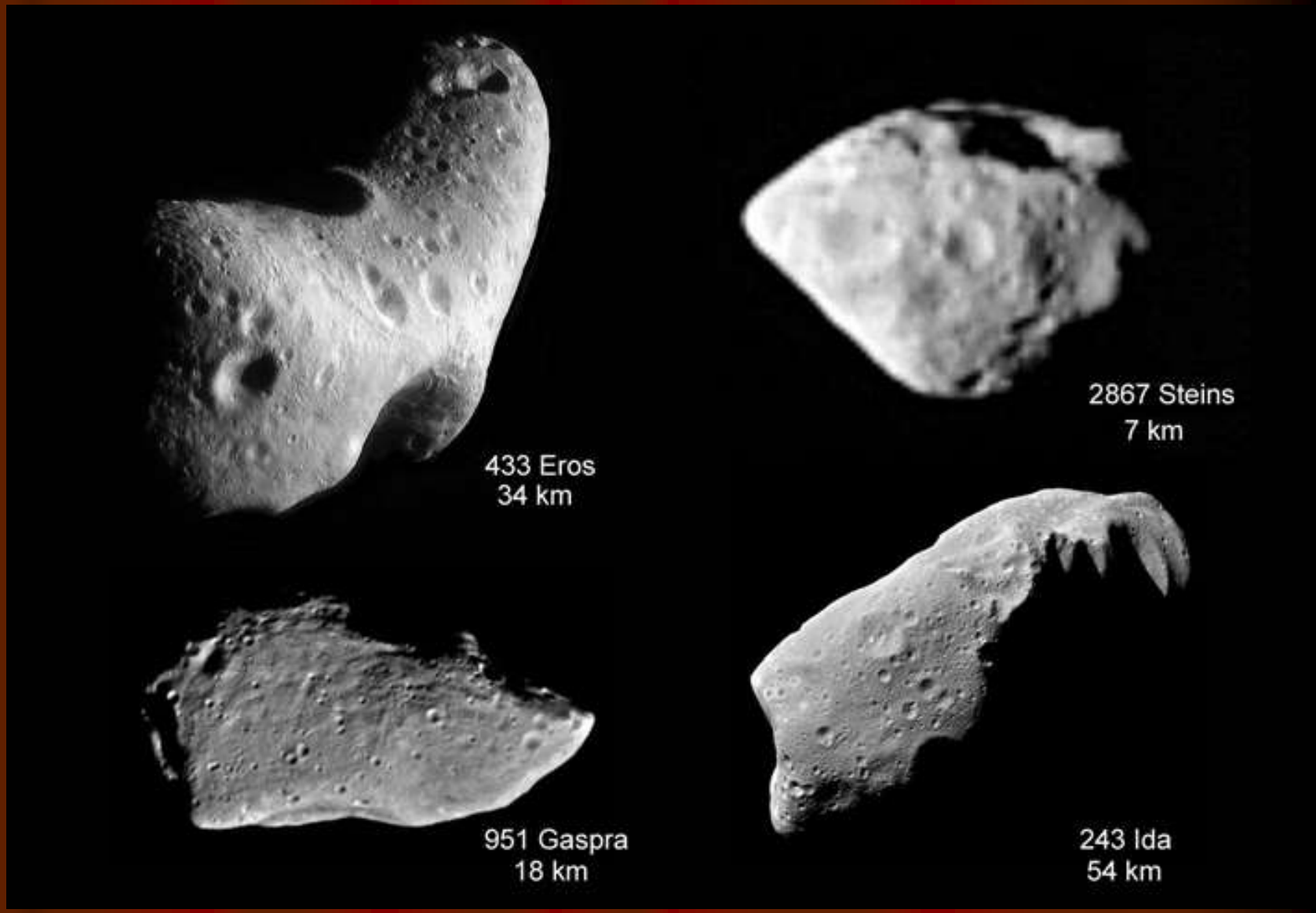
- Apohele : 2003 CP_{20} Atira is an IEO with diameter between 1,461 and 3,266 m. Scientists calculated that its closest near miss Earth distance will be approximately 8,724,315 km on August 2174

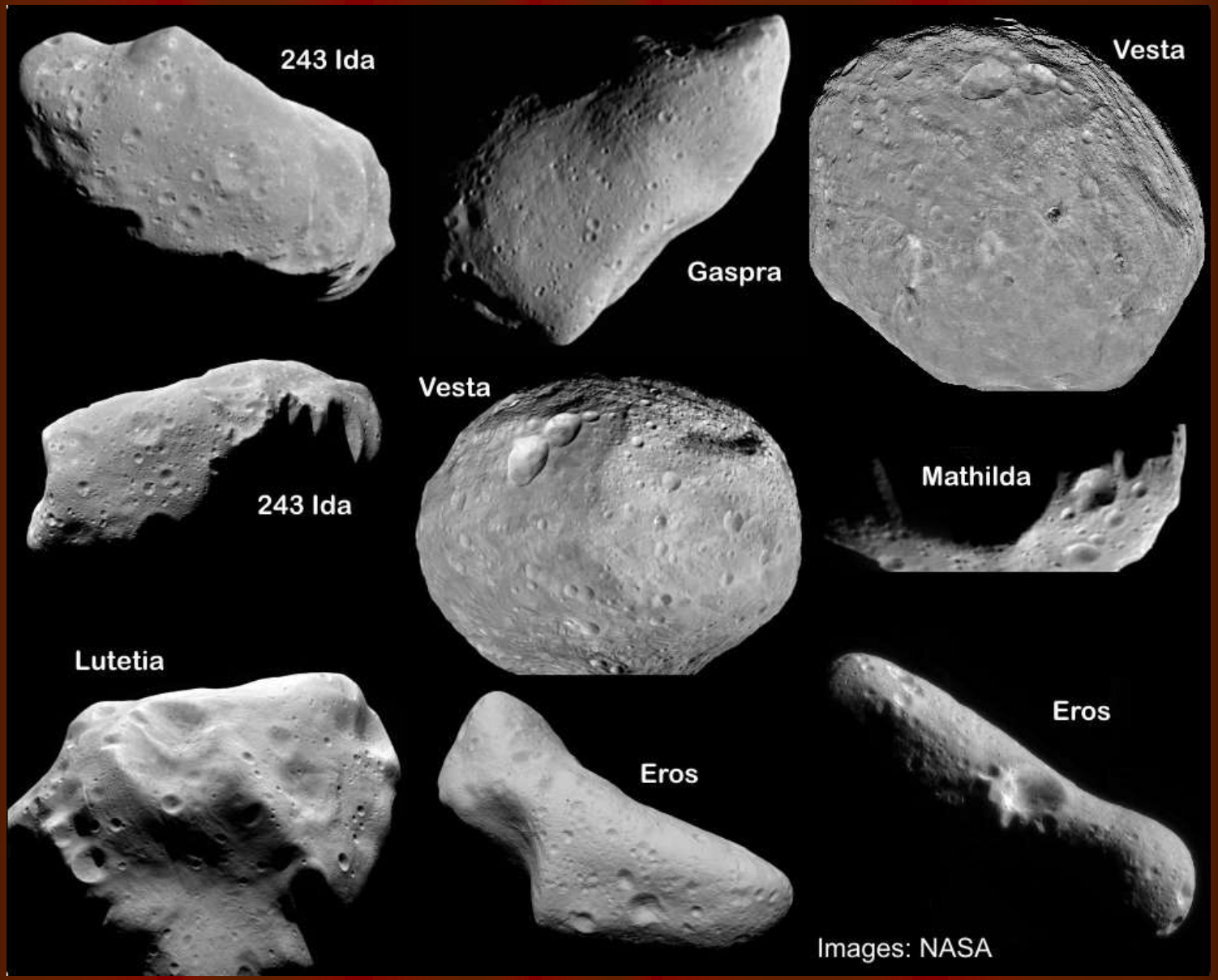

Near-Earth Asteroids Discovered
Most recent discovery: 2019-Apr-13
All
140m+
1km+
Cumulative Number Discovered
25 000
20 000
15 000
10 000
5 000
0
1980
1990
2000
2010
Discovery Date
https://cneos.jpl.nasa.gov/stats/
Alan Chamberlin (JPL/Caltech)

Asteroids have different shapes and sizes from nearly spherical to very irregular. The largest is Ceres 穀神星 with diameter at 946 km follow by Vesta, Pallas and Hygiea. Just these four already contain 50% the mass of the whole Asteroid belt

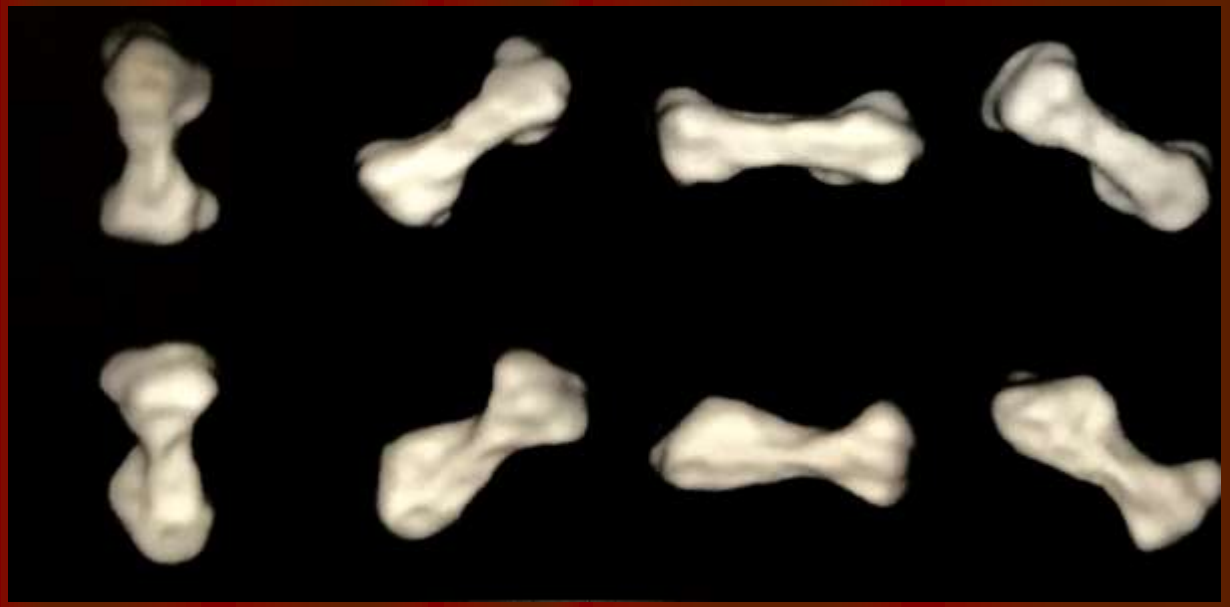
Asteroids of the Solar System categorized by size and number




433 Eros
34 km
2867 Steins
7 km
951 Gaspra
18 km
243 Ida
54 km


243 Ida
Gaspra
Vesta
243 Ida
Vesta
Mathilda
Lutetia
Eros
Eros
Images: NASA

- Dog bone shaped asteroid 216 Kleopatra is the size of New Jersey



- Skull like Halloween asteroid 2015-TB145 is an Apollo type NEA

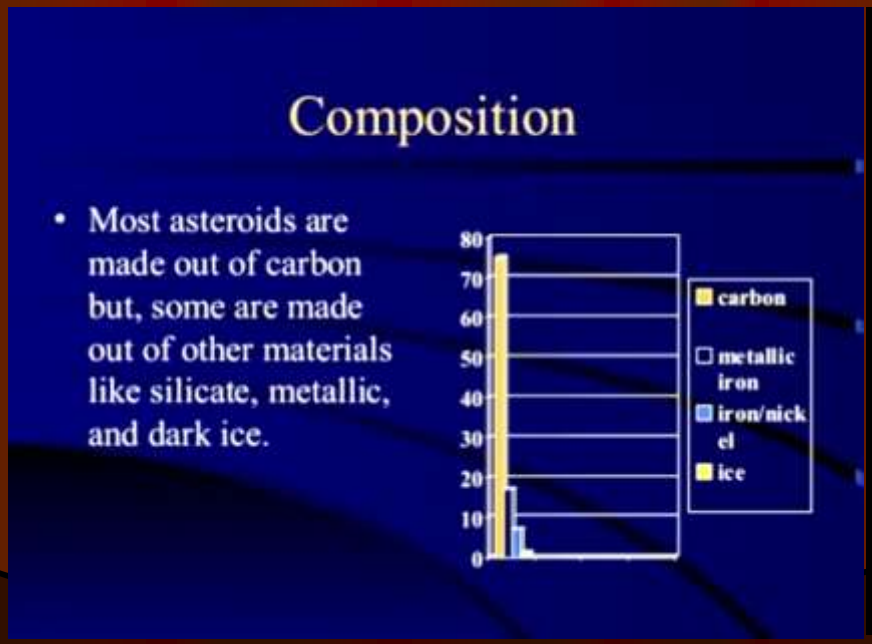
Classification of Asteroids according to colour and composition

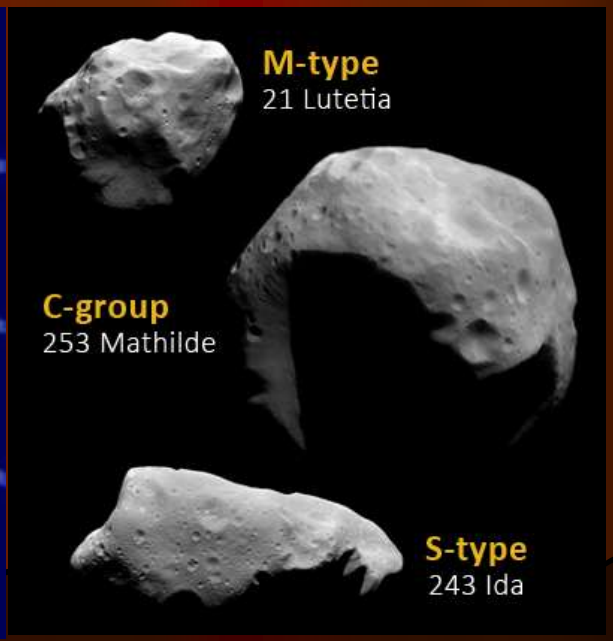
- 1. C - Type : Carbon rich, very dark and carbonaceous. *Albedo 0.03-0.1. 75% of known asteroids are of this type and they frequently occurred near the other edge of the Asteroid Belt

- 2. S - Type : Silicate, rusty red in colour and are composed of iron and magnesium silicate. Albedo 0.1- 0.22. 17% of known asteroids

- 3. M - Type : Metallic, rich with metallic substances (pure nickel-iron). Albedo 0.1 -0.18. 8% of known asteroids

(*Albedo (reflectivity) 反照率 0 to 1 : 0 = absorbs, 1 = 100% reflected)



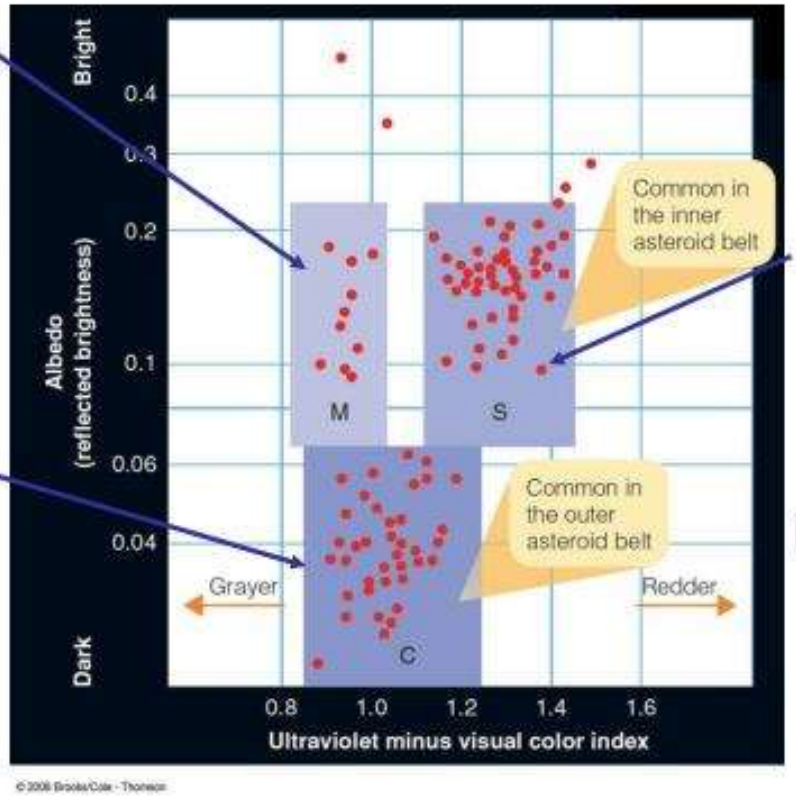


Colors of Asteroids

"Colors" to be interpreted as albedo (reflectivity) at different wavelengths.

M-type: Brighter, less reddish asteroids, probably made out of metal-rich materials; probably iron cores of fragmented asteroids

C-type: Dark asteroids, probably made out of carbon-rich materials (carbonaceous chondrites); common in the outer asteroid belt

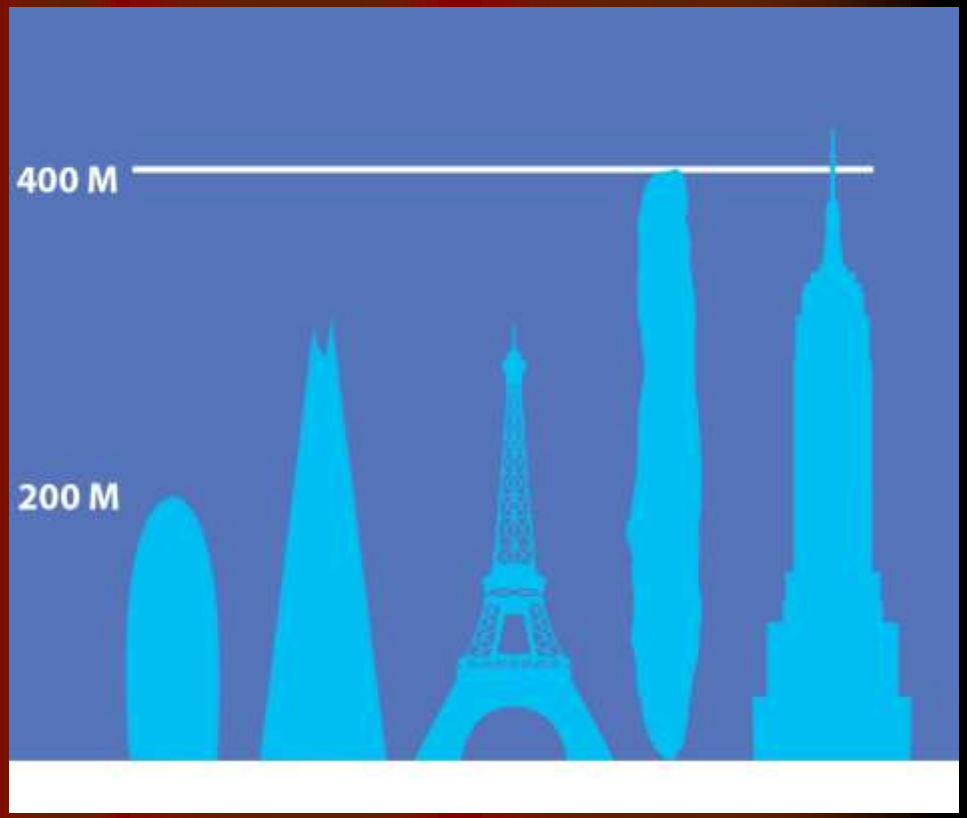


S-type: Brighter, redder asteroids, probably made out of rocky materials; very common in the inner asteroid belt

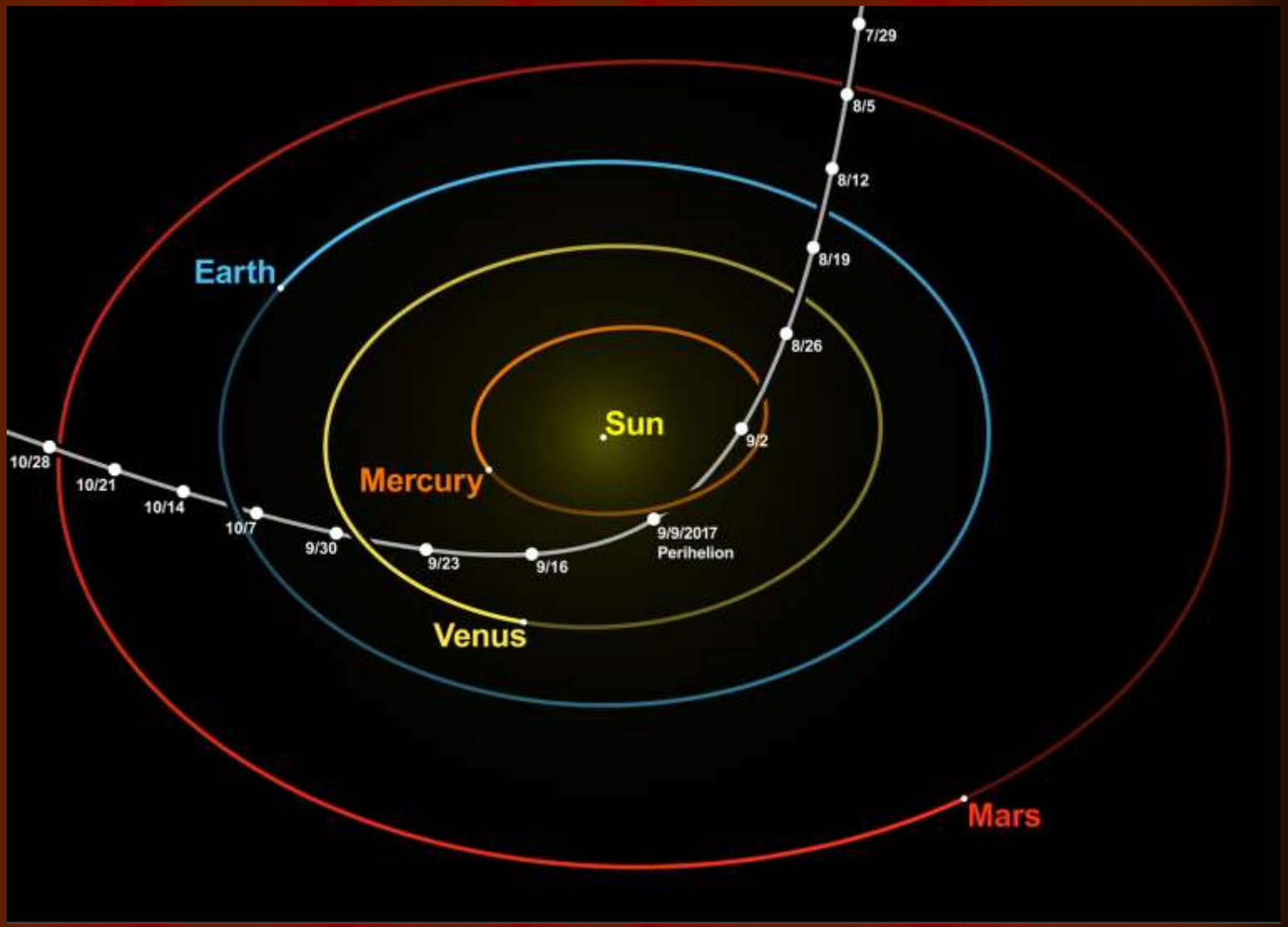
- Meteoroids 流星體 are fragments from asteroids or comets or collision impact debris ejected from bodies such as Moon or Mars revolving in interplanetary space around the sun. They are significantly smaller than asteroids and range in size from small grains to one metre wide objects. Objects smaller than this are classified as micrometeoroids or space dust/ cosmic dust most are between a few molecules to 0.1 Um in size . An estimated 25 million meteoroids and micrometeoroids equivalent to 15,000 tons enter the Earth's atmosphere each day but most typically vaporize during their passage

First Interstellar asteroid

- Asteroid 1I/2017U1 or "Oumuamua" Hawaiian meaning "messenger from a far arriving first" was discovered by NASA zipping through our solar system. From its trajectory and speed (86 km per second) scientists determined it may have came from another solar system from a star in a component of the Milky Way Galaxy known as the Thick Disk which contains older stars. At 400m long and 20m thick scientists also suspect part of it disintegrated above Papua New Guinea

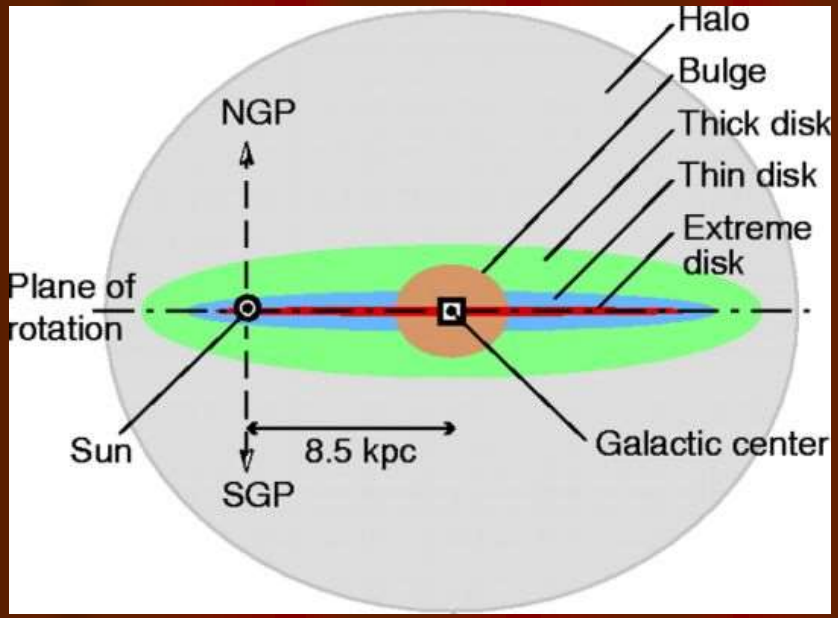


Qumuamua is the very first interstellar asteroid ever observed from Earth



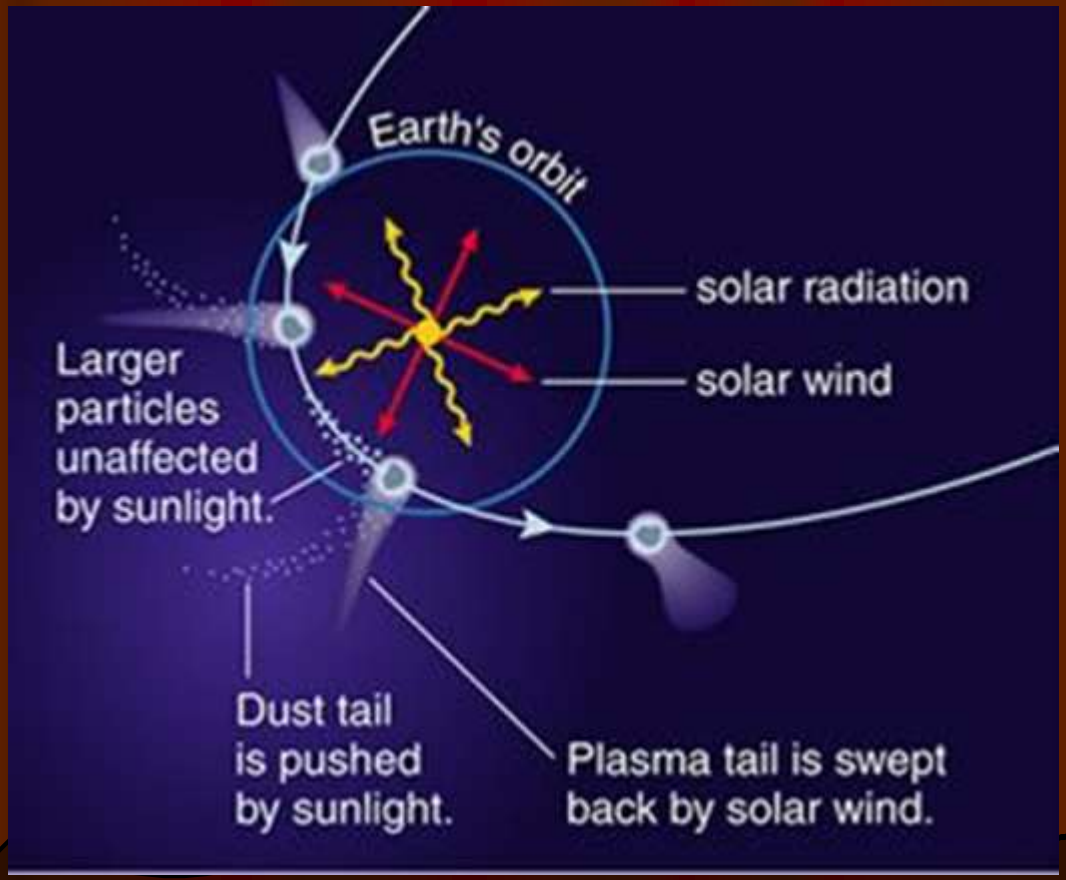
Milky Way Galaxy

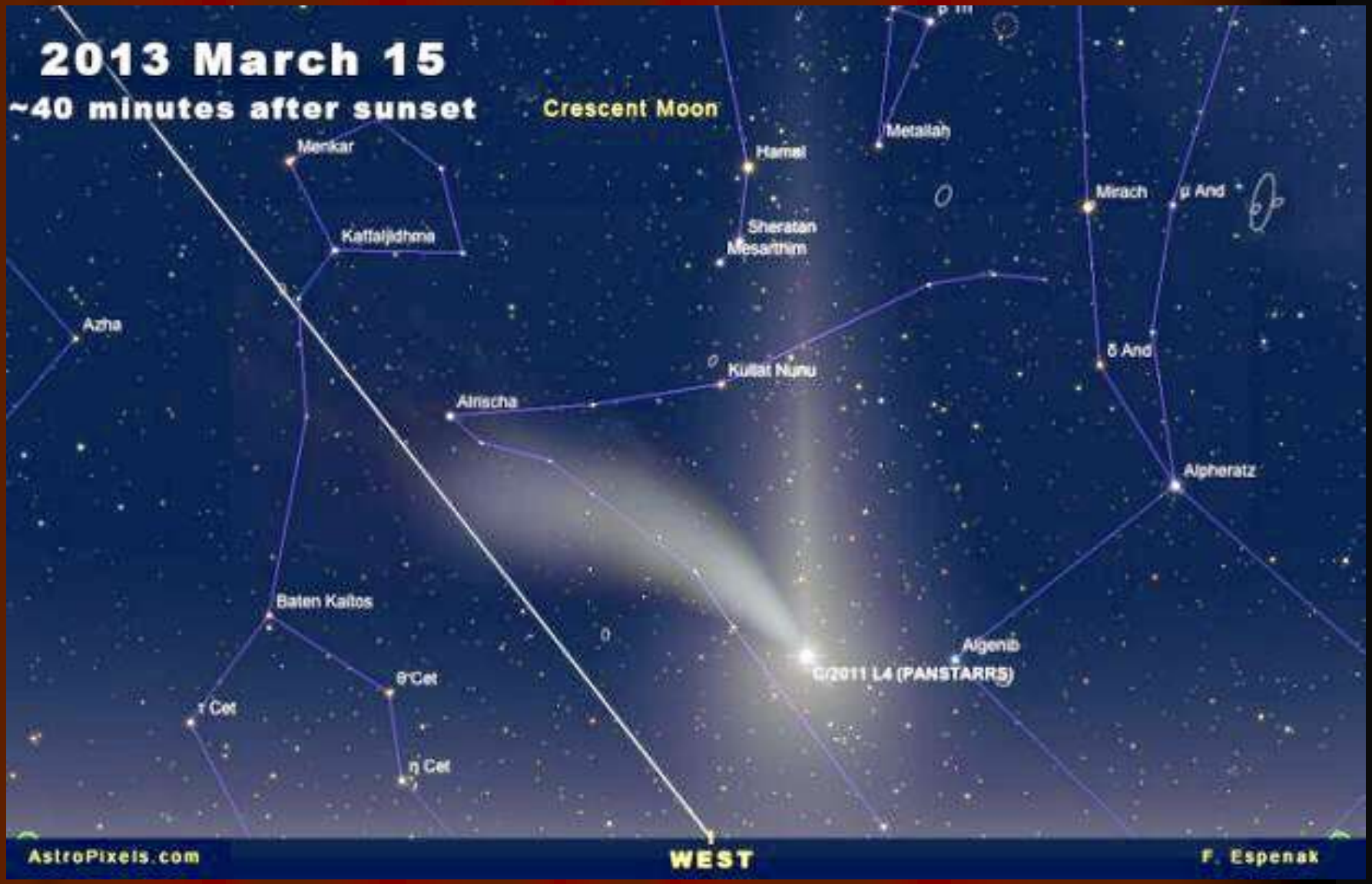
1 light years = 9.5 million million km



Comet
彗星

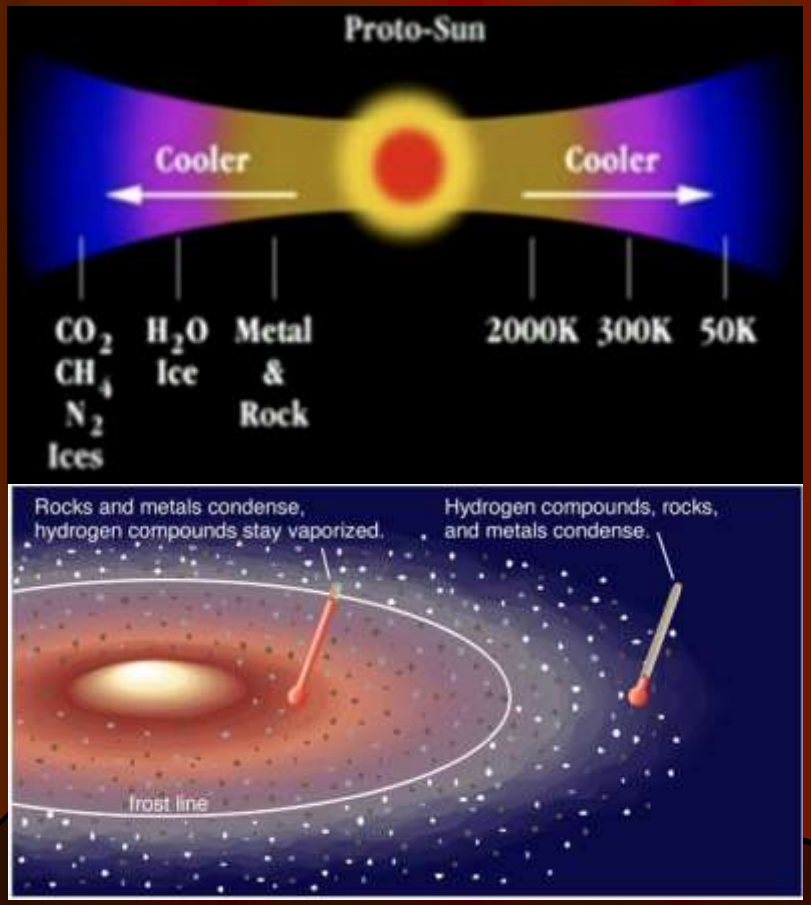
- Comets 彗星 in Greek means “hair of the head” are “Dirty Snowballs” which contain cold chunks of ice, rock dust (mainly silicate) and gas (ammonia, methane, carbon dioxide) left over from the formation of our Solar System. As a comet enters the inner solar system and passes the sun it vaporizes forming an envelope called a coma. A coma has two tails : a Type I - Ion/plasma tail 離子氣体尾巴 swept by solar wind and a Type II - Dust tail 星塵尾巴 pushed by solar radiation



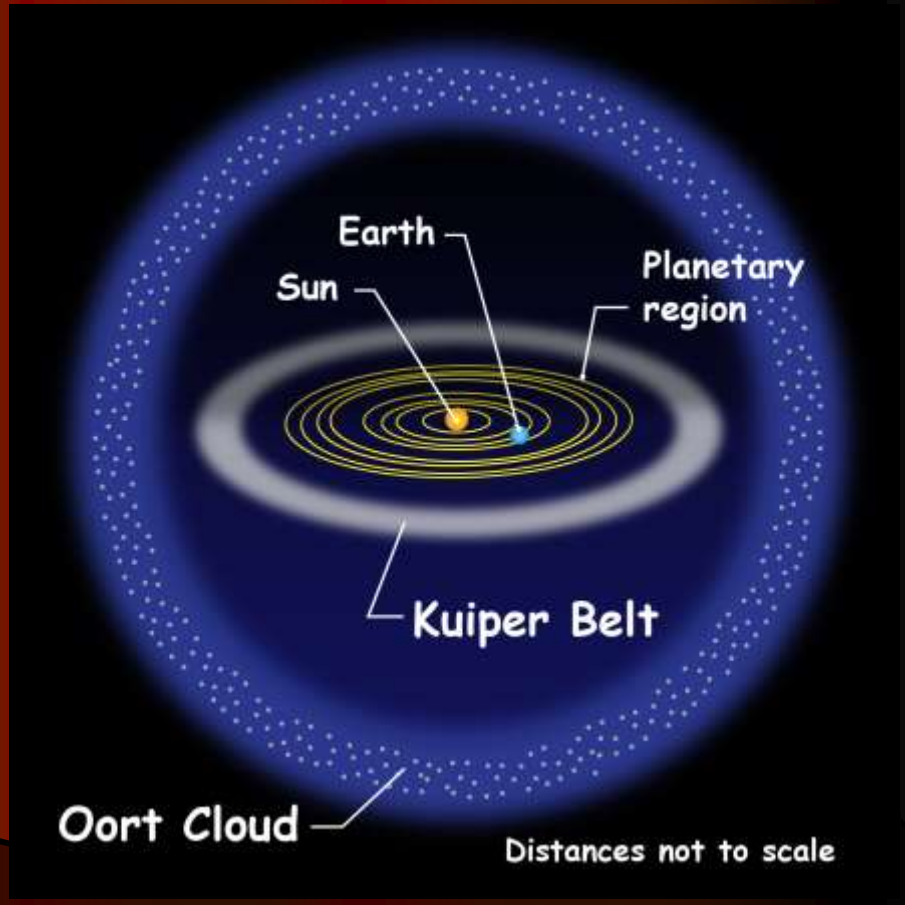

2013 March 15
~40 minutes after sunset
Crescent Moon
Menkar
Kaffaljidhma
Azha
Hamal
Sheratan
Mesarthim
Metallah
Mirach
μ And
δ And
Kullat Nunu
Alrischa
Alpheratz
Baten Kaitos
θ Cet
τ Cet
η Cet
Algenib
C/2011 L4 (PANSTARRS)
AstroPixels.com
WEST
F. Espenak

Comets are icy because they were formed beyond the Frost Line or Ice Line which is the boundary where simple molecules condense. The line is a little less than 5 AU (750m km) from the sun well beyond the asteroid belt & just before the orbit of Jupiter. Comet orbits are eccentric. Short-period comets or SP comets (<200 years) originate from the Edgeworth-Kuiper belt (30-50 AU) 柯伊伯帶 & Long-period comets or LP comets (>200 to thousands of years) originate from the Oort Cloud (5000-100,000 AU) 奧爾特雲

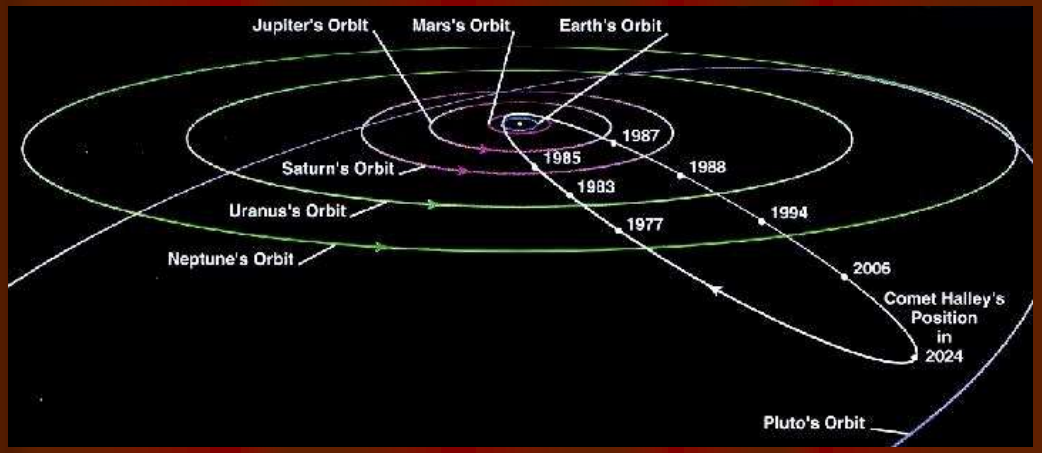
Kelvin Scale 273.15 k = 0 C



Location of the Edgeworth-Kuiper Belt & Oort Cloud



- Short Period Comet : about 100 known e.g. Halley's comet : Officially 1P/Halley is visible from Earth every 75 to 76 years last appeared 1986 and will next appear in mid 2061. The shortest period comet is Encke's comet with a period of 3.3 years



- Long Period Comet : most comets are Long Period Comet e.g. The Great Comet of 1882 is visible from Earth every 669 years

Long-period periodic comet catalogue

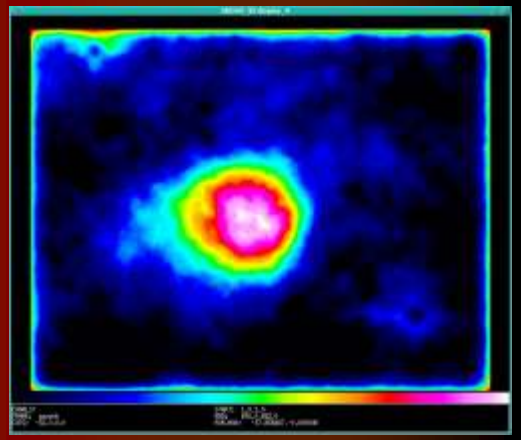
me	Period (years
1811 W1 - Pons	755.00
1840 U1 - Bremiker	286.00
1843 D1 - Great Comet of 1843	513.00
1846 J1 - Brorsen	538.00
1853 G1 - Schweizer	781.00
1855 G1 - Schweizer	500.00
1855 L1 - Donati	252.00

- Comet Mrkos

  Comet can be huge. The comet Mrkos exhibited a coma that was estimated to be 15 times the Earth's diameter when it appeared on 13th August 1957

- Comet Hale-Bopp

  Thought to be the most widely observed comet of all time it was visible on Earth to the naked eye for 18 months 1995/6. With a 60 km wide nucleus, it was also one of the brightest comet seen for many decades displaying a spectacular blue gas tail and yellow dust tail. Previous visit 4,200 years ago. Next visit only 2,380 years away due to orbit change

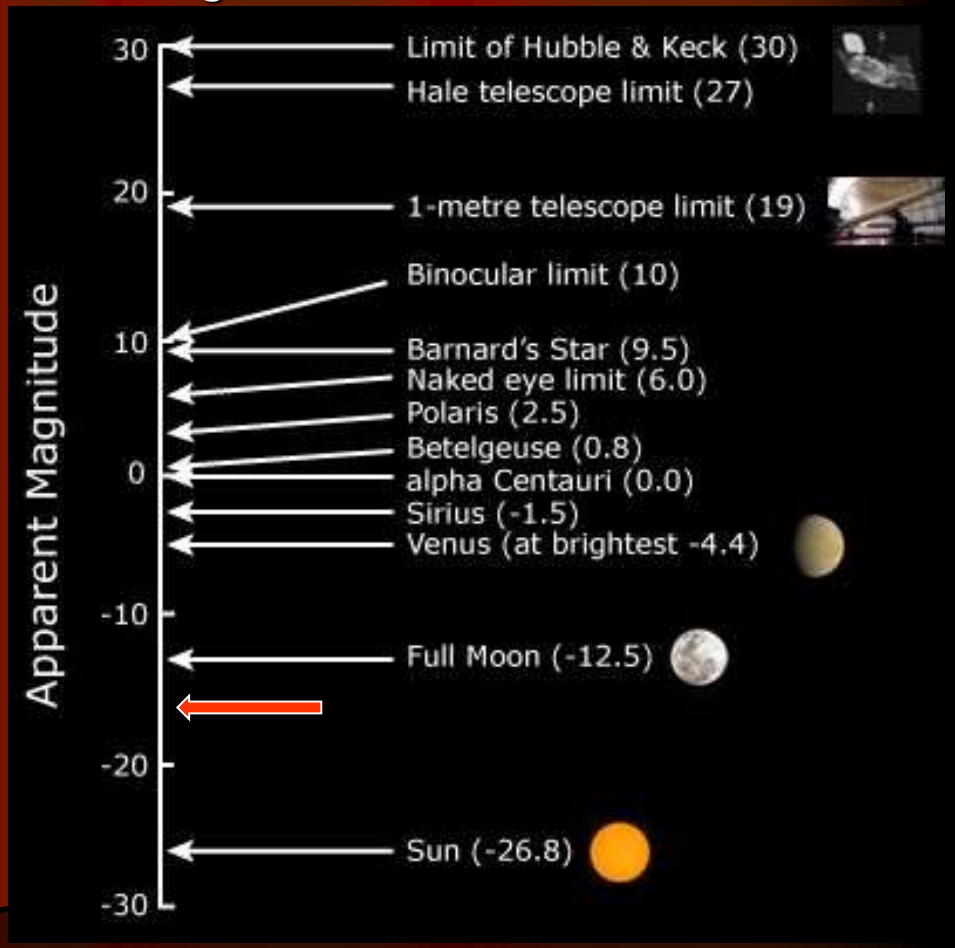


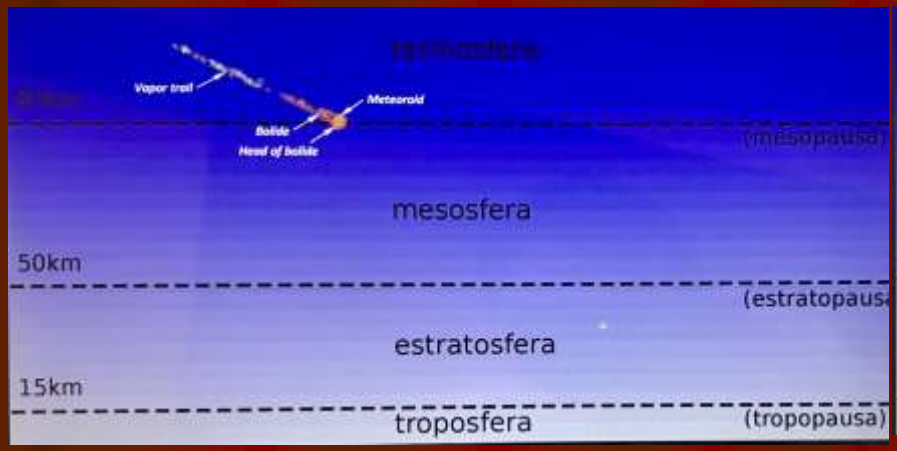
Meteor
流星

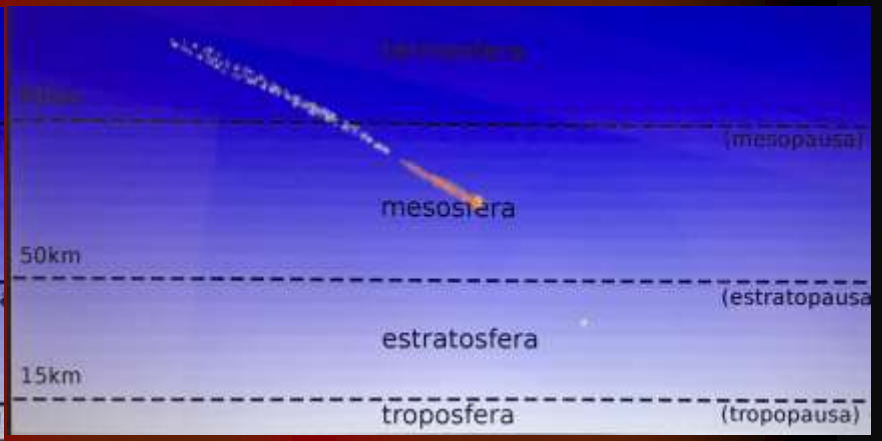
- A Meteor 流星 or Shooting star or Falling star is a small body of space rock mostly being fragments from Asteroids, Meteoroid or Comet from outer space with others being debris ejected from collision with the Moon or Mars that enters the Earth's atmosphere in excess of 20 km/s and become incandescent as a result of friction with air molecules and appearing as a streak of light which differs in color depending on its chemical composition. Meteors typically occur in the mesosphere at altitudes from 76 to 100 km

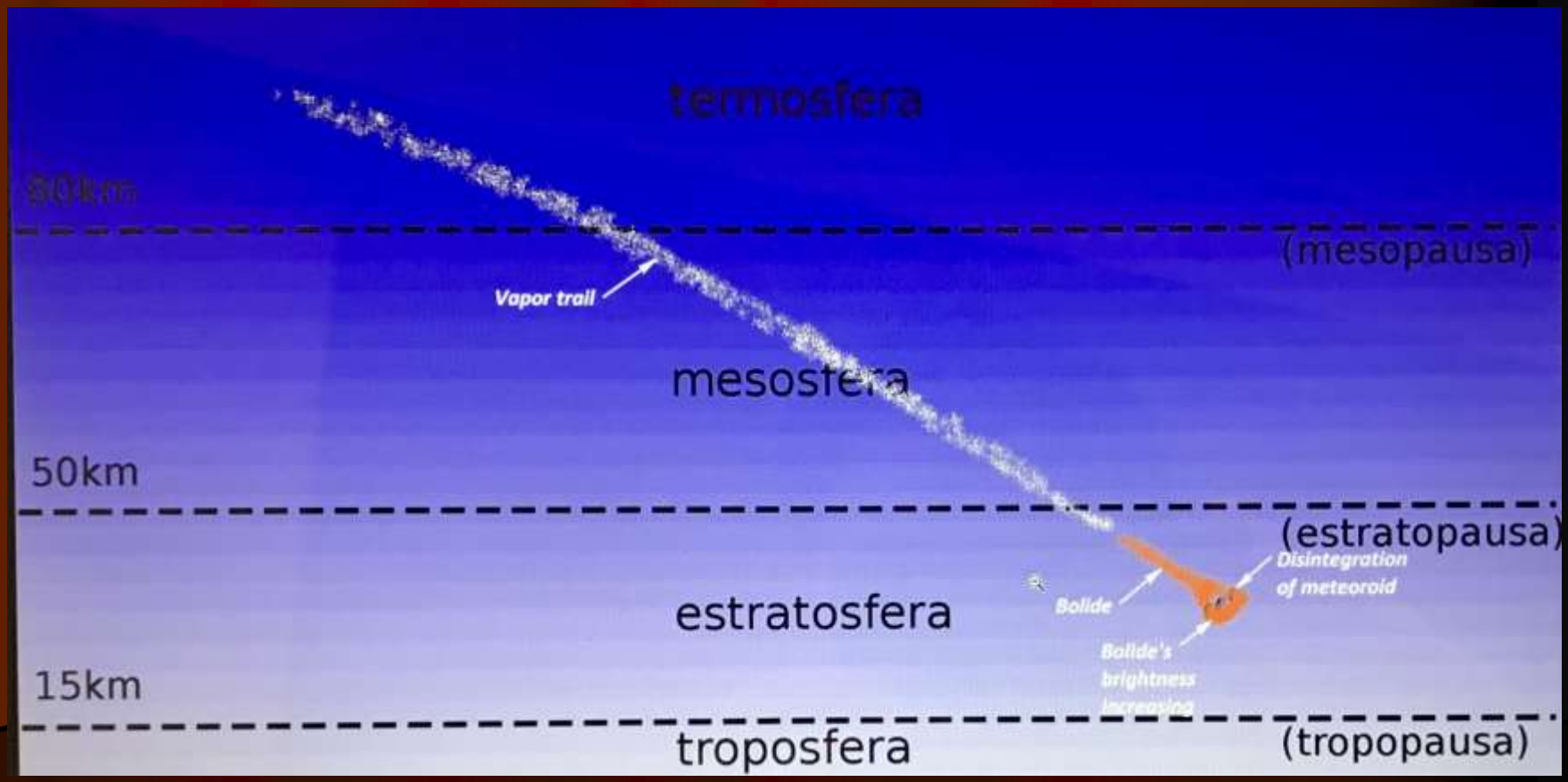
Fireball & Bolide

A Fireball 火流星 is a brighter than usual meteor which is brighter than Venus (Brightness Magnitude Scale of -4.4). A Bolide (Latin meaning "missile") is an extremely bright asteroid or meteoroid about as bright as the full Moon (-12.5) which explode and disintegrate in Earth's atmosphere. A Super Bolide will be one that has a brightness magnitude of -17.0 or higher



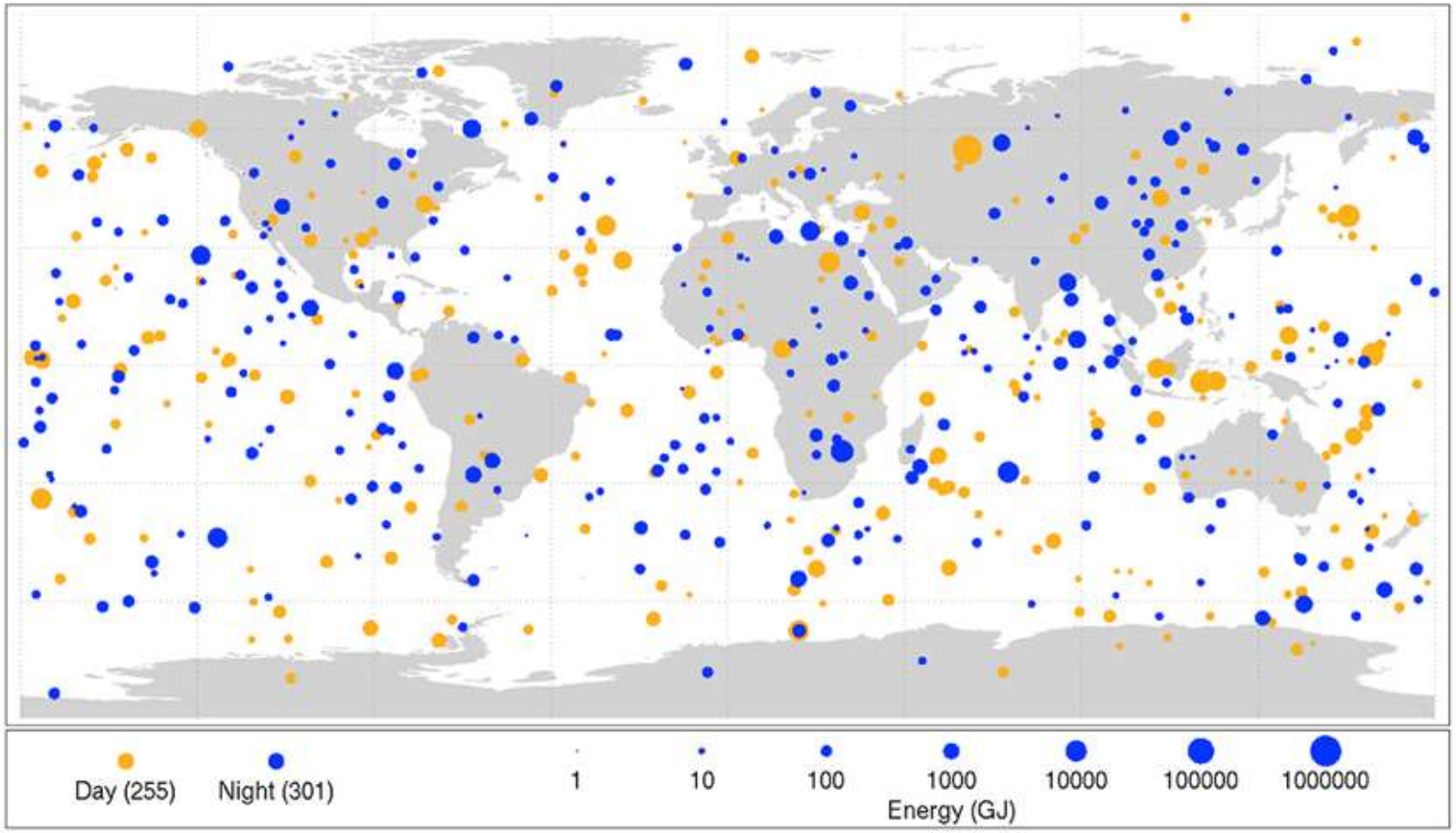

Vapor trail
Meteoroid
Bolide
Head of bolide
(mesopausa)
mesosfera
50km
(estratopausa
estratosfera
15km
troposfera
(tropopausa)


(mesopausa)
mesosfera
50km
(estratopausa
estratosfera
15km
troposfera
(tropopausa)

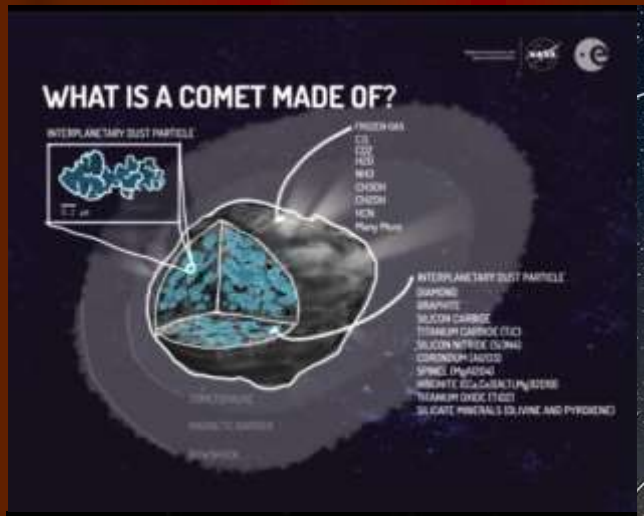

termosfera
80km
(mesopausa)
Vapor trail
mesosfera
50km
(estratopausa)
Disintegration
of meteoroid
Bolide
estratosfera
Bolide's
brightness
15km
troposfera
(tropopausa)

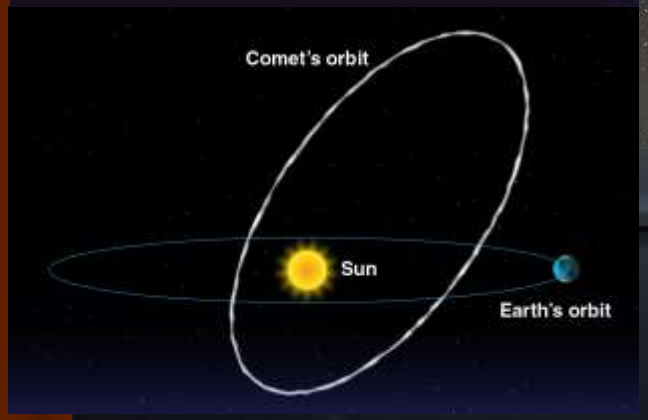
Bolide Events 1994–2013

(Small Asteroids that Disintegrated in Earth's Atmosphere)



- Meteor Shower 流星雨 : a celestial event in which many meteors can be observed over a few days. It happens when the Earth passes through a meteoroid stream produced by a comet. As comets have known orbits occurrence of meteor shower can be well defined during the year

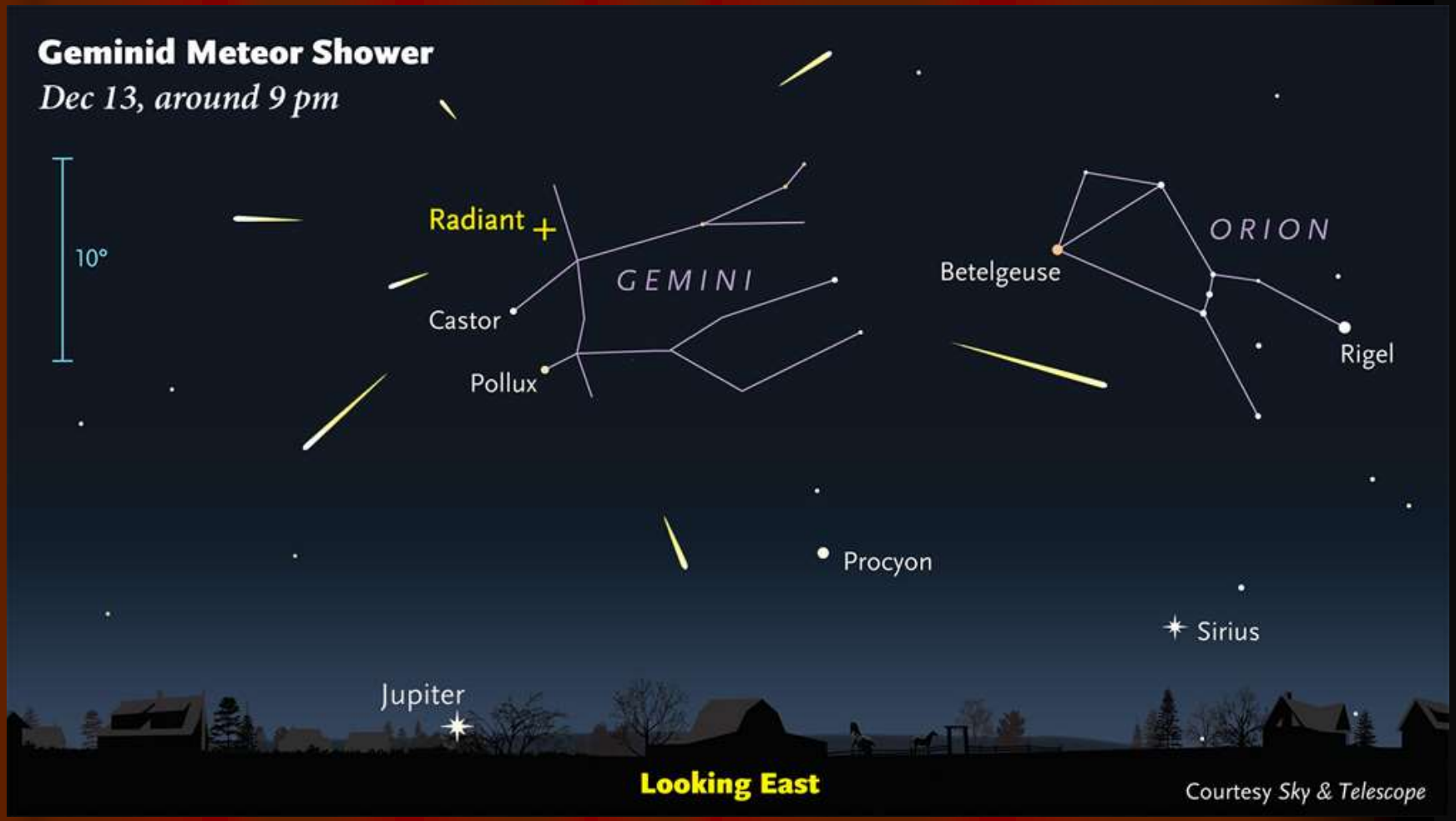




Meteor Shower Calendar for 2018

Meteor shower	Dates / Peak Night	Moon Phase	Meteors per Hour	Constellation	Radiant (Right ascension/ Declination)	Associated Comet
Quadrantids	Jan 1-6 **Jan 3-4**	98%	120	Boötes	15h 28m +49.5°	2003 EH1 (asteroid)
Lyrids	Apr 16-25 **April 22-23**	38%	20	Lyra	18h 08m +32°	C/1861 G1 Thatcher
Eta Aquariids	Apr 19 - May 28 **May 6-7**	61%	45	Aquarius	22h 32m -1°	1P/Halley
Delta Aquariids	Jul 12 - Aug 23 **Jul 29-30**	96%	20	Aquarius	22h 40m -16.4°	Unkown, 96P Machholz suspected
Perseids	Jul 17 - Aug 24 **Aug 12-13**	3%	100	Perseus	03h 04m +58°	109P/Swift-Tuttle
Orionids	Oct 4 - Nov 14 **Oct 21-22**	91%	20	Orion	06h 20m +15.5°	1P/Halley
Leonids	Nov 5-30 **Nov 17-18**	62%	15	Leo	10h 08m +21.6°	55P/Tempel-Tuttle
Geminids	Dec 4-16 **Dec 13-14**	35%	120	Gemini	07h 28m +32.2°	3200 Phaethon

Meteor shower Geminids appeared to originate from the same fixed point in the sky



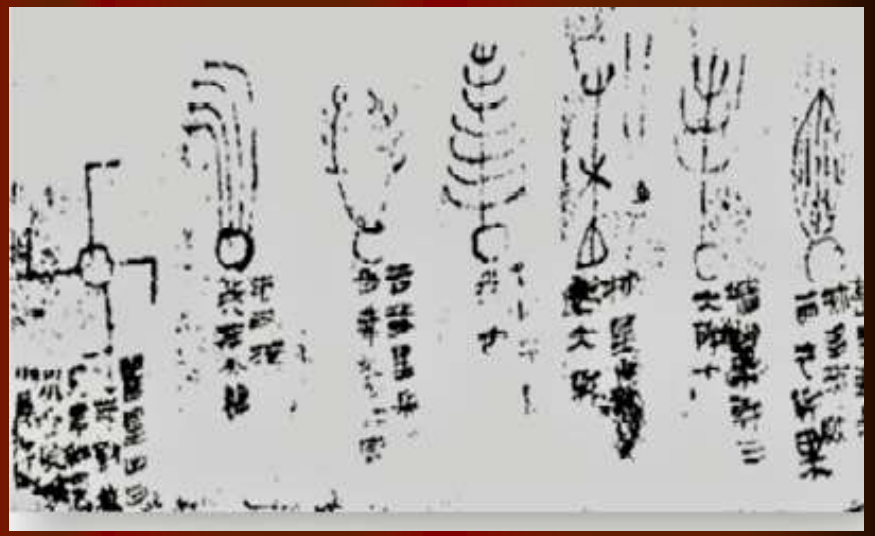
Meteor Shower Calendar for 2019

Meteor shower	Dates / Peak Night	Moon Phase	Meteors per Hour	Constellation	Radiant (Right ascension/ Declination)	Associated Comet
Quadrantids	Dec 28 - Jan 12 **Jan 3-4**	4%	120	Boötes	15h 28m +49.5°	2003 EH1 (asteroid)
Lyrids	Apr 14-30 **April 22-23**	85%	20	Lyra	18h 08m +32°	C/1861 G1 Thatcher
Eta Aquariids	Apr 19 - May 28 **May 6-7**	1%	45	Aquarius	22h 32m -1°	1P/Halley
Delta Aquariids	Jul 12 - Aug 23 **Jul 30-31**	6%	20	Aquarius	22h 40m -16.4°	Unkown, 96P Machholz suspected
Perseids	Jul 17 - Aug 24 **Aug 12-13**	94%	100	Perseus	03h 04m +58°	109P/Swift-Tuttle
Orionids	Oct 2 - Nov 7 **Oct 21-22**	45%	20	Orion	06h 20m +15.5°	1P/Halley
Leonids	Nov 6-30 **Nov 17-18**	69%	15	Leo	10h 08m +21.6°	55P/Tempel-Tuttle
Geminids	Dec 4-17 **Dec 14-15**	96%	120	Gemini	07h 28m +32.2°	3200 Phaethon

Meteor Sightings

- Arriving amid thunderous blast and flame, asteroids were once thought to be the messenger of gods and being worshipped by early human. The Bushman rock painting below depicts a bolide found in the foothill of the Maloti Mountains, South Africa

- China is one of the earliest countries to observe and record “falling stars”. There are 581 sightings recorded and the oldest one was dated at 645 BC. The first iron meteor shower was at 368 BC：秦献公十七年 - ”棟陽雨金”. Similar to many ancient civilization, meteor appearance were considered bad omens !



- Weighing more than 1 metric ton, the Jilin Meteorite is the largest chondrite ever discovered which fallen in Jilin, Kirin Province as part of a meteoric shower, in March 1976. This was considered an extremely bad omen as "proven" thereafter by a very severe earthquake at Tangshan 唐山大地震 that same year in August killing more than 240,000 people thence followed by Chairman Mao's death in September !

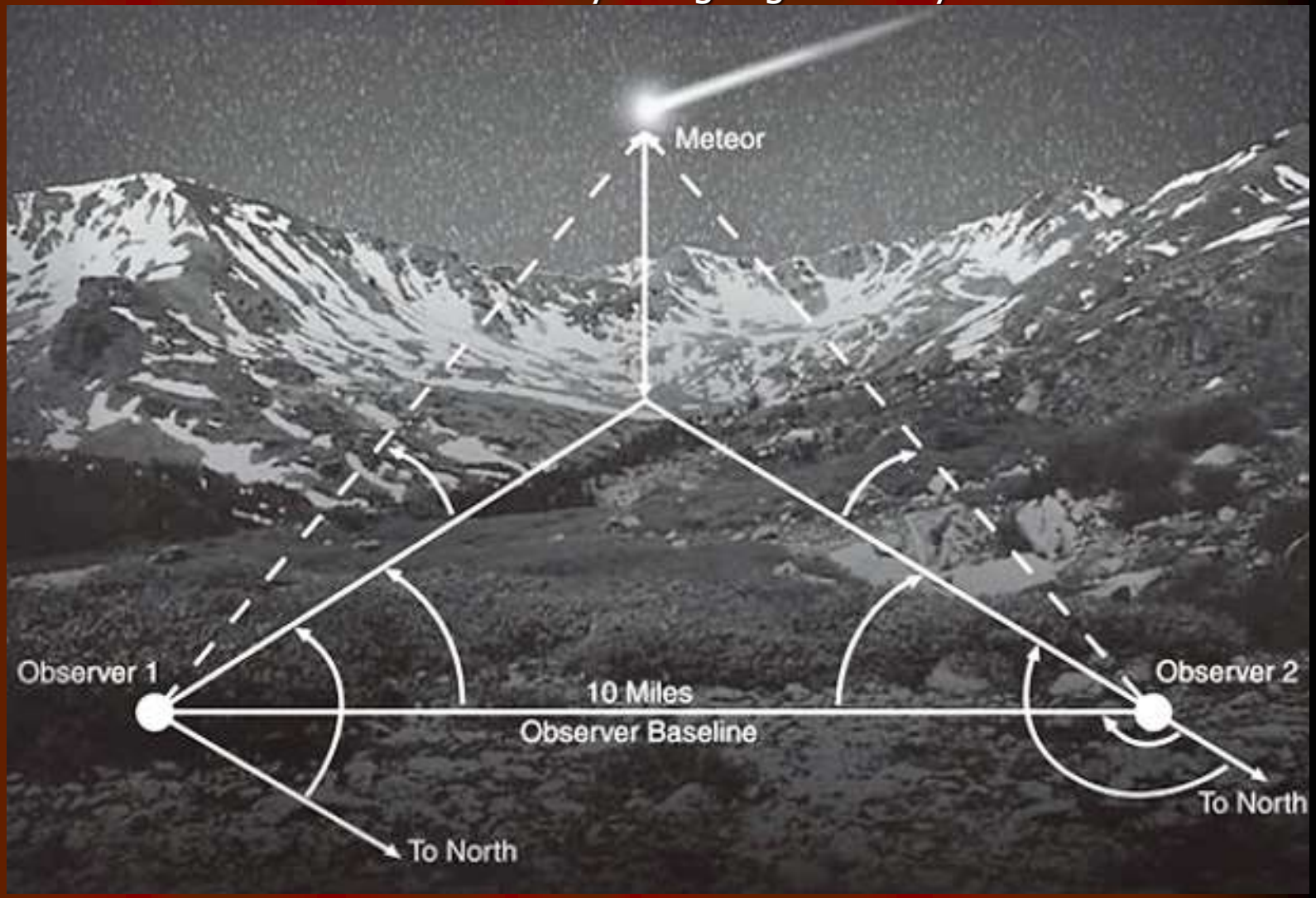
- Halley's comet was observed and recorded since at least at 240 BC. It was shown as the Star of Bethlehem in the painting "Adoration of the Magi" by Leonardo da Vinci. The omen was the death of Harold II. It was also shown in the Bayeux Tapestry depicting the Battle of Hastings in 1066. It was alleged that the appearance of the comet inspired the Norman king William the Conqueror to launch the battle

- Left “What our ancestors saw in a comet” – war and death. Right A declaration describing the fall by the Holy Roman Empire in Latin and German in 1492

- A 1628 German engraving depicts artillery shells from embattled celestial legions falling to Earth as meteorites and injured the farmers

- Some early European engravings of meteors. The right one indicates the Leonid Meteor shower of November 1799 and the left again in 1833

- The approximate height of a meteor seen by 2 observers at 2 different locations can be determined by using trigonometry



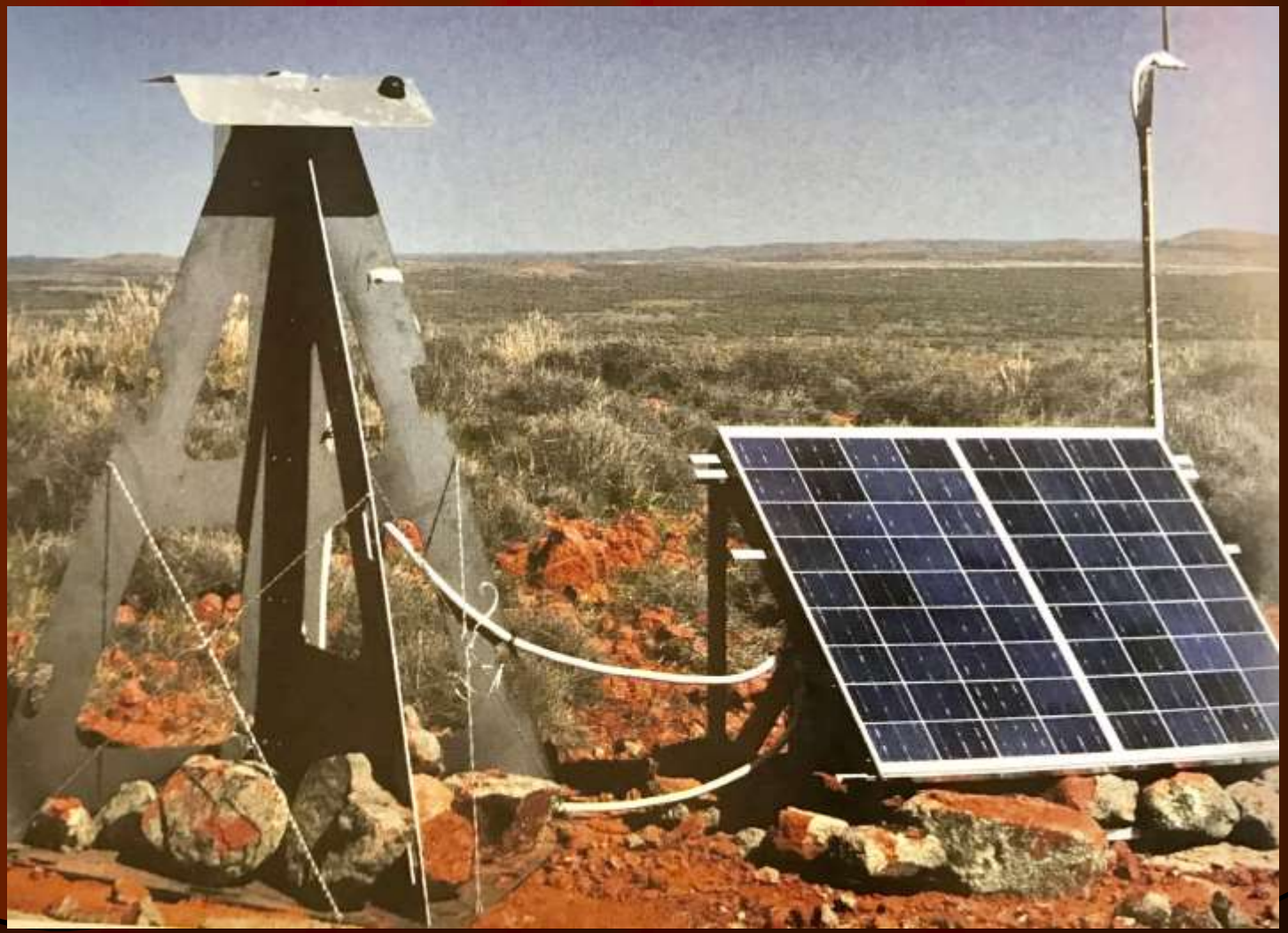
The Great Meteor Procession of February 9, 1913

Technology improvement allowed a total recorded ground track of over 11,000 km

Global distribution of meteor sighting

Skewed towards developed/populous areas due to better equipment, transportation communication structure which enable better reporting

A camera station of the Desert Fireball Network located in the Nullabor Desert of Western Australia. Similar network include the European Fireball Network, Spanish Meteor Network & the Fireball Recovery and Planetary Observation Network in France. Some success but still too few



Meteorite
隕石

Chelyabinsk meteorite is a classic "oriented meteorite" with the conical shape points in the direction of travel during the atmospheric flight. The sun-like ridges 溶流線 that flow away from the centre were produced by ablation during entry. It was sold for nearly US$100,000

- The Middlesbrough Meteorite is another oriented meteorite (York Museum)

Each year about 3,000 meteorites each weighing over 1 kg reach Earth. Despite improvement in observation technology and communication, out of the 61,000 meteorites known to date only 1,180 are documented "falls" 墜落隕石 which are meteorites collected after their fall from apace were observed. The balance are called "finds" 發現隕石. As the material in the meteorite from observed falls has not been subjected to terrestrial weathering (corrosion and rusting) making them much more desirable for scientific study

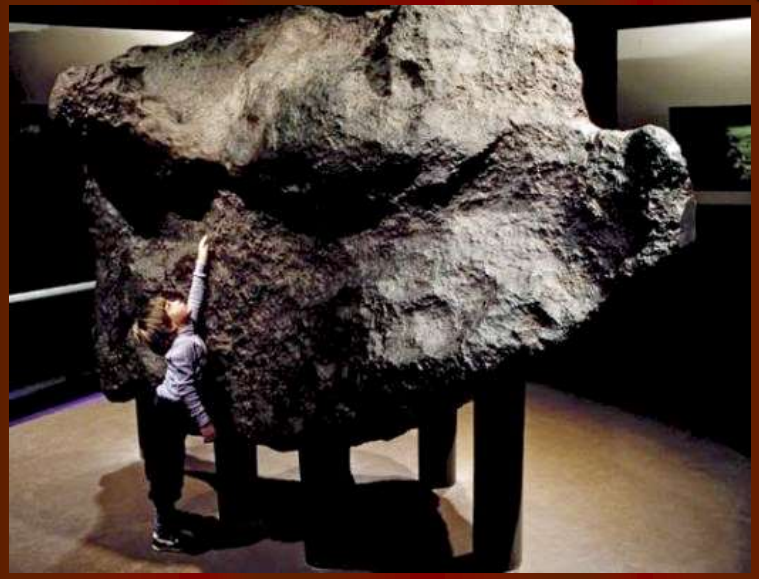
Era	Number of falls	Average per year
Pre-1900	401	–
1900–1949	341	6.8
1950–1959	60	6.0
1960–1969	64	6.4
1970–1979	61	6.1
1980–1989	56	5.6
1990–1999	58	5.8
2000–2009	68	6.8
2010–2018	71	7.8
Total	1180	–

In reality meteorite comes in many different shapes, size, weight and color

Most meteorites landed on Earth are relatively small & even in dust form

This is a group of tiny Chelyabinsk meteorites that range in weight from around 25 milligrams to under 100 milligrams. Note the pin as a size reference.

But there are huge and very heavy ones !



- Hoba – world's heaviest discovered in Namibia weighing 60.2 tonnes

- El Chaco – second heaviest discovered in Argentina weighing 37.3 tonnes

- Gancedo 3rd heaviest just discovered near Chaco Argentina weighing 30.8 tonnes. It has been attributed to a meteor shower that hit the region more than 4,000 years ago

- Mbozi – fourth heaviest discovered in Tanzania 3 m long 25 tonnes iron meteorite

- The Cape York ranks 5th discovered in Greenland 3 m weighing 20 tonnes

- Iron meteorite (90% NiFe) **鐵隕石** melted, came from planets' core. 5.7% of fall

- Stony-Iron meteorite (50% NiFe 50% silicate) **鐵石隕石** melted, 2% of fall

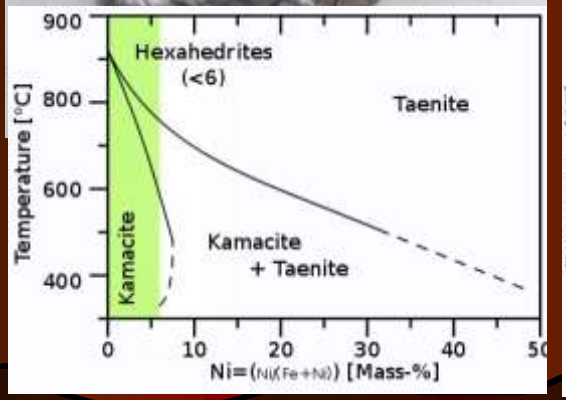

- Stony meteorite or chondrites **球粒隕石** not melted, mostly silicate 矽酸鹽. 86% of meteorites fallen on earth are chondrites which are typically formed 4.5 Ba represented material that never formed into large bodies



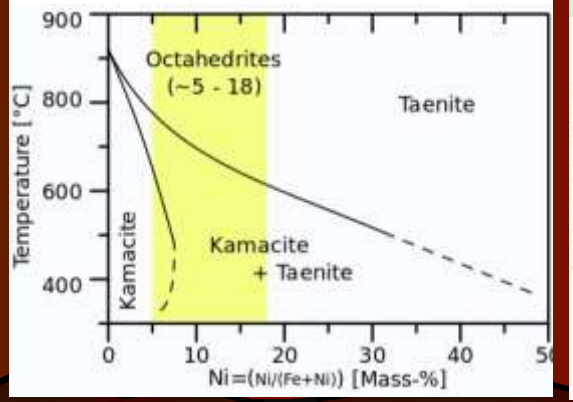
Iron Meteorite 鐵隕石

5.7% of fall. Consist overwhelmingly of an iron-nickel alloy known as meteoric iron that usually consist of two mineral phases kamasite 錐紋石 and taenite 鎳纹石. Iron meteorite is divided into 3 subgroups basis on the percentage of its nickel content

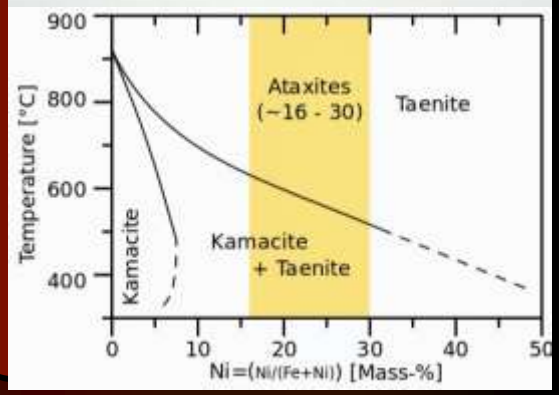
Hexahedrites (H)
(<6% Ni)



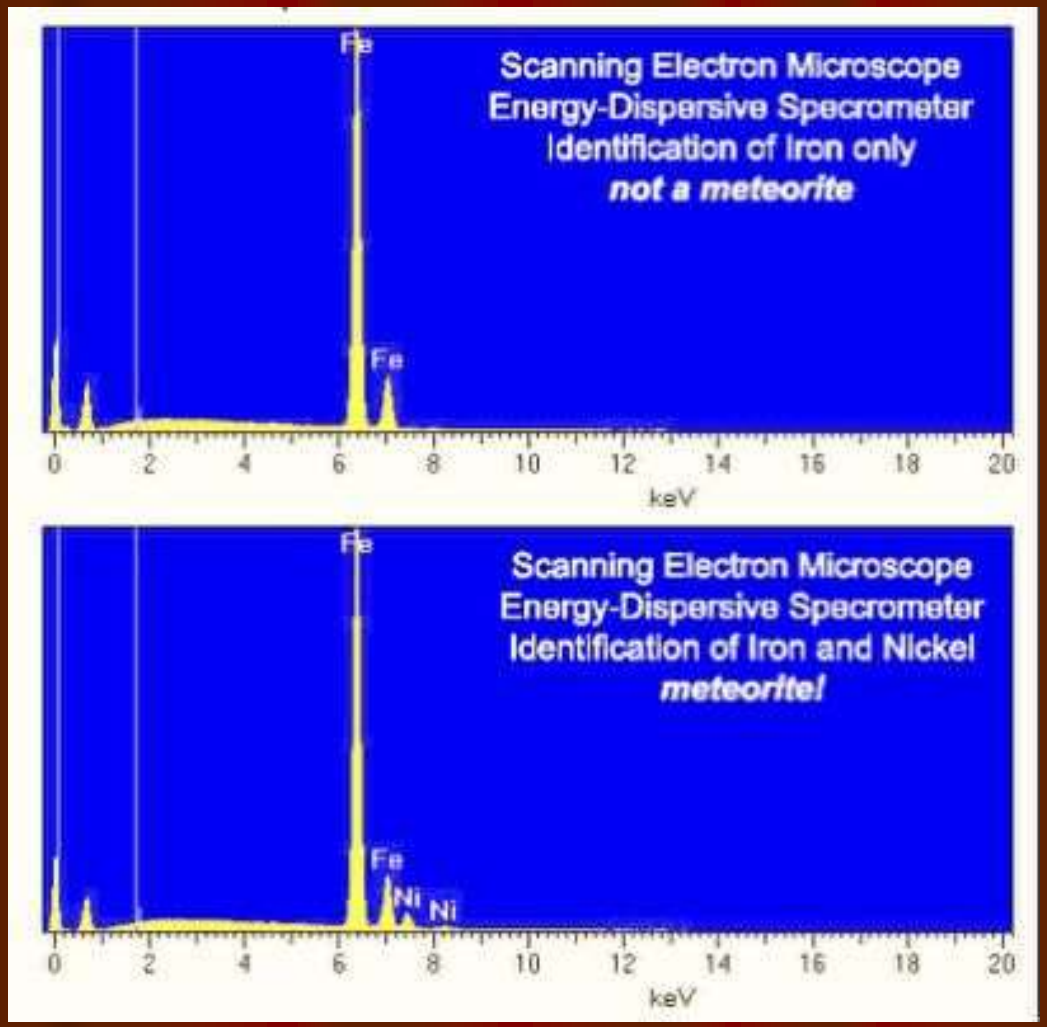
Octahedrites (O)
(6-17% Ni)



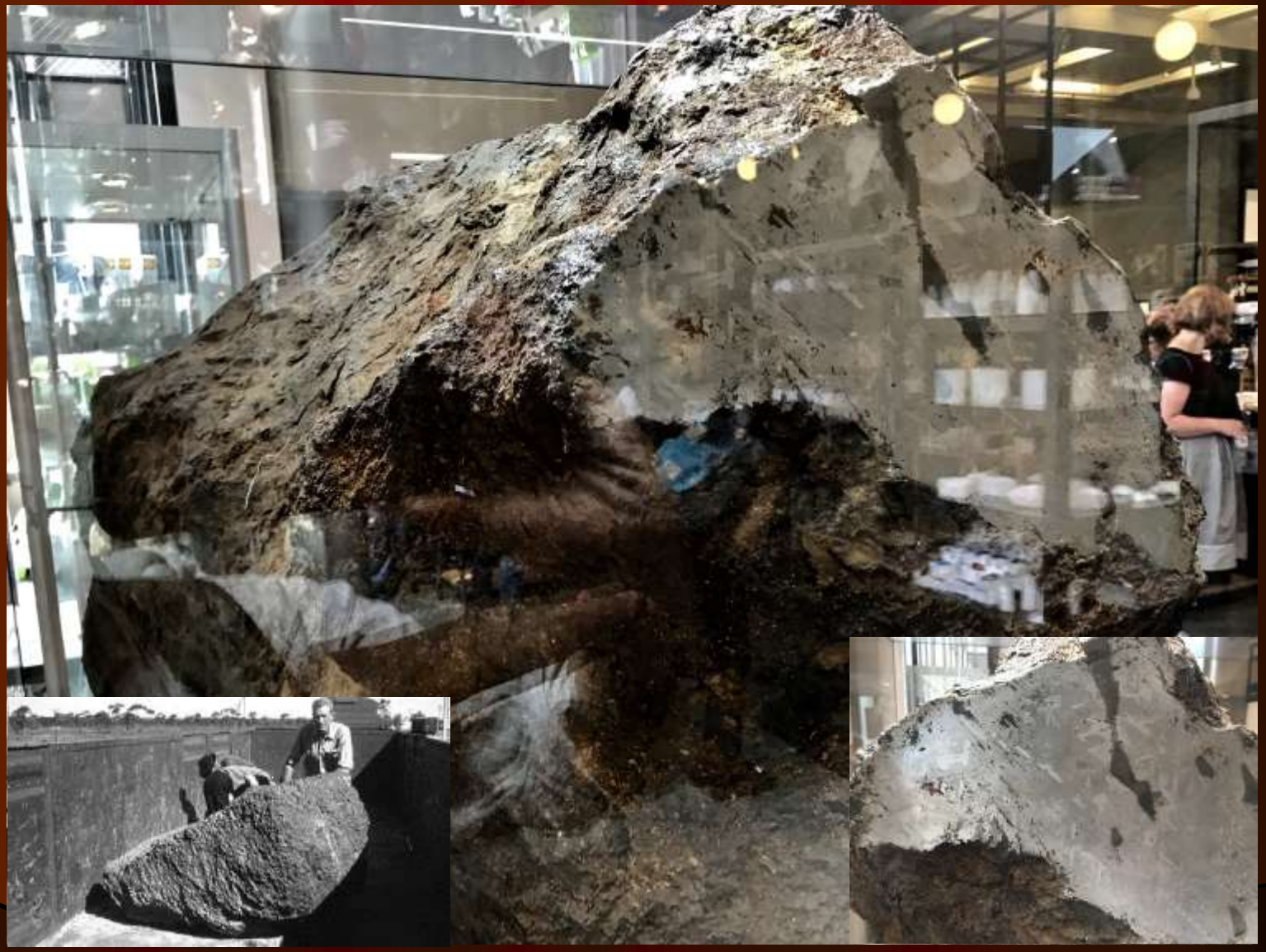
Ataxites (D)
(high Ni content)



Identification can be done by Electron Microscope. Campo del Cielo , Argentina (NHML)



Cranbourne meteorite, an octahedrite meteorite found in Victoria, Australia. When found in 1854 it was the largest known meteorite in the world (NHML)



Henbury, an iron meteorite found in the Northern Territory, Australia, 1931. Note the thumb print like indentations called regmaglypts 指纹氣印 formed by differential ablation 消蝕/消融 whereby the lower melting point inclusions (e.g. troilite FeS) were melted away during its passage through the Earth's atmosphere (NHML)

Many Hexahedrite iron meteorites 六面體鐵隕石 display Neumann Lines or Neumann bands which are indicative of a shock-induced deformation of the kamacite crystal

Octahedrite (O) iron meteorite 八面體鐵隕石 like this one from Sweden when cut, etched with acid and polished displays the Widmanstädter pattern 魏德曼花纹 (Thompson Structure) of interwoven kamacite and taenite which indicate extremely slow process of crystallization

Stony-iron meteorite

Only 2% of fall, rarest. Contains almost equal part of silicates and meteoric iron and all show signs of alteration. 2 main types Pallasites and Mesosiderites

Pallasite

Mesosiderite

Pallasites 橄欖石鐵隕石

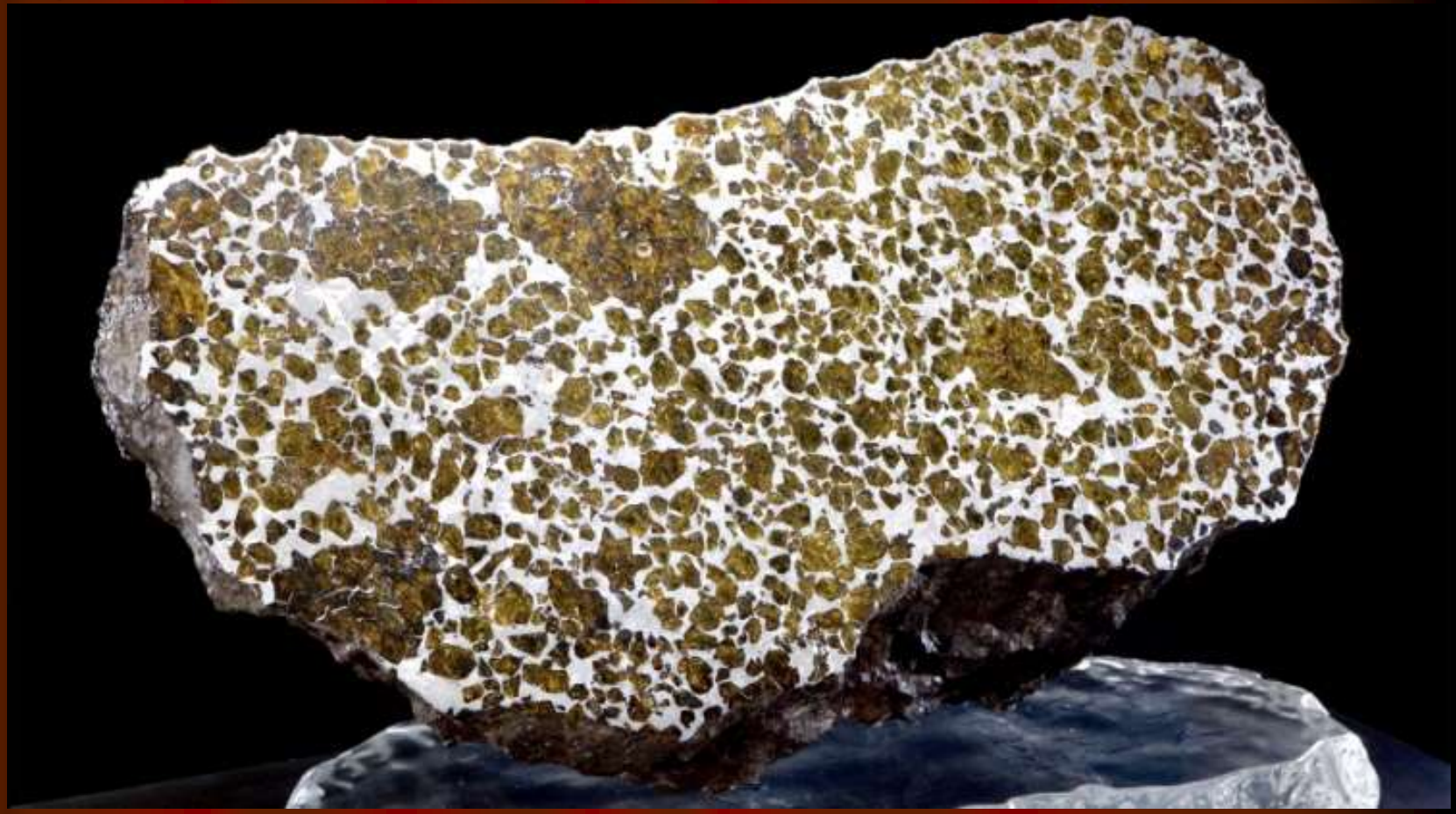
Have about 50:50 mixture of olivine crystals (peridot - a magnesium iron silicate) and iron-nickel base. It is rare and only 93 falls are known today including 10 from Antarctica and others from Japan, Finland, United States, Australia, Australia, Chile and China. Pallasite might have originated from the core-mantle boundary of the asteroid or by impact of core and mantle material i.e. thought to be relics of forming planets

Some olivine crystals in pallasites are of gem quality

Springwater, a stony-iron pallasite found in Saskatchewan, Canada in 1931 (NHM)

This gem filled pallasite dates from the very dawn of our Solar System (NHML)

Discovered in China's Gobi Desert in 2000 and named "Fukang" this 420 kgs pallasite exhibits large and highly refractive translucent golden green olivine crystals unmatched by other pallasites

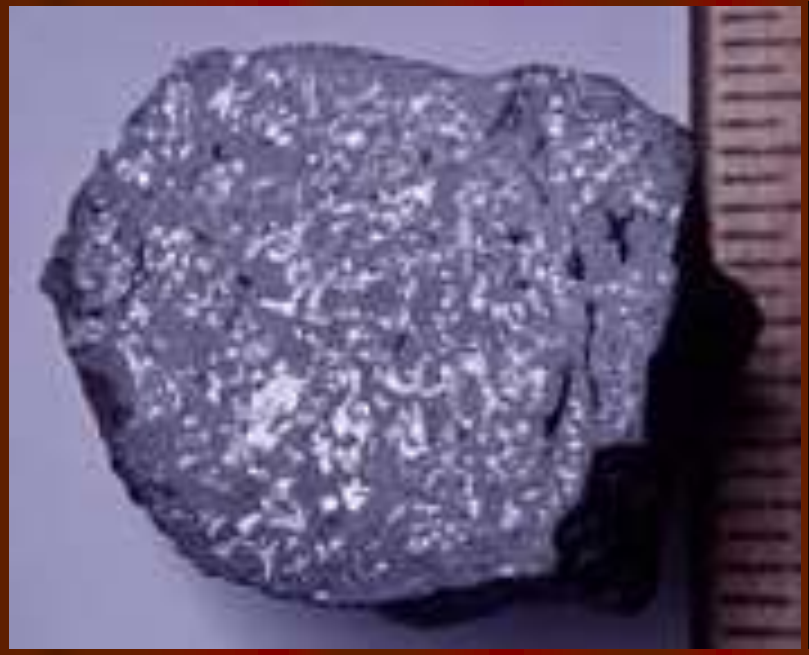


Mesosiderite 中鐵隕石

It is the rarest type of stony-iron meteorite with only 208 specimens being identified to date. They are brecciated with a irregular texture with silicate and metal occur in lumps or pebbles as well as fine grained intergrowths with signs of metamorphism. The sample below is found in Northwest Africa in 2005. It is thought that mesosiderites form when magma mixes with the core during a collision between two asteroids

Vaca muerta mesosiderite

Atacama Desert Chile



Chinguetti mesosiderite

Sahara Desert

- Crab Orchard, a stony-iron mesosiderite found in Tennessee, USA, 1887 (NHM)

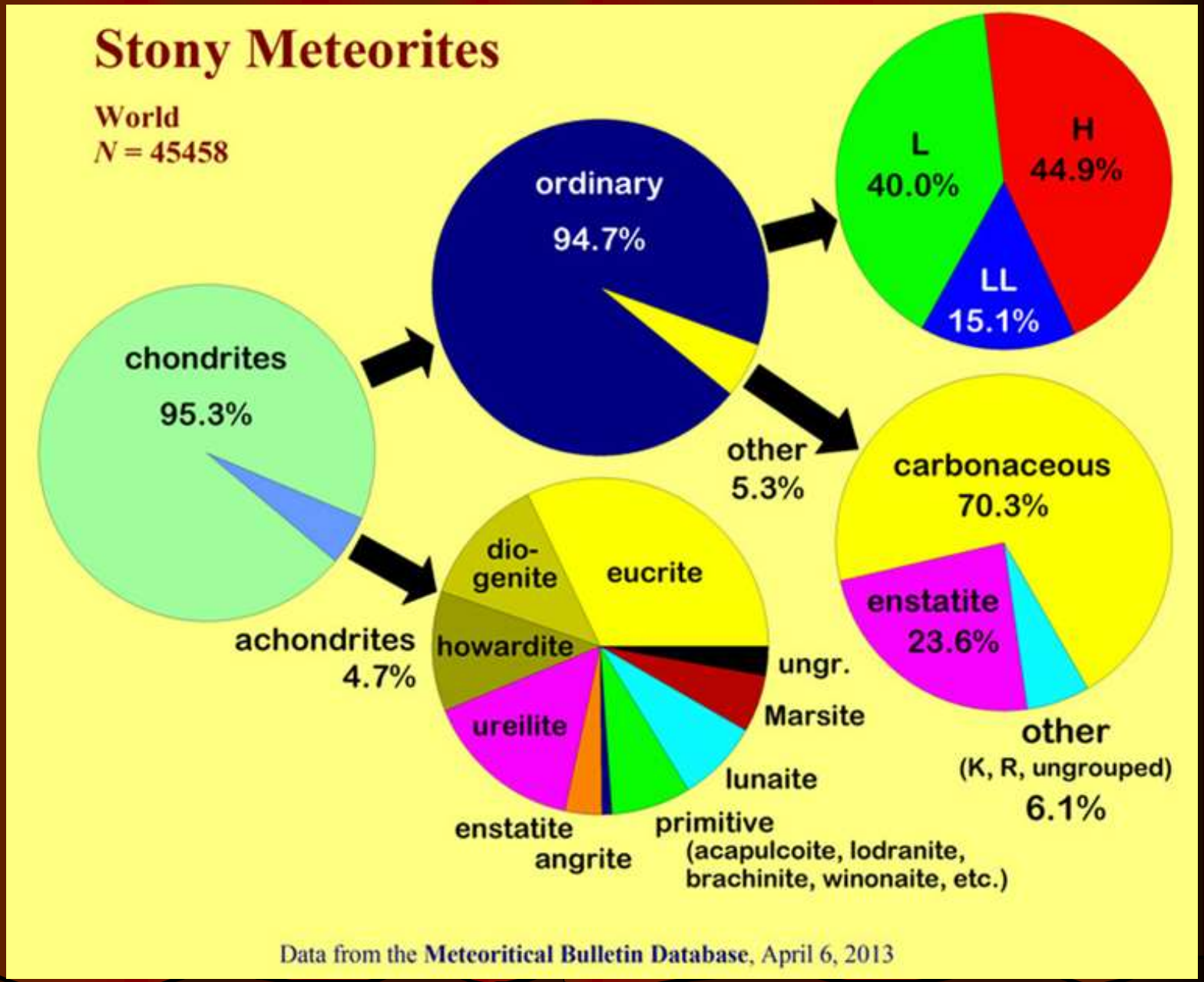
Stony meteorites or chondrites

86%. As stone meteorites are most abundant and still retain the chemical composition of the primordial solar nebula that the solar system originally formed in, their study provides important clues for understanding the origin and age of the Solar System, the synthesis or organic compounds, the origin of life and the presence of water on Earth. So far some 27,000 stone meteorites have been studied and they are divided into 2 main classes :

Chondrites 球粒隕石 (95.3%) undifferentiated material which is characterized by the presence of millimeter sized chondrules being rounded grains formed by partially melted droplets that normally constitute between 20 to 80% of a chondrite. Subdivided into 14 groups



Achondrites 無球粒隕石 (4.7%) which has no chondrule and consist of minerals which have been melted and differentiated from their parent bodies. They are similar to terrestrial basalts and plutonic rocks representing the crust of a differentiated Planetesimal. Much younger than chondrites they are subdivided into 10 groups the biggest of which comes from asteroids similar to Vista. Others are planetary coming from the Moon or Mars


Stony Meteorites
World
N = 45458
chondrites
95.3%
achondrites
4.7%
ordinary
94.7%
other
5.3%
L
40.0%
H
44.9%
LL
15.1%
carbonaceous
70.3%
enstatite
23.6%
other
(K, R, ungrouped)
6.1%
dio-
genite
eucrite
howardite
ureilite
ungr.
Marsite
lunaite
primitive
(acapulcoite, lodranite,
brachinite, winonaite, etc.)
enstatite
angrite
Data from the Meteoritical Bulletin Database, April 6, 2013

Ordinary Chondrite

94.7% of all chondrites. Subdivided into H (High Metal 44.9%), L (Low Metal 40%), LL (Very Low Metal 15.1%). Outside crusted inside brecciated



	H	L	LL
Fall statistics (%)	34	37	9
Fe (wt%)	28	22	19
Fe/Si (atomic)	0.81	0.57	0.52
Metal (vol%)	8.4	4.1	2
Fa content of olivine*	16-20	21-26	27-31
Fs content of pyroxene*	15-17	18-22	22-30
~$\Delta^{17}O$ ** (‰)**	0.7	1.1	1.3
Ol / (Ol + Px)*	51-60	60-67	70-82

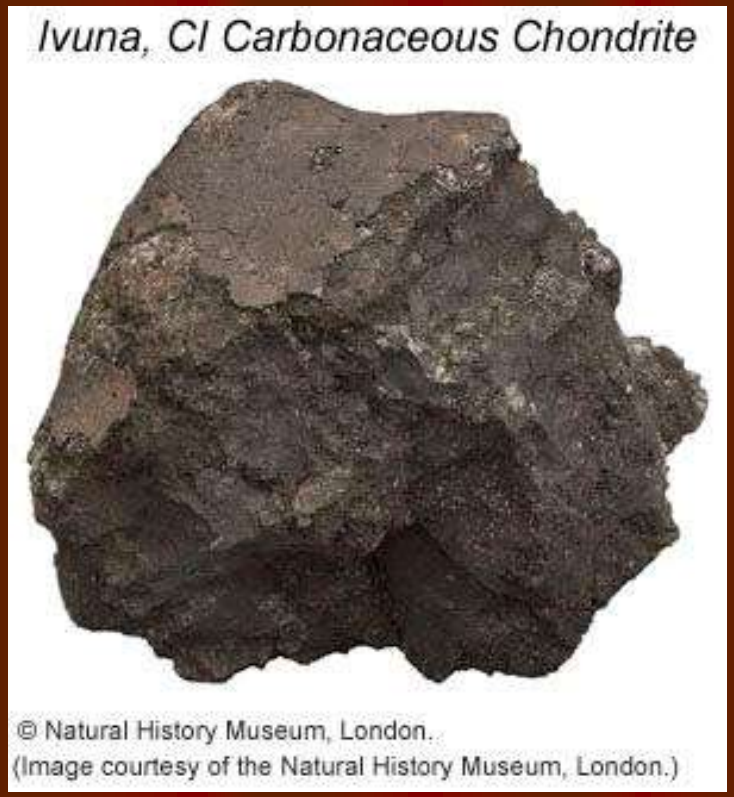
* Olivine (Ol) is $(Fe,Mg)_2SiO_4$; pyroxene (Px) is $(Fe,Mg,Ca)_2Si_2O_6$. Fayalite (Fa) content of olivine and ferrosilite (Fs) content of pyroxene correspond to the relative abundance of Fe atoms compared to other cations: Fe / (Fe + Mg) and Fe / (Fe + Mg + Ca) respectively. Ol / (Ol + Px) values are after *Vernazza et al.* (2008) and after *Dunn et al.* (2010). The properties listed above are those of equilibrated (metamorphosed) ordinary chondrites. Fa content of olivine and Fs content of pyroxenes are highly variable in unequilibrated chondrites.

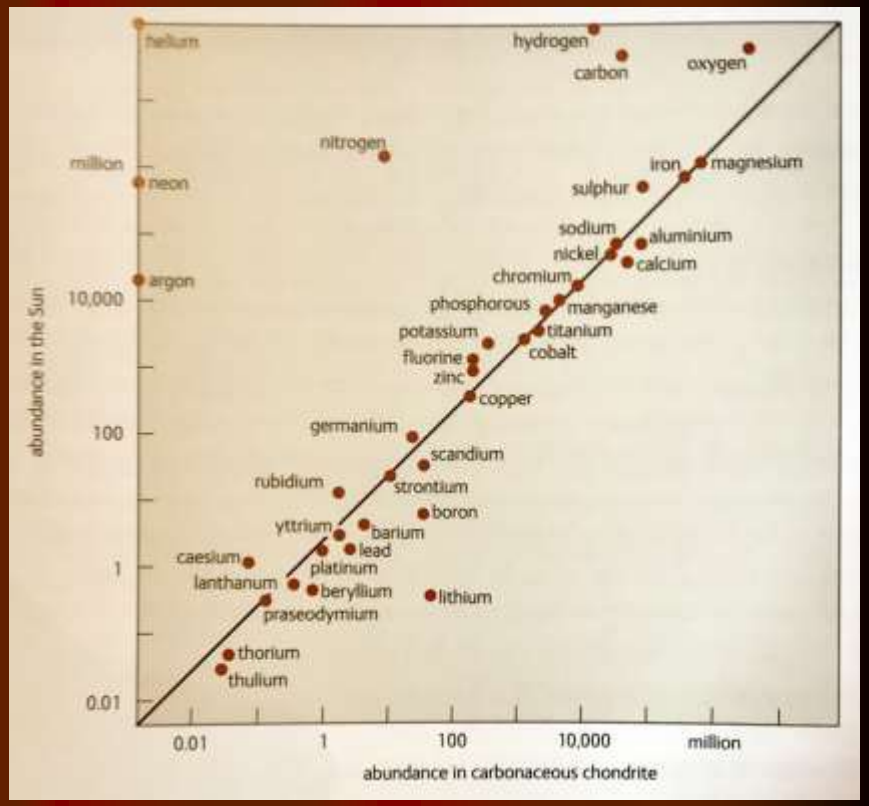
**$\Delta^{17}O$ measures the distance to the terrestrial fractionation line in the oxygen 3-isotope plot. It is defined as $\Delta^{17}O = \partial^{17}O - 0.52 \times \partial^{18}O$, where $\partial^{17}O$ and $\partial^{18}O$ measure respectively the excess of ^{17}O and ^{18}O with respect to ^{16}O and to a standard (Standard Mean Ocean Water), multiplied by 1000.

- LL4 chondrite meteorites are among the most primitive and unaltered remnants of the Proto-Solar System dated 4.565 billion years old during the formation of our Solar System. This specimen shows large clearly defined chondrules in dark green and orange – red color on an orange matrix

Carbonaceous Chondrite 碳質球粒隕石（C Chondrite）

At 4.6% of all chondrites they are characterized by the presence of carbon compounds including amino acids. Except for gases such as hydrogen and helium, their chemical composition and that of the sun is very similar e.g. on Ivuna meteorite found in Tanzania





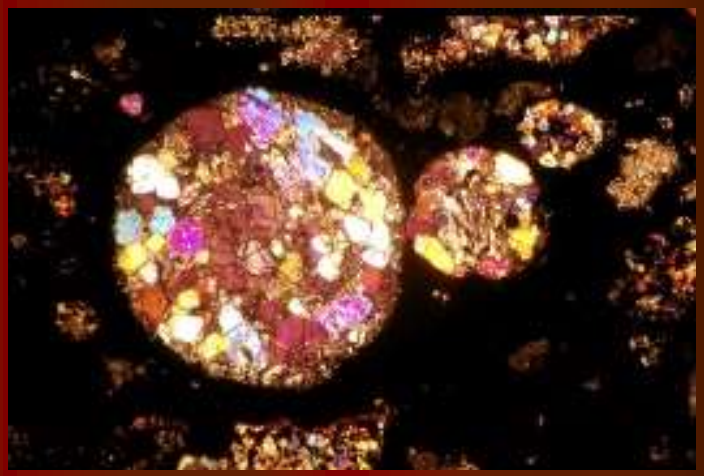
- Meteoric diamond – about 3 percent of the carbon in meteorite is in the form of Nano diamond with size below one micrometer (NHM)

Diamonds from star dust

Cold Bokkeveld, stony meteorite (CM2 chondrite).
Fell 1838, Cold Bokkeveld, South Africa.

If you look carefully in the bottom of this little tube you can see a white smudge of powder. This smudge is made up of millions of microscopic diamonds. These are the oldest things you will ever see. They formed in the dust around dying stars billions of years ago, before our solar system existed. The diamonds dispersed in space and eventually became part of the material that formed our solar system. Ultimately, some of them fell to Earth in meteorites, like the ones you see here.

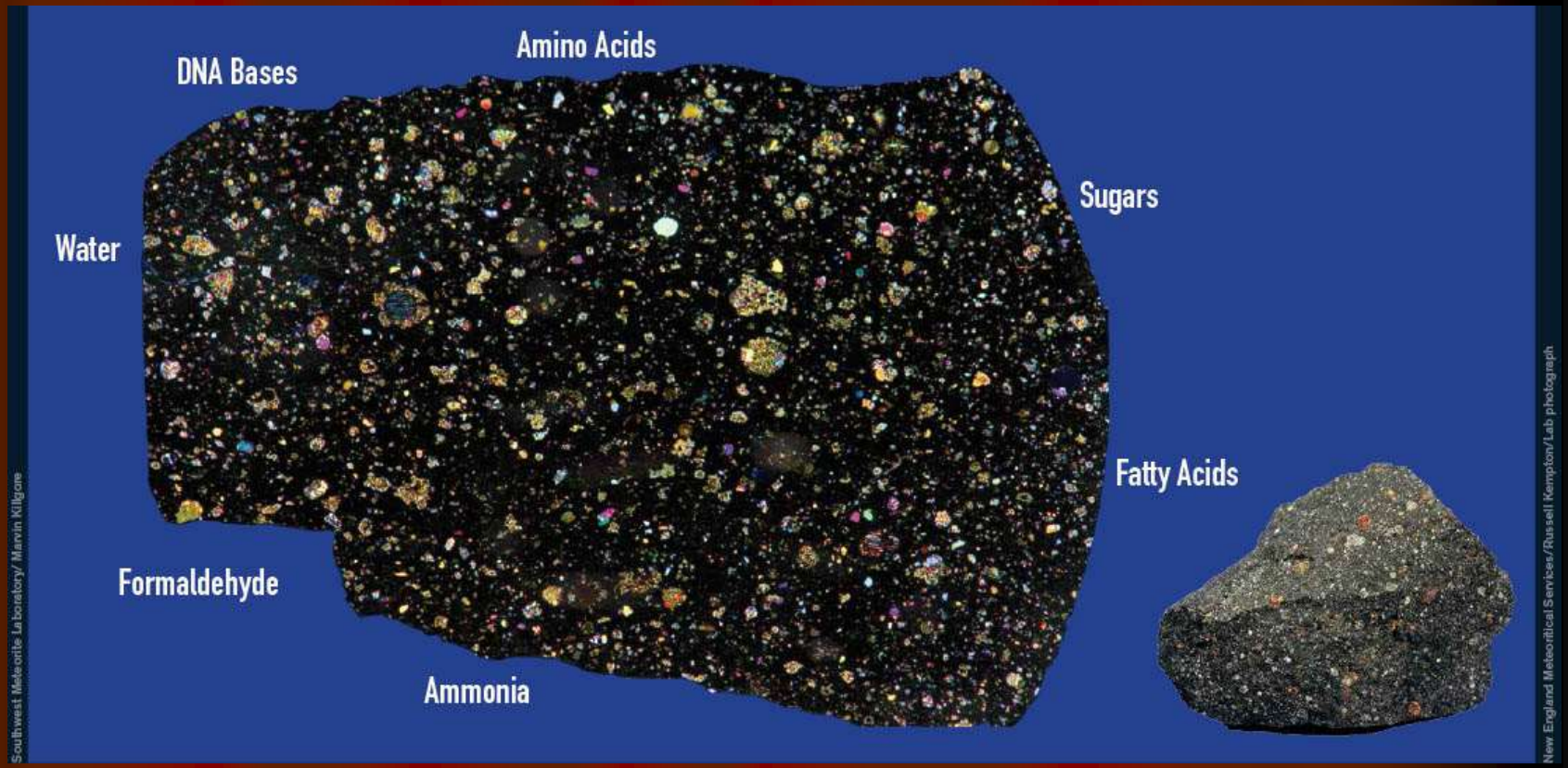
- Allende 5846 is a carbonaceous chondrite which fell in Chihuahua, New Mexico in 1969. The meteorite is diamond bearing !



Enstatite chondrite (E chondrite)

It is a chondrite high in enstatite (MgSio3). Only 200 are currently known and mainly found in Antarctica and the Sahara Desert

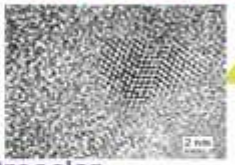
Murchison meteorite : Found in Victoria, Australia, it is a more than 4.55 By carbonaceous chondrite which contains primitive minerals condensed from the solar nebula, water and complex organic molecules including more than 70 kinds of amino acids



The Murchison Meteorite – A "Messenger from Space"

Amino Acids	17-60 ppm
Aliphatic Hydrocarbons	>35 ppm
Aromatic Hydrocarbons	3319 ppm
Fullerenes	>100 ppm
Carboxylic Acids	>300 ppm
Hydrocarboxylic Acids	15 ppm
Purines and Pyrimidines	1.3 ppm
Alcohols	11 ppm
Sulphonic Acids	68 ppm
Phosphonic Acids	2

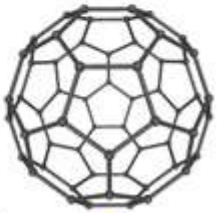
Fall Date is 28 September 1969
100 kg known weight
36°37′ S, 145° 12′ E



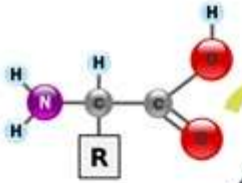
Presolar Nanodiamonds

Type Chondrite
Class Carbonaceous Chondrite
Group CM2

Over 100 amino acids have been identified, some of which are the basic components of Life.



Composition
22.13% total iron
12% water



CM chondrites, together with the CI group, are rich in carbon and are among the most chemically primitive meteorites in our collections.

CI1 aka C1 chondrites

A very rare type of unmelted stony carbonaceous meteorite have characteristics that suggest they may have originated from comet. Only nine are known representing <0.03% of all known meteorites

Achondrites

Eucrite chondrite is an achondrite believed to be from the 4 Vesta asteroid. Only 100 found so far



Dio-genite is believed to originate far deep within the crust of the asteroid 4 Vesta. Only 40 samples are found


Ureilite : technical name olivine - pigeonite achondrite is a rare type of stony meteorite with unknown origin but contained Nano diamonds of only a few micrometres in diameter



Rumuruti chondrite : a new chondrite recently identified. Breccias containing a variety of different clasts embedded in a clastic matrix. Only 107 pieces found in Australia



Acapulcoites

a group of the primitive achondrite class of stony meteorites

Angrite

Aubrite

Different Asteroid & Meteorite Types

Source: Smithsonian Museum of Natural History http://www.mnh.si.edu/earth/text/5_1_4_0.html

Chondritic Stony Meteorite

Iron Meteorite

Pallasite Meteorite

Achondritic Stony Meteorite

Asteroid Type C

Asteroid Type M

Asteroid Type S

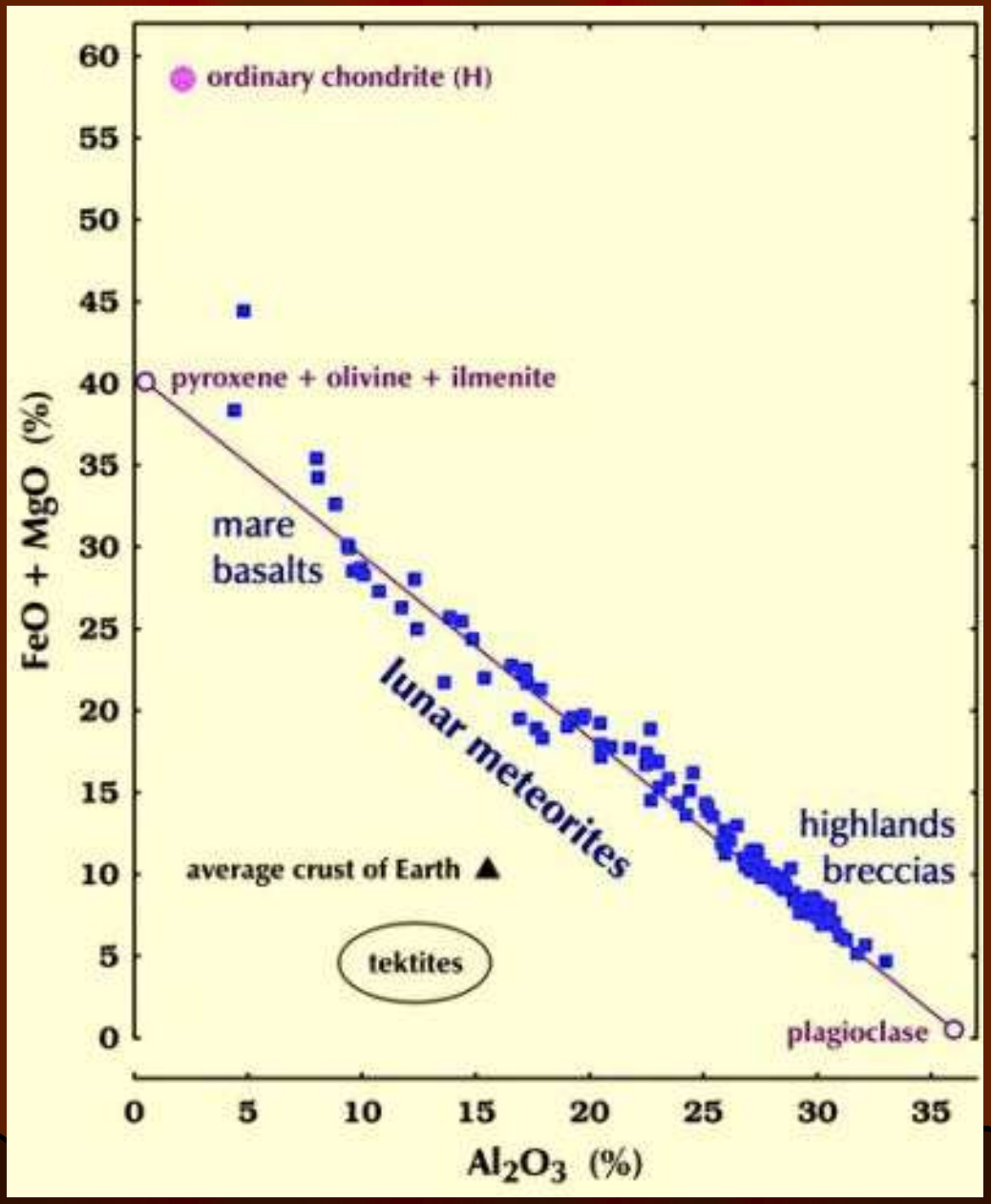
Planetary Meteorites

Most planetary meteorites including those originated from the Moon, Mars and Mercury are achondrites launched by the impact of an asteroid or comet, go into orbit around the Earth and finally succumb to its gravity and landed on Earth. It is worth pointing out that similar process could have launched some very old Earth rocks to the Moon as well !

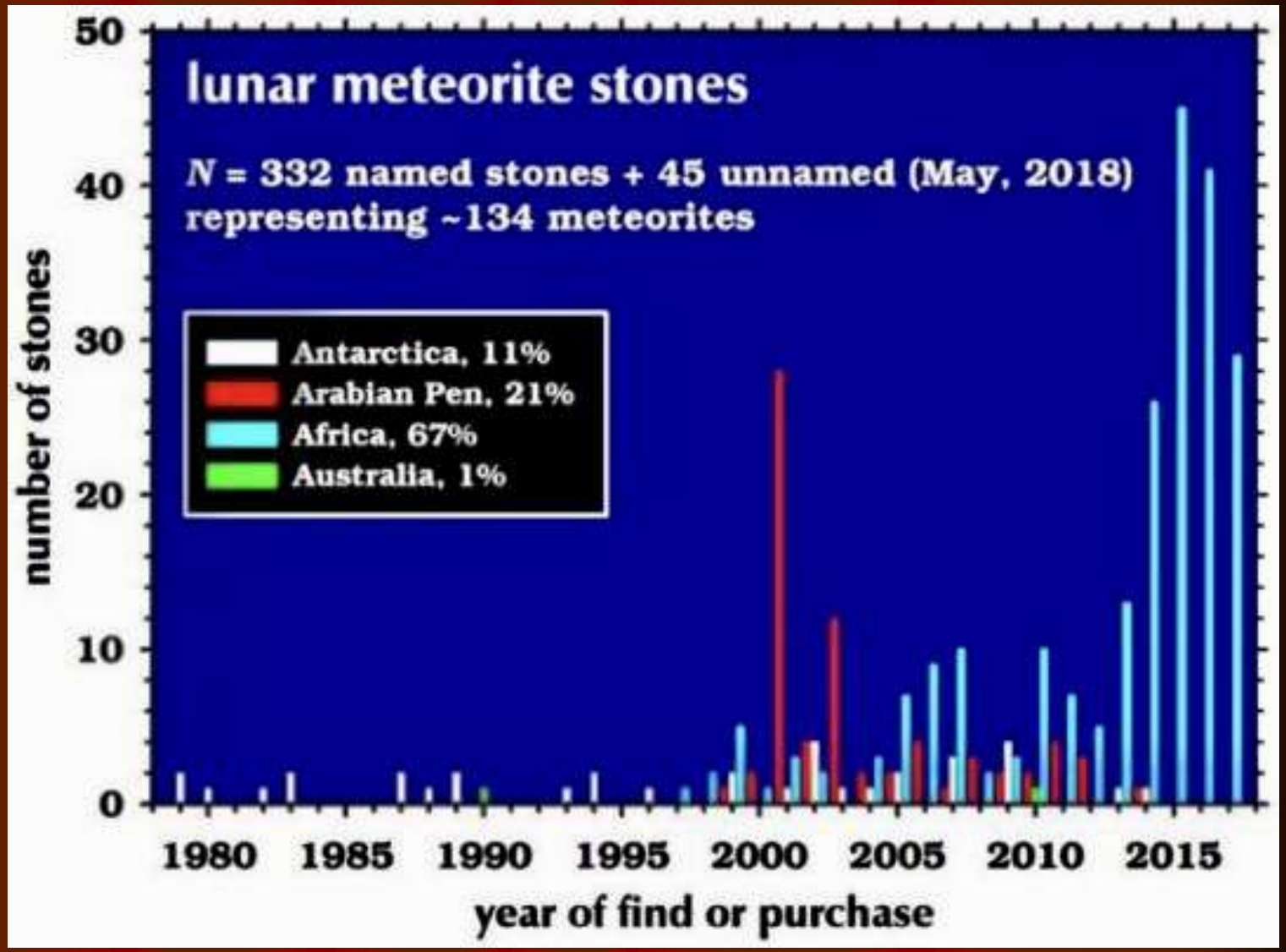
Lunar Meteorite or Lunaites

- These are basaltic rock ejected from the Moon by the impact of asteroid proven by comparing with Apollo project samples. Cosmic-ray exposure history have shown that all lunar meteorites were ejected from the moon in the last 20 million years with most left the moon in the past 100,000 years. There are altogether 134 specimens with a total weight of 90 kilogram subdivided into LUN A (highland breccia), LUN B (Lunar mare basalt) and LUN M (mixed)

Composition of Lunar meteorite



Size/number ratio & locations of finds



Dar al Gani 400, a stony lunaite (achondrite) found 1998 in Libya. This piece of moon rock was sent hurtling to Earth when a larges object hit the moon and landed on Earth after a journey of 400,000 km !

This rare lunarite is a regolith breccia made of shock-welded lunar soil composed of fragments of many different kinds of rock and minerals including fine grains and powders

Weighing 11.53 kg this large slice of NWA5000 is the largest known lunar meteorite (achondrite) found in the Sahara Desert in Morocco in 2007

Exhibited in the Space Museum in Hong Kong NWA 11474 is a lunar meteorite (achondrite) found in the northwest Africa in 2007

Take a Look at a Lunar Meteorite

它是一顆編號為NWA 11474的月球隕石，在2017年於非洲西北部被發現。

當隕石撞擊月面，有些岩石拋射至地球，受到地球引力吸引，穿過大氣層，跌落地面形成月球隕石。

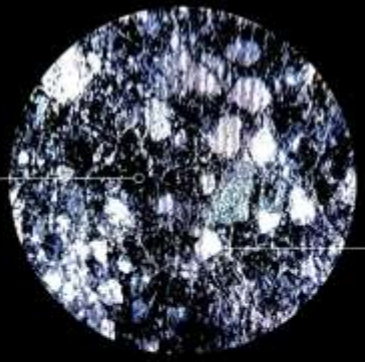
Here is a piece of lunar meteorite, NWA 11474. It was discovered in northwest Africa in 2017.

When meteorites hit the lunar surface, some rocks were ejected to the Earth. They were attracted by the Earth's gravity, passed through the atmosphere, fell to the ground and became lunar meteorites.

分類 Classification	月球隕石 Lunar meteorite（長石角礫岩 feldspathic breccia）
質量 Mass（克 g）	1.86
氧化亞鐵的重量百分濃度 Weight percent of iron oxide (FeO)	4.2 ± 1.3 %
氧化鎂的重量百分濃度 Weight percent of magnesium oxide (MgO)	5.7 ± 1.4 %
氧化鋁的重量百分濃度 Weight percent of aluminium oxide (Al_2O_3)	27.5 ± 1.1 %

從顯微鏡觀察，你看見什麼？ What can you see under the microscope?

這顆月球隕石樣本含有熔融玻璃和白色長石碎屑。長石是地球和月球地殼中常見的礦物，含豐富的鋁、鈣和少量的鐵。



放大倍數 Magnification 20x

Pieces of melt glass and white feldspathic clasts can be found from this lunar meteorite sample. Feldspar is a common mineral that can be founded in Earth and lunar crust. Feldspar is rich in aluminum, calcium and limited iron.

為什麼它是月球隕石？ Why is it a lunar meteorite?

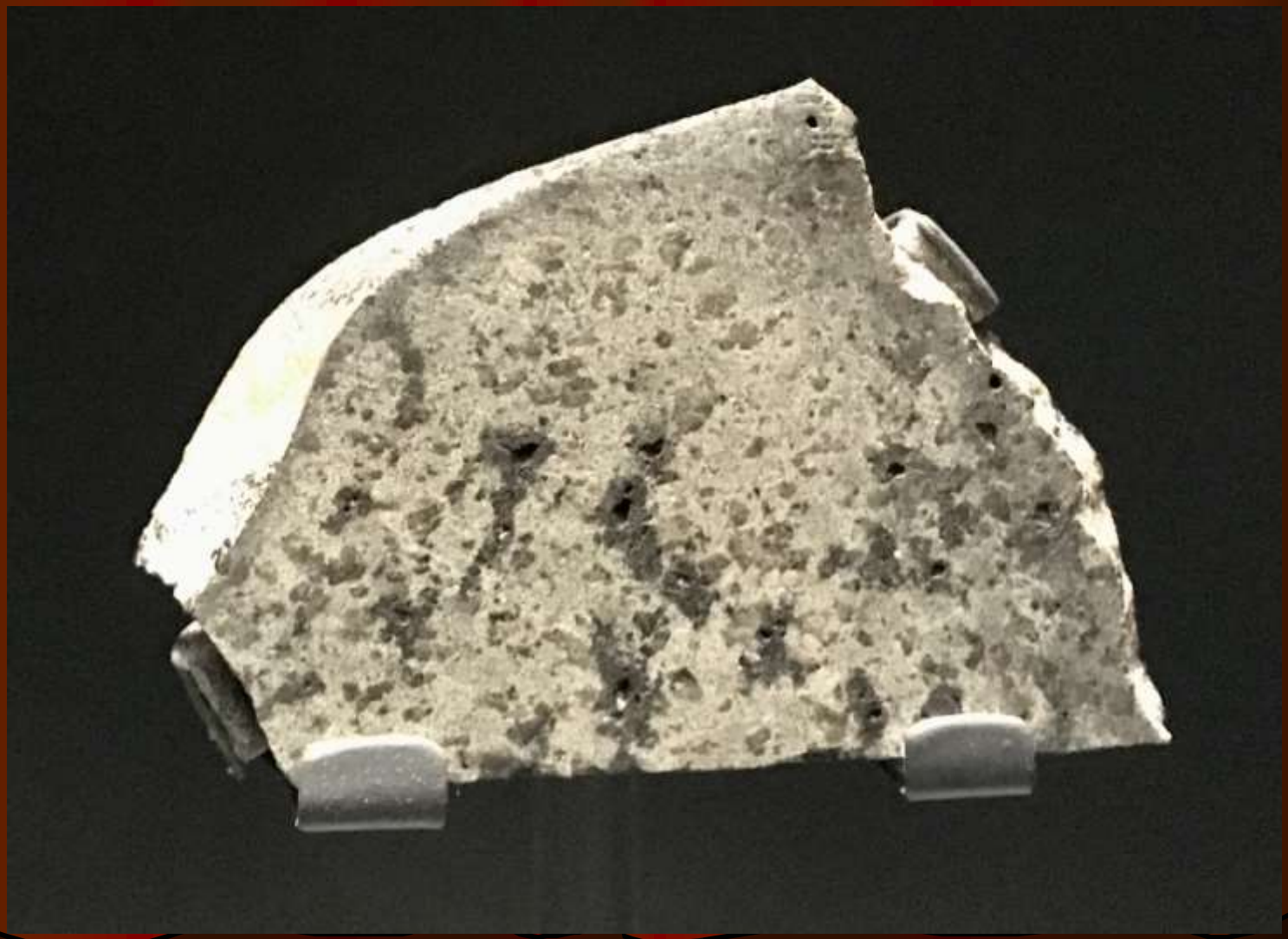
這顆隕石來自月球，是因為隕石內的元素，例如鐵(Fe)、鎂(Mg)和鋁(Al)含量，與阿波羅月球岩石樣本和繞月衛星獲得的數據元素含量相符。

The meteorite is identified as being lunar because its abundances of some elements, for examples, iron (Fe), magnesium (Mg) and aluminium (Al), matches with those measured by analyses of Apollo samples and lunar remote sensing.

Martian Meteorite / Marsite

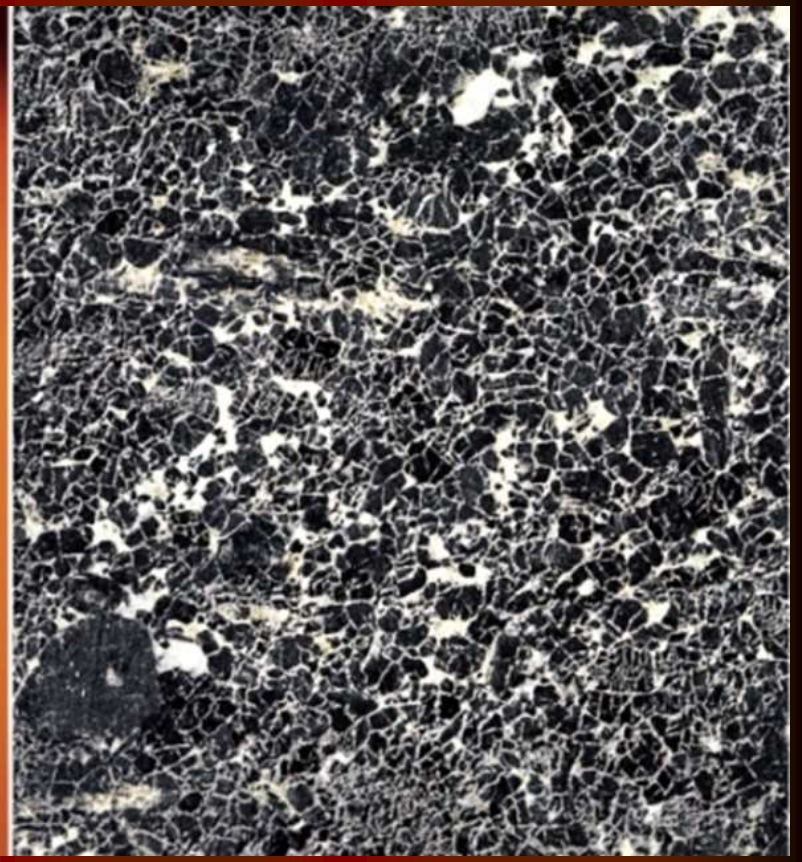
- These are rocks ejected from Mars by the impact of asteroid. There are only 224 known Martian meteorites as of 2019

Shargottite Sayh al Uhaymir 008 is a slice from a meteorite that was blast off Mars by the impact of an asteroid or comet about 800,000 years ago. It was found in yhr Al Wista, Oman in 1999 (BM2000 M39)



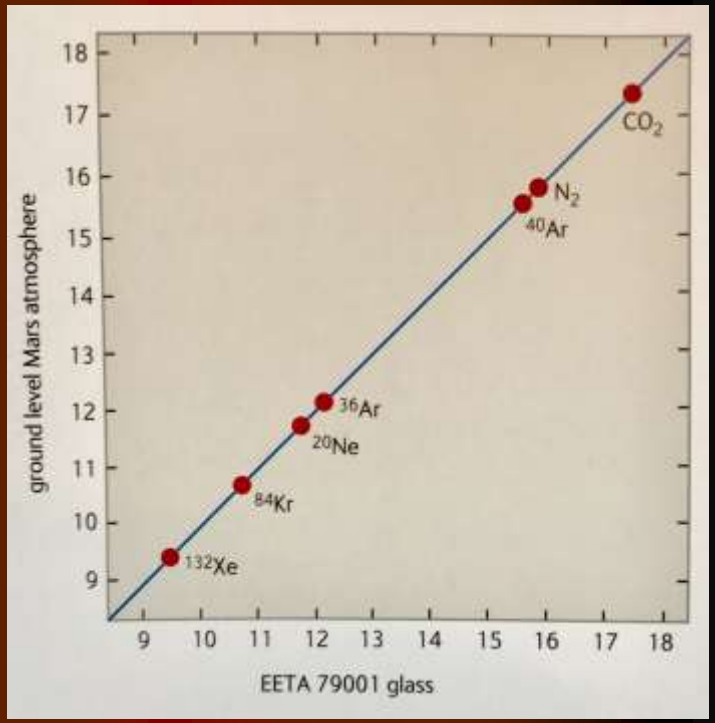
Known as NWA7034, this one below nicknamed "Black Beauty" which landed in the Sahara Desert is around 4.2 billion years old and water-rich

Found in Morocco the Martian Dunite below is the rarest. The predominant olivine appeared to be almost black. It also contains a new type of mineral unknown to science



Nakhl is an achondrite fell 1911 at Abu Hommos Egypt. It was thrown off Mars about 11 million years ago. We know it is from Mars by comparing its chemistry to information collected by space probes that have been there (NHM)

EET A79001 the large Martian Achondrite Meteorite below contains inclusion of black glass in which pockets of Mar's atmosphere are trapped ! Tests confirmed it was the same as those found in Mars by the Viking landing measurement in 1976



- A slide of another Martian meteorite discovered in Dar al Gani, Sahara Desert, Libya. This spinach-green matrix is interspersed with large black olivine phenocrysts

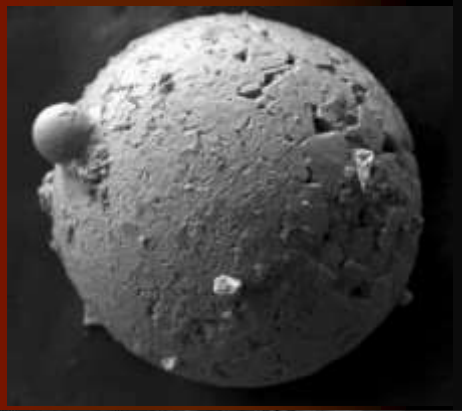
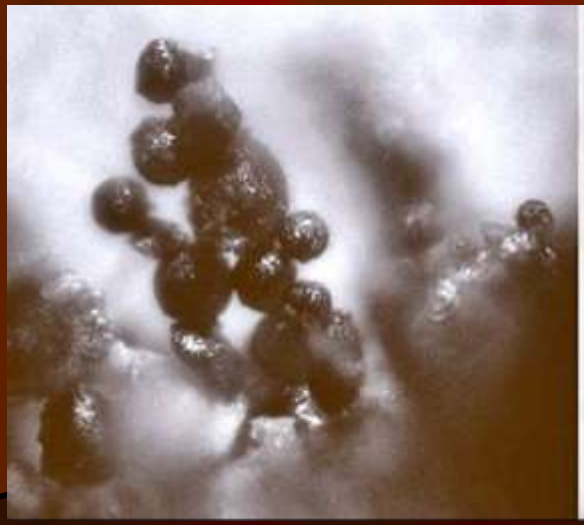
Meteorite from Mercury

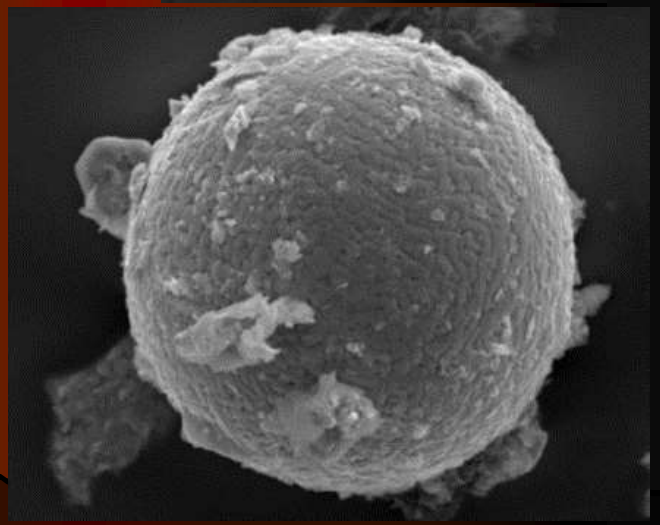
- This angrite or achondrite meteorite found in the Sahara Desert may have come from the planet Mercury. Basaltic it contains large grains of pink-purple anorthite, shocked black olivine and ruby-red spinel in a fine grained matrix

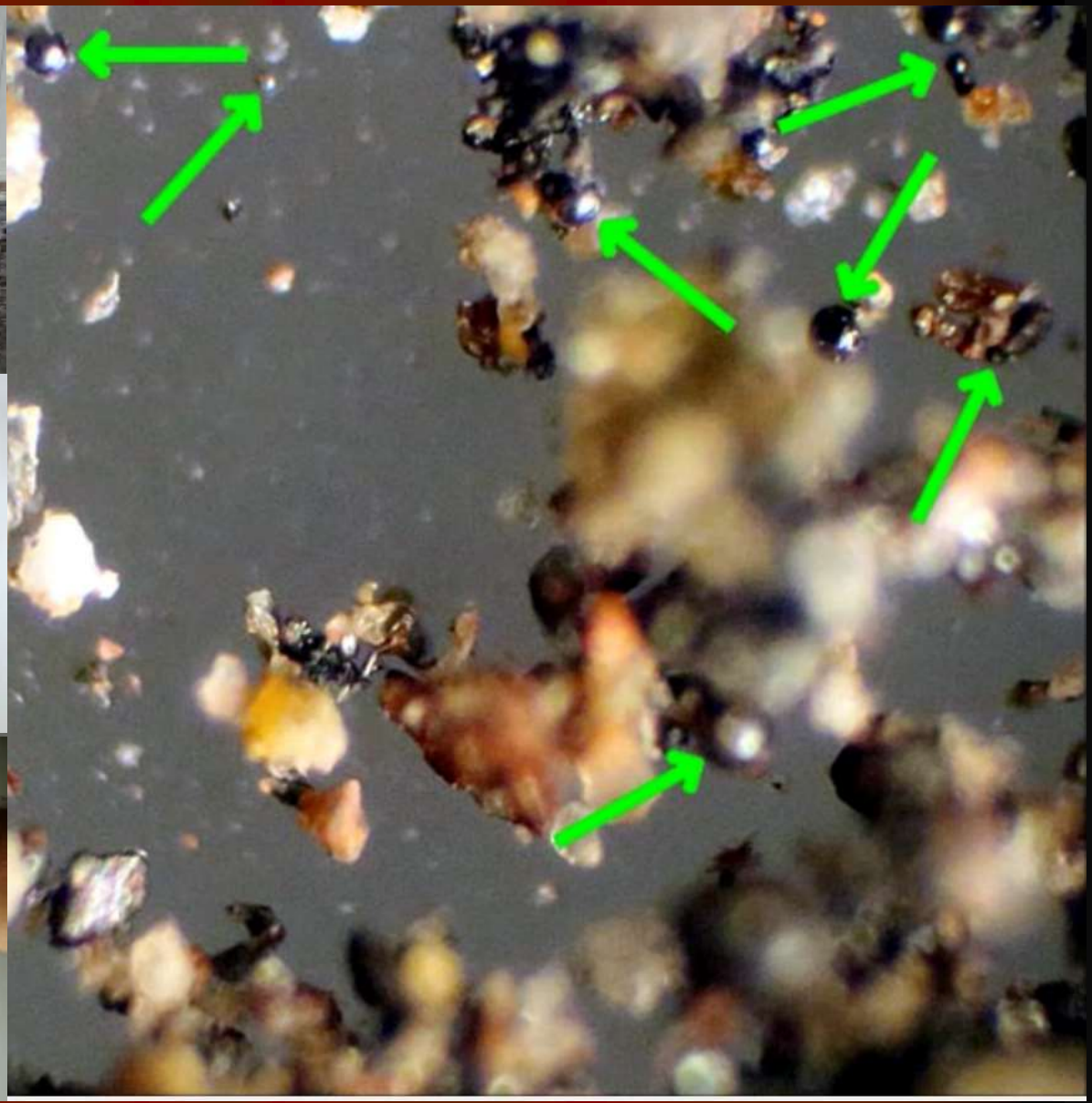
Micrometeorite 微隕石

- Micrometeorite or MM are micrometeoroid that survived entry through Earth's atmosphere. About 15,000 tons collides with Earth every day with their size ranges from 50 um to 2 mm. Fewer than 1% of MMs are achondrites and more are similar to carbonaceous chondrite which some scientists suggested they might originate from comets. About 80% is magnetic due to the presence of iron and nickel





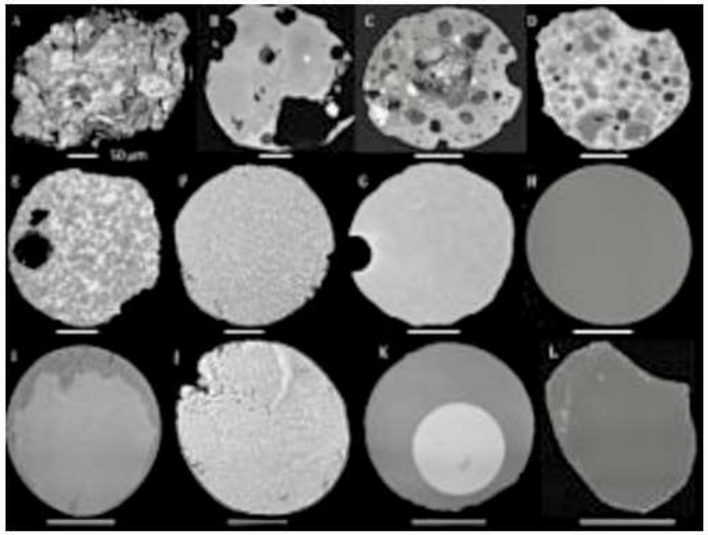


Figure 1. Cross sections of different micrometeorite classes: a) Fine-grained unmelted; b) Coarse-grained Unmelted; c) Scoriaceous; d) Relict-grain Bearing; e) Porphyritic; f) Barred olivine; g) Cryptocrystalline; h) Glass; i) CAT; j) G-type; k) I-type; and l) Single mineral. Except for G- and I-types all are silicate rich, called stony MMs. Scale bars are 50µm.

GLASS MICROMETEORITES

73

440

349

421

375

380

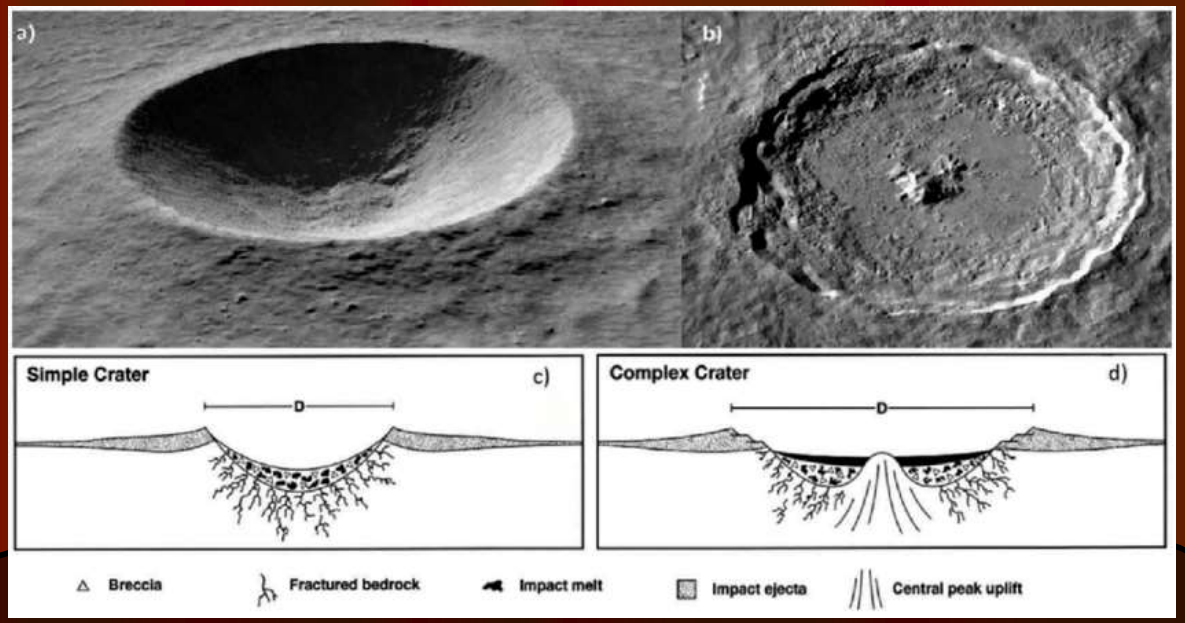
Other Evidence of Impact

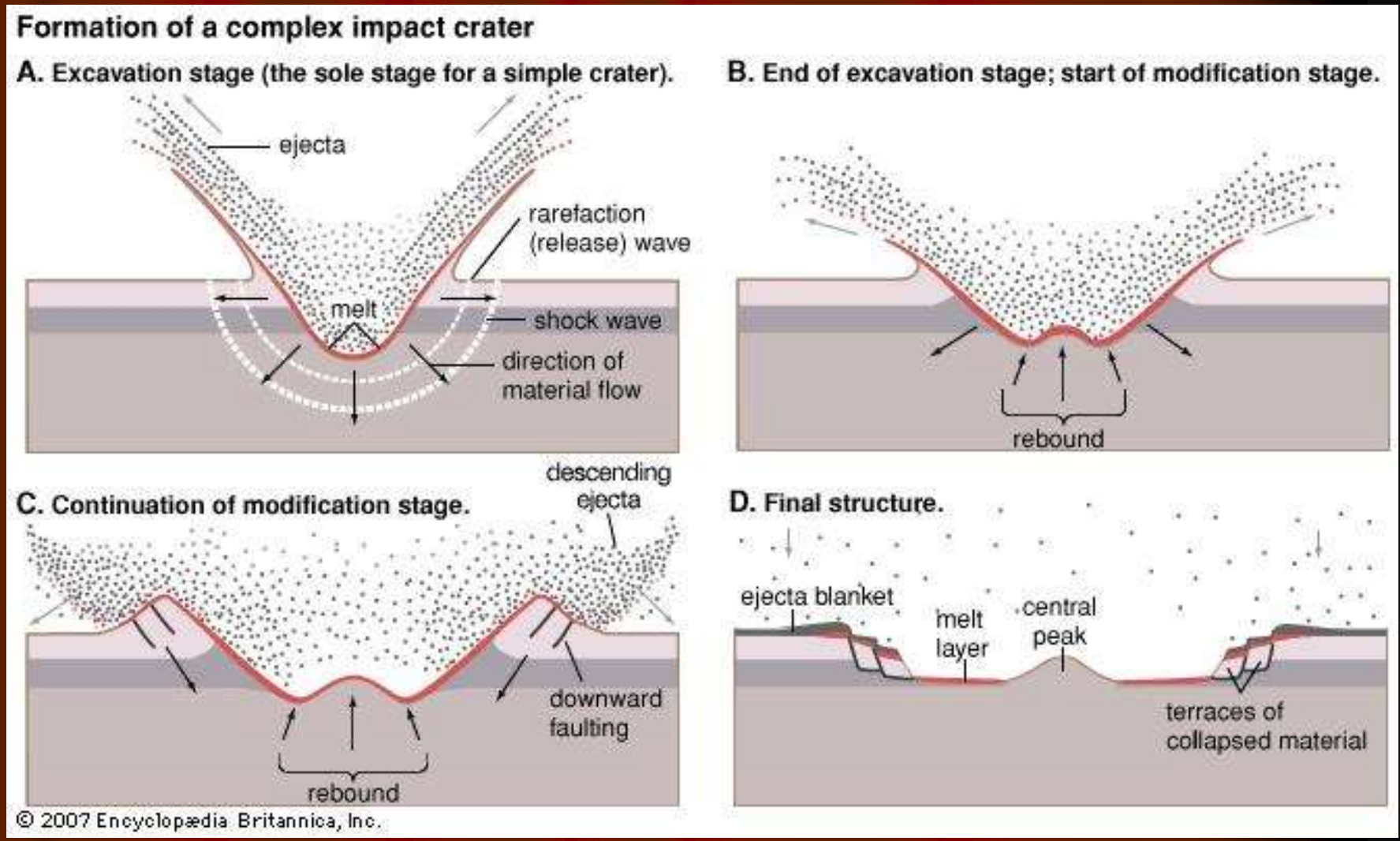
Evidence of Meteor Impact

Apart from the meteorites, other evidence of meteorite impact includes the Impact Craters, shocked quartz, shatter cones and tektites

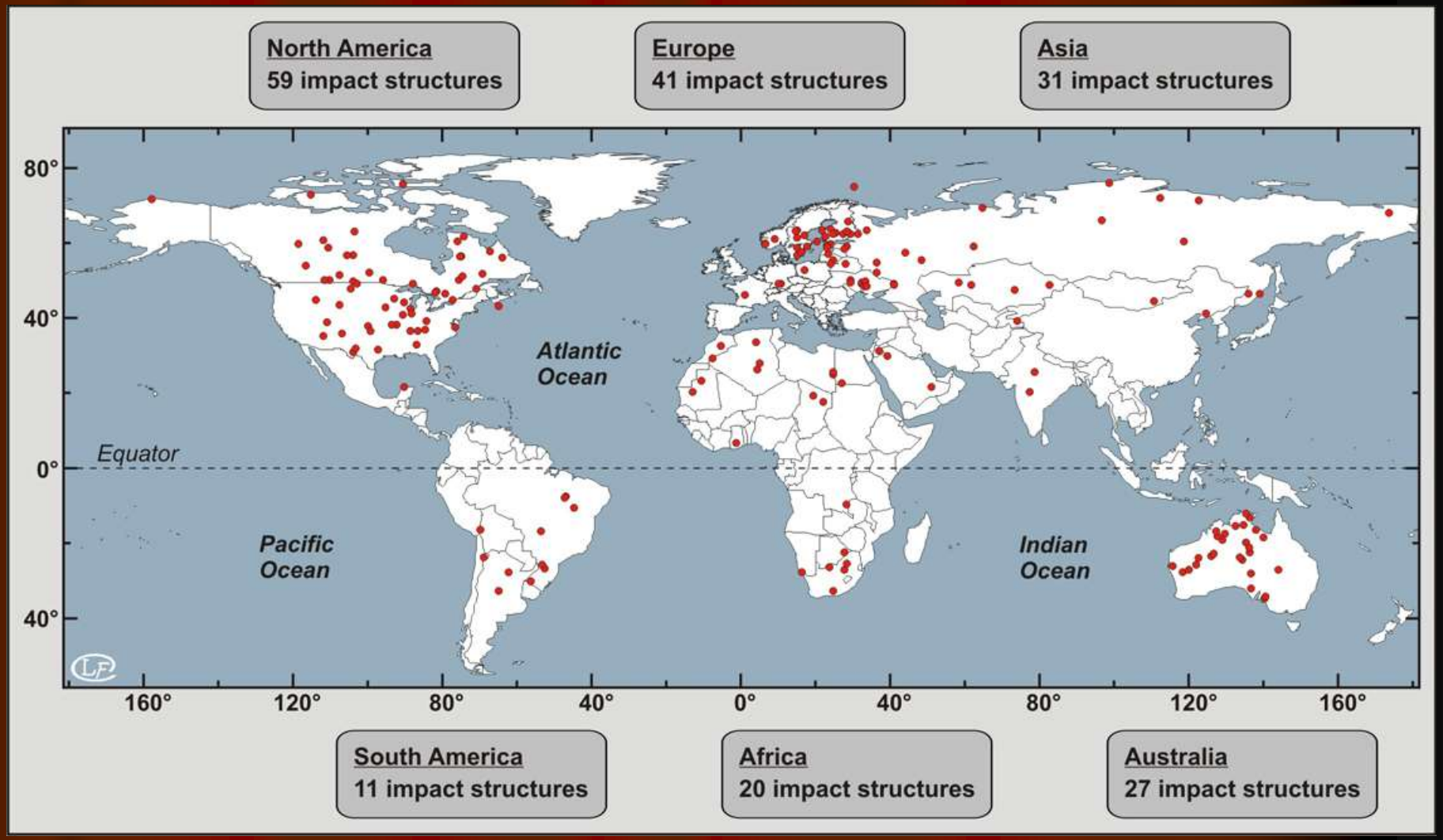
Impact Craters 隕石坑

- Meteorites are sometimes but not always found in association with impact craters which are depressions formed by hyper velocity impact of asteroids. Craters can be classified into simple and complex types. The former occur as bowl-shaped depressions with raised rims above the surrounding terrain. The latter typically display a central peak uplift and multi-ring basins

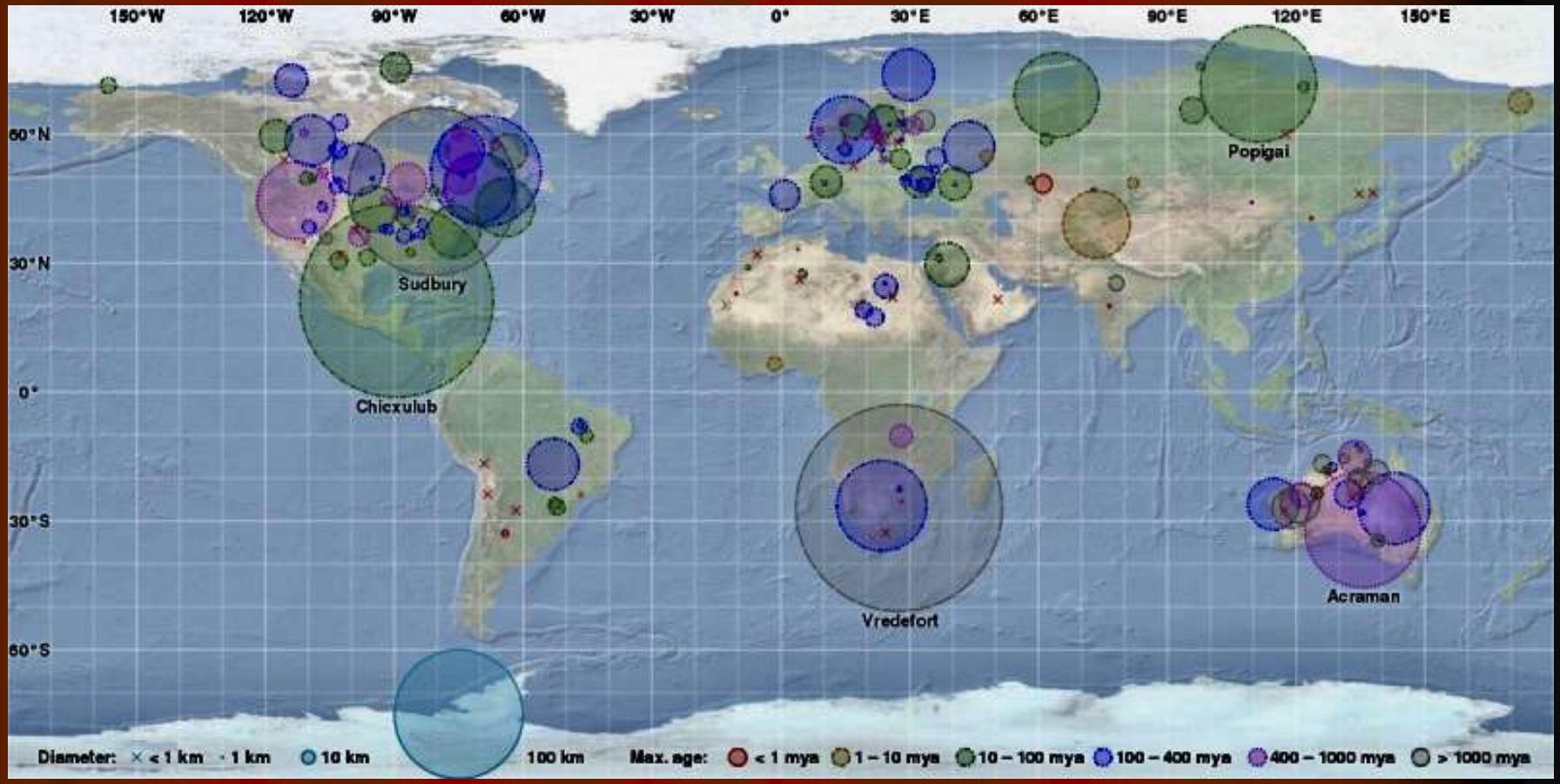



Formation of a complex impact crater
A. Excavation stage (the sole stage for a simple crater).
ejecta
rarefaction (release) wave
melt
shock wave
direction of material flow
B. End of excavation stage; start of modification stage.
rebound
C. Continuation of modification stage.
descending ejecta
downward faulting
rebound
D. Final structure.
ejecta blanket
melt layer
central peak
terraces of collapsed material
© 2007 Encyclopædia Britannica, Inc.

Global distribution of 189 meteorite impact structures identified

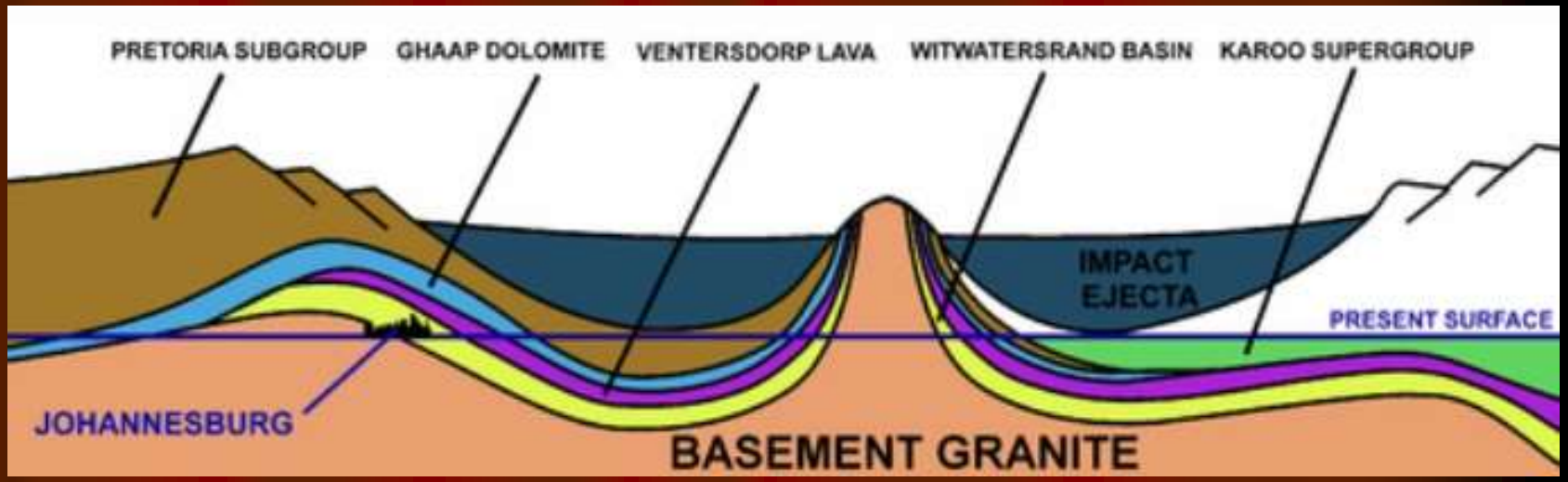


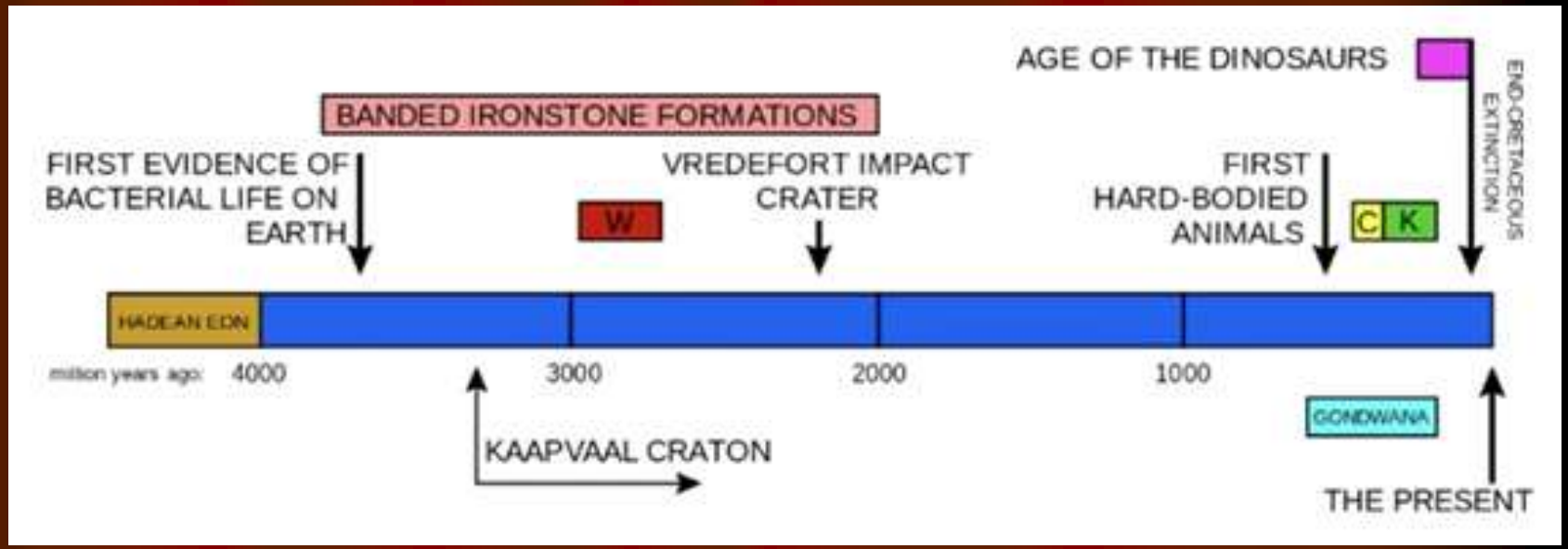
Impact craters vary in age as well as size from a few km to 240 km in diameter



Vredefort crater

Located in Free State Province South Africa, it is the largest verified impact crater on Earth. It was more than 300 km across when it was formed 2.023 billion years ago


PRETORIA SUBGROUP
GHAAP DOLOMITE
VENTERSDORP LAVA
WITWATERSRAND BASIN
KAROO SUPERGROUP
IMPACT EJECTA
PRESENT SURFACE
JOHANNESBURG
BASEMENT GRANITE

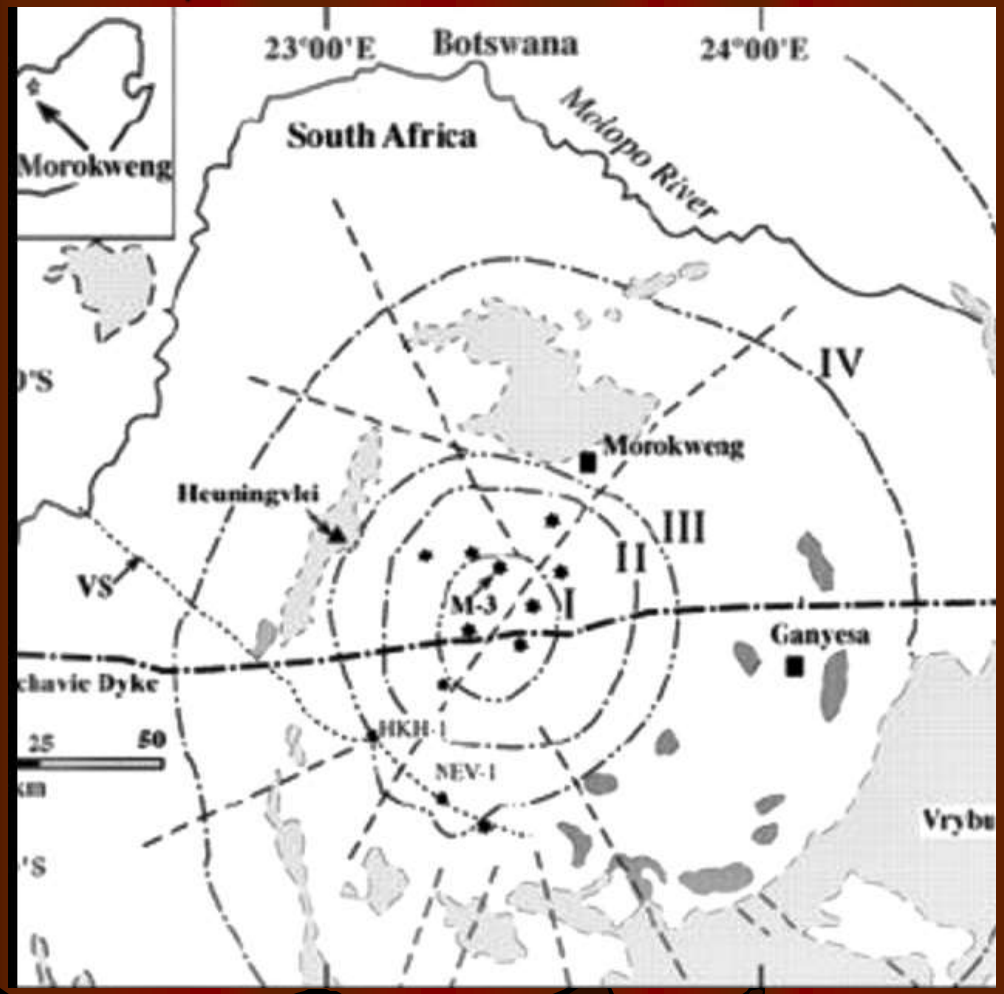

AGE OF THE DINOSAURS
END-CRETACEOUS EXTINCTION
BANDED IRONSTONE FORMATIONS
FIRST EVIDENCE OF BACTERIAL LIFE ON EARTH
VREDEFORT IMPACT CRATER
FIRST HARD-BODIED ANIMALS
W
C K
HADEAN EON
million years ago: 4000
3000
2000
1000
GONDWANA
KAAPVAAL CRATON
THE PRESENT

Lake Manicouagan crater

This structure in Quebec Canada was created 214 my by the impact of a meteorite of 5 km diameter. With a volume of 138 km3 the lake is also called the "eye of Quebec"

Morokweng Crater

- Formed 145 million years ago it is an impact crater 70 km in diameter buried beneath the Kalahari Desert near the town of Morokweng in South Africa's North West province

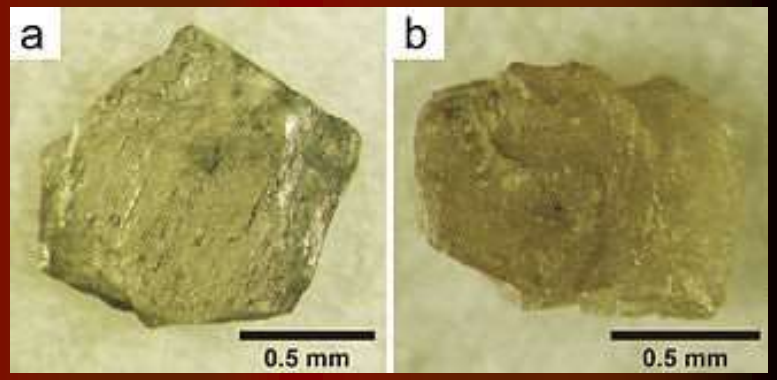


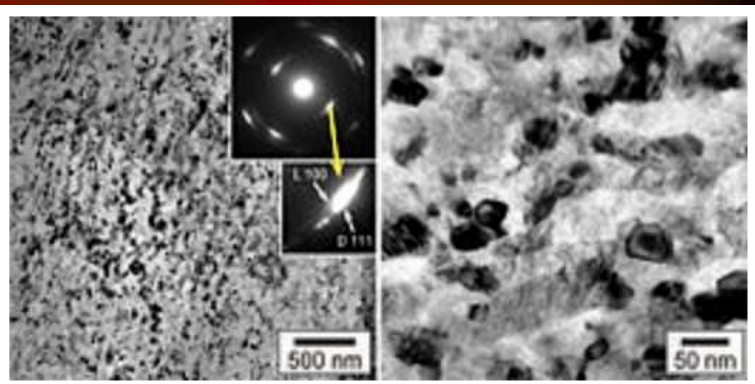
Chicxulub Crater

- Formed 66 million years ago it is an impact crater buried underneath the Yucatan Peninsular in Mexico. It was formed by a large asteroid about 11 to 81 km in diameter resulting in the Cretaceous-paleogene (Kpg) mass extinction. The crater is 150 m in diameter and 20 m in depth

The Popigal crater in Siberia

This crater may have the world's largest diamond deposit, estimated at trillions of carats all formed by an asteroid impact changing graphite into nanodiamond aggregates. The crater is 95 km in diameter and formed about 35.7 million years ago. The area is off limit and during Stalin's time was mined by the gulag prisoners. The diamond are usually 0.5 to 2 mm in diameter good only for industrial use

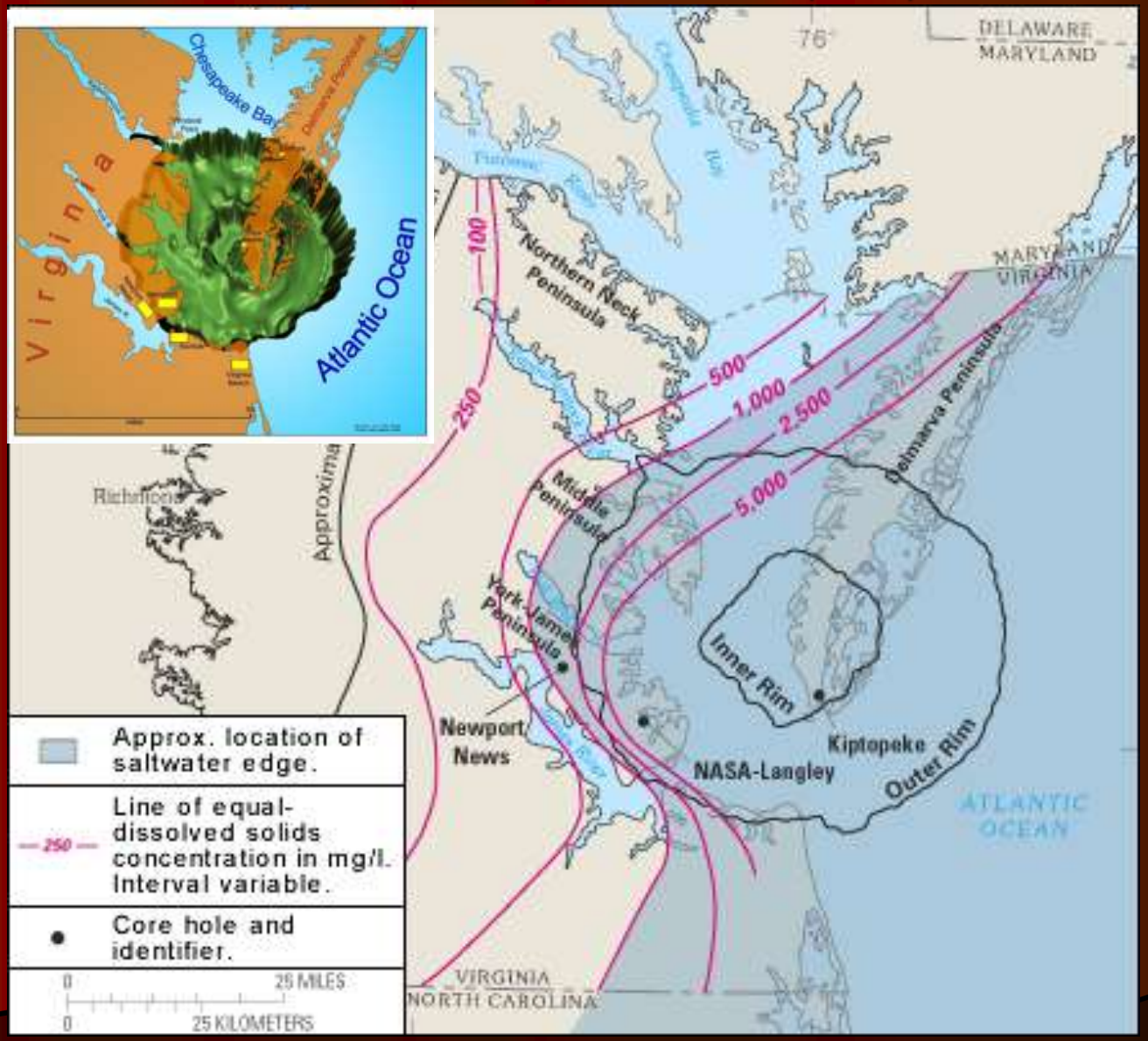




Internal structure of the Popigai nanodiamonds.[1]

Chesapeake Bay Impact Crater

Created by a meteorite strike about 35.5 my. The bolide impact speed is around 60 km/s



Roter Kamm crater

Roter Kamm in German means the Red Ridge. Located in the Namid Desert, it is 2.5 km in diameter and has a rim that rises 140 m above the surrounding desert plain and 160 m above the crater floor. The structure is dated at 4.8 m years old

Pingualuit crater

Formerly called the Chubb Crater and later the New Quebec Crater, is a young impact crater located on the Ungava Peninsula in Quebec. At 3.44 km in diameter, the structure was created only 1.4 my

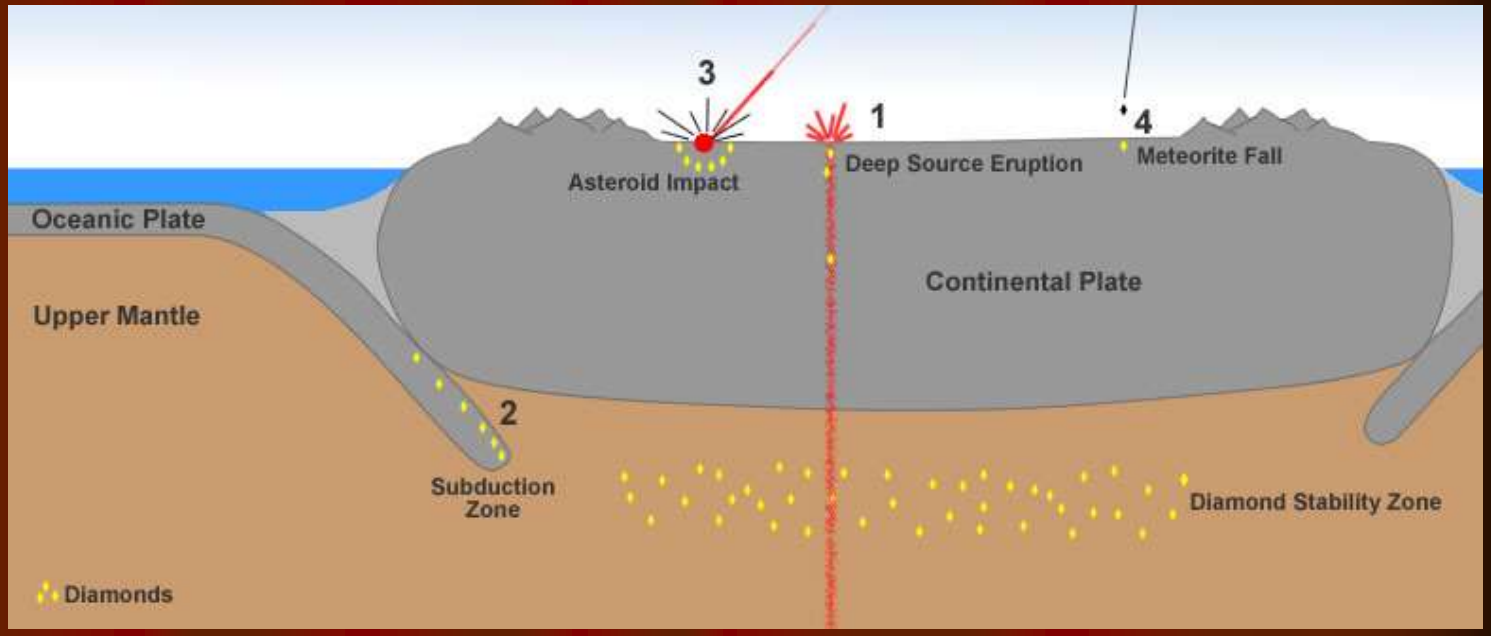
Bosumtwi crater

Located om Ghana it is an ancient impact crater created by a 500m wide chondrite meteorite 1.07 my. The lake has an area of 49 km2 and a depth of 240 feet

Meteor/Barringer Crater

Located near Flagstaff in central Arizona, this famous 1.2 km wide Crater is dated at 50,000 years old. The asteroid created the crater would be around 50-100 meters across. The fragments of the meteorites are called Canyon Diablo Meteorites

Meteoric Diamond found in Arizona



Impact diamonds

Canyon Diablo, iron meteorite (IAB). Found 1891, Arizona, USA.

Around 50,000 years ago a massive meteorite struck Arizona carving out a crater 1.2 kilometres wide and 180 metres deep. The impact was so strong that most of the meteorite vaporised. The tremendous pressure generated caused the carbon in some of the remaining fragments to transform into tiny diamonds. You can see a black lump on the surface. This is where the cutter's wheel has been interrupted by a nodule containing these hard diamonds, not much bigger than grains of sand.

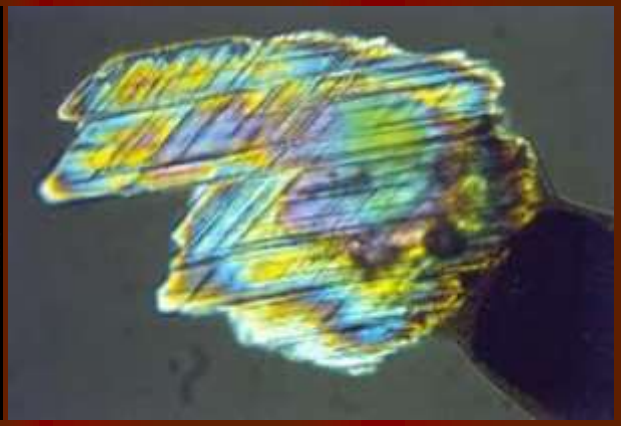
Lonar crater

Located in Maharastra India this 1.2 km wide and 137m deep crater was formed by a meteorite strike which took place 35,000 to 50,000 years ago

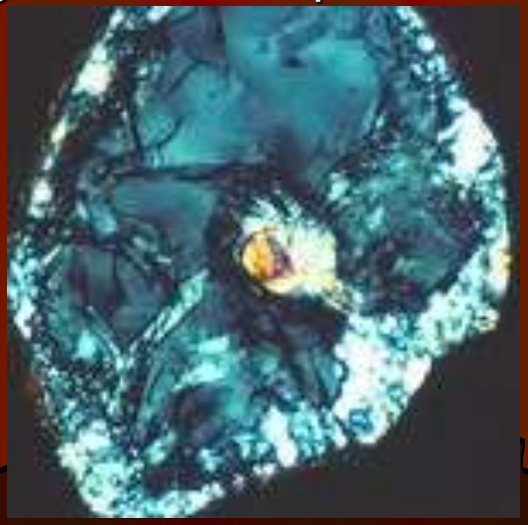
China's first confirmed impact crater in Xinyan Liaoning by the Chinese Academy of Science is sparking controversy. Formed 50,000 ya the crater is 1800 m wide and 150 m deep. Evidence includes coesite found in drill holes which is a form of SiO_2 that forms under very high pressure

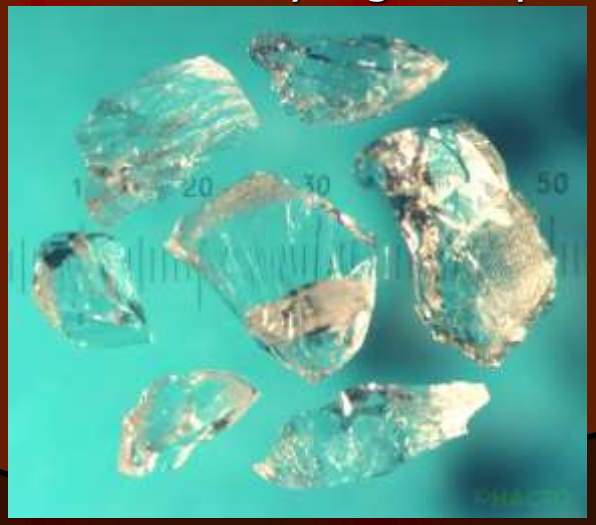
Shocked quartz 冲撞石英

- It is a form of quartz that has been deformed under intense pressure exerted by an asteroid strike



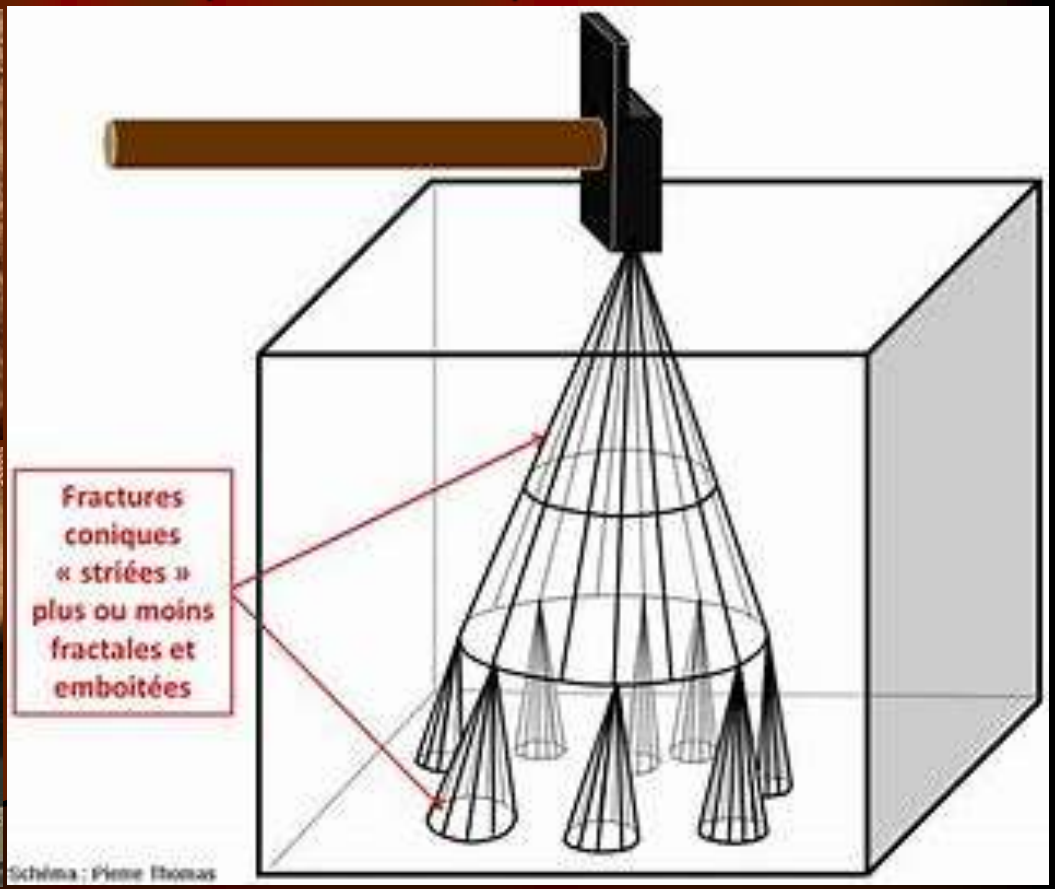
- Presence of coesite and stishovite which were formed when quartz is subject to intense pressure and moderately high temperature





Shatter Cones 震裂錐

- These are cone-shaped fragments of rock that form as a result of the high velocity and pressure of the shock wave produced by the meteorite impact. Their size can range from microscopic to a few meters. The apex of the shatter cone always points to the centre of the impact thus mapping their distribution and orientation can help define an impact site



Tektites 熔融石/玻隕石/似曜石/雷公墨

- Derived from Greek word tektos meaning "Melted" or "Molten". These are gravel size bodies composed of predominantly black but can also be grey, brown or green natural glass typically contain around 70% SiO_2 formed from terrestrial debris ejected during meteorite impacts

- Unlike obsidians, tektites are completely glassy and lack any microlites. They also contain virtually no water (<0.002 wt%) and few contain grains of shocked quartz

Chemical composition of tektites and similar materials

	Australasian strewn-field				Europe	North	Ivory	Henbury	average
	microtektites		austra-	Muong-	moldavite	America	Coast	subgray-	granite
	basic	regular	lite	Nong		bediasite	tektite	wacke	
SiO_2	56.8	64.2	73.45	81.36	80.07	76.37	68.02	77.40	74.22
TiO_2	0.6	0.6	0.69	0.47	0.80	0.76	–	0.77	0.20
Al_2O_3	8.0	11.0	11.53	8.87	10.56	13.78	16.39	10.92	13.61
Fe_2O_3			0.58	0.39	0.15	0.19	0.57	3.01	
FeO	8.4*	9.6*	4.05	2.81	2.29	3.81	5.99	1.28	1.83*
MgO	20.6	7.2	2.05	1.14	1.46	0.63	3.32	2.07	0.27
CaO	2.9	3.3	3.50	1.00	1.87	0.65	1.12	0.65	0.71
Na_2O	0.8	1.8	1.28	1.17	0.51	1.54	2.06	0.91	3.48
K_2O	0.3	1.5	2.28	2.26	2.95	2.08	1.88	2.86	5.06

Basis on morphology and physical characteristics, tektites can be subdivided into 4 groups :

(1) Splash-form (normal) tektites - they are shaped like spheres, ellipsoids, tear - drops, dumbbells and other forms characteristic of isolated molten bodies. They are formed by the solidification of rotating liquids instead of atmospheric ablation e.g. Indochinites

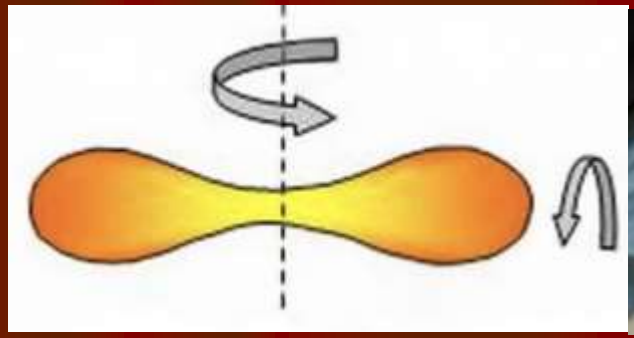
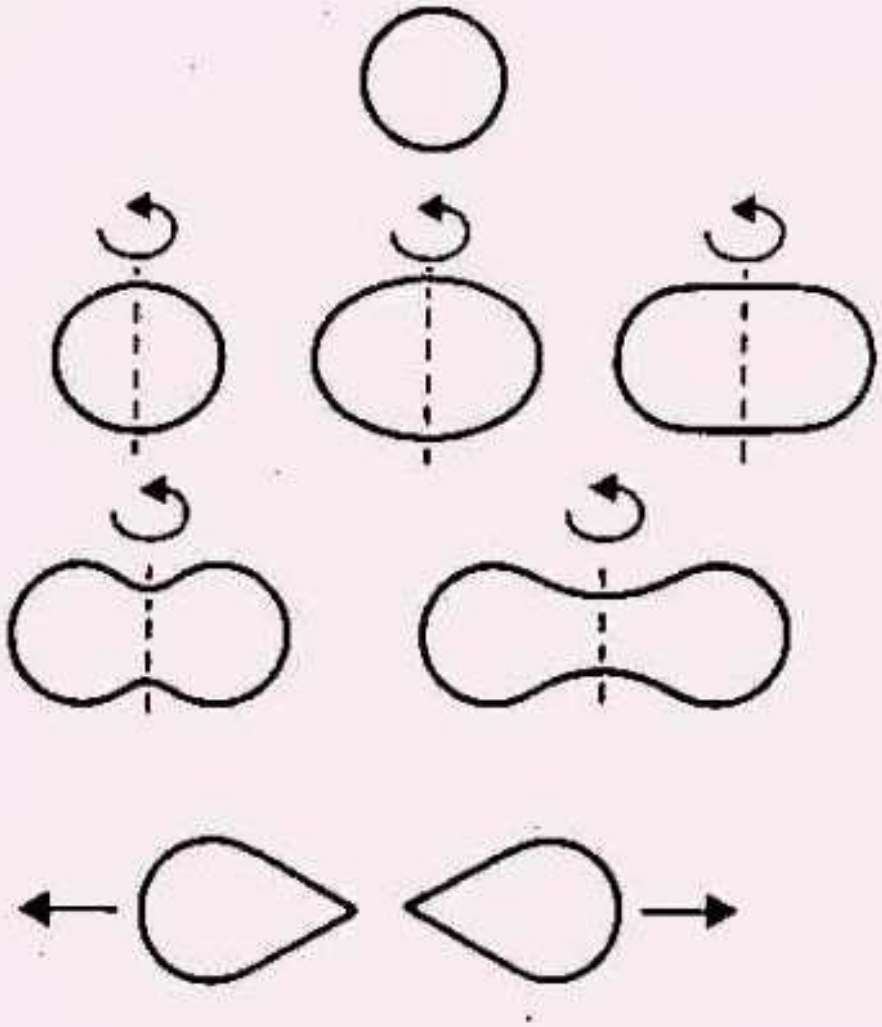





Diagram showing the development of primary shapes in Tektites



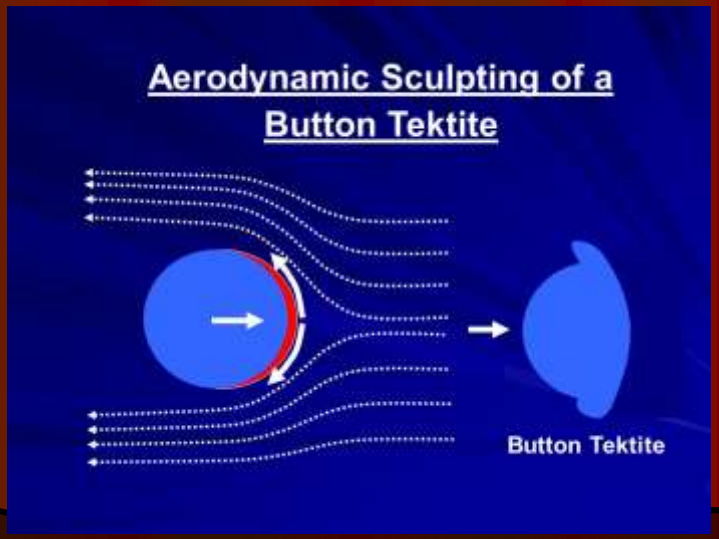
Spheres (60–70%) from non-rotating blobs

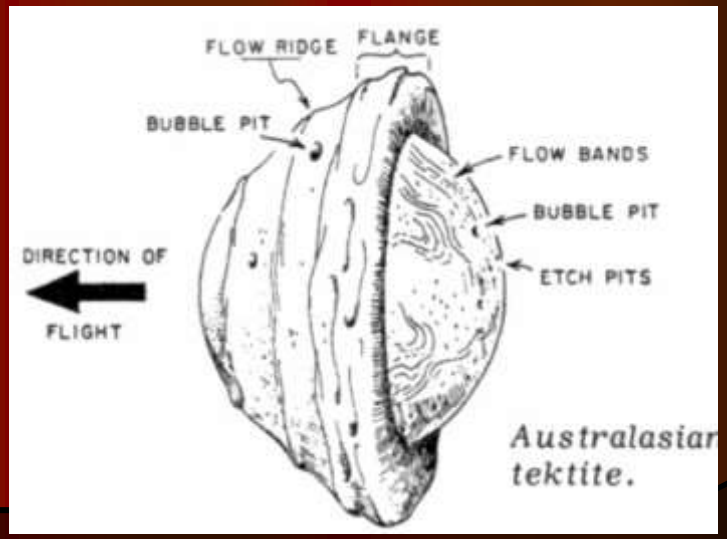
Spheroids and ellipsoids (25%) under slow to moderate rates of rotation

Dumbbells (8%) under rapid rates of rotation

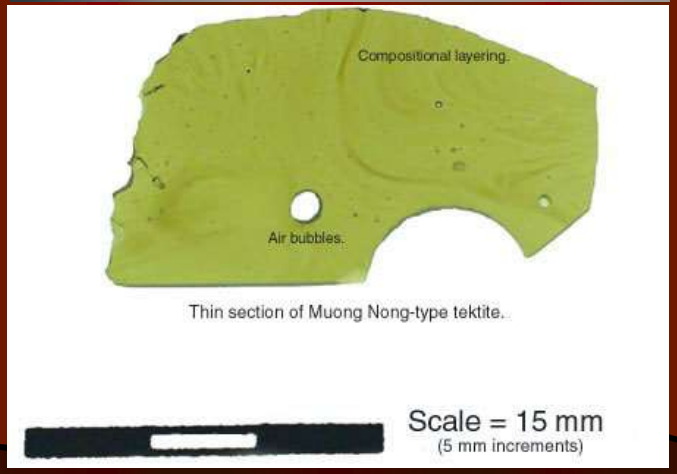
Apioids (3%) formed by separation of the most rapidly rotating dumbbells (non-rotation after separation)

(2) Aerodynamically shaped tektites are splash form tektites (buttons) which display a secondary ring or flange produced during the high speed re-entry and ablation of already solidified splash-form tektite into the atmosphere e.g. Australites

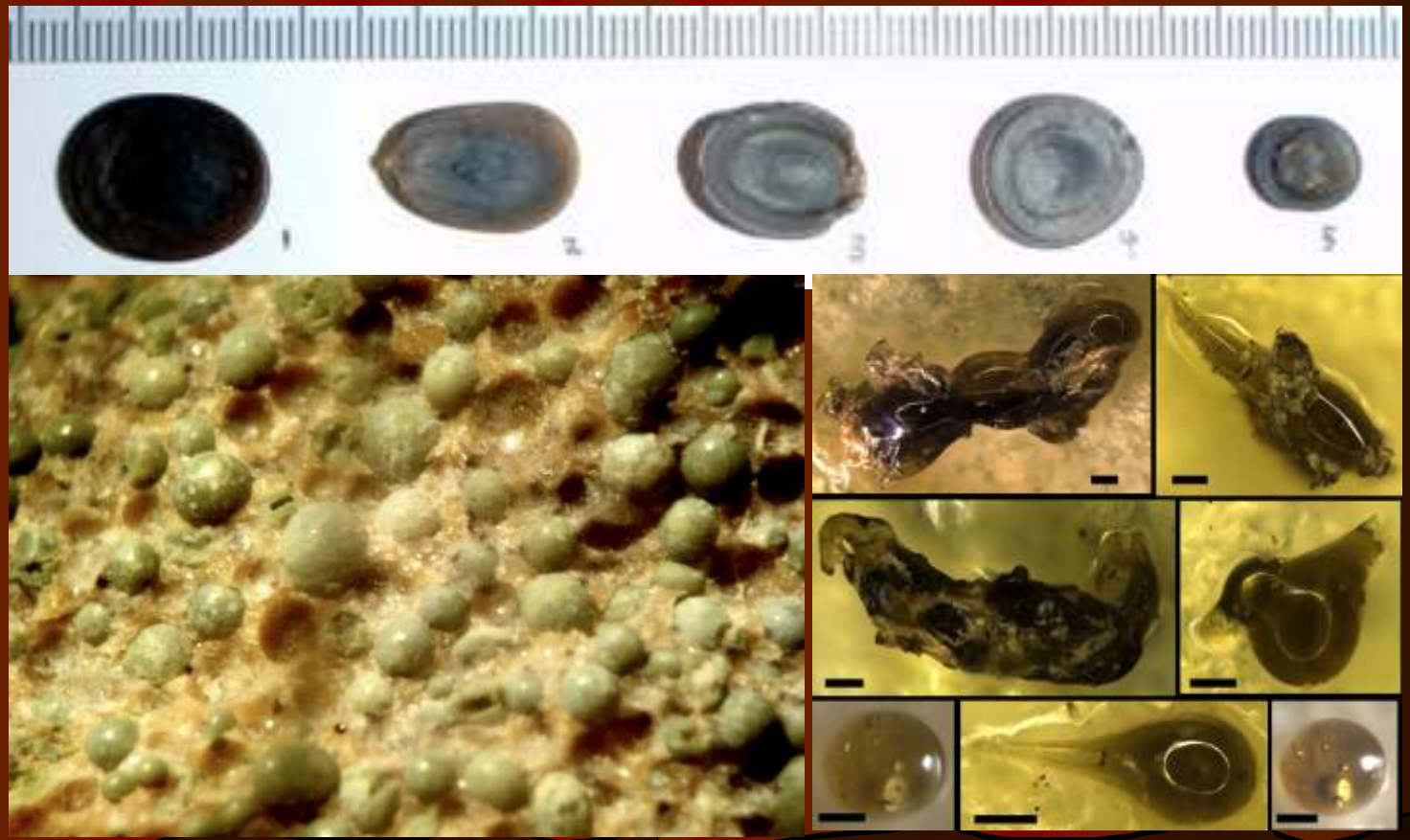


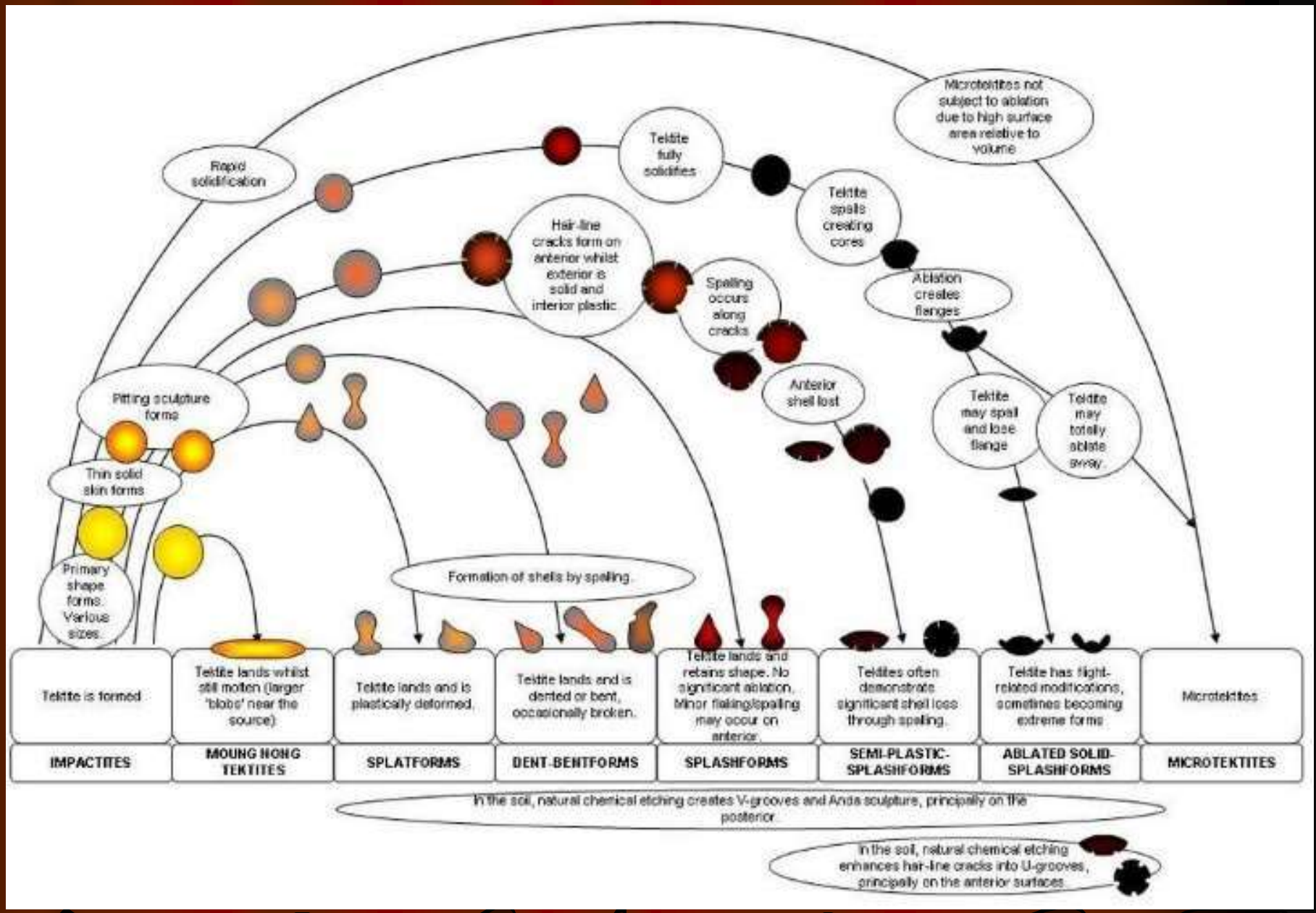


(3) Muong-Nong or layered tektites are typically larger greater than 10 cm in size 24 kg in weight and typically found in the Indochinite (Laos) strewn field. They were formed by the repeating flowing of thin layers of molten glass and did not travel up into the atmosphere. They have a chunky, blocky appearance with a layered structure and contain mineral inclusions such as corundum and rutile



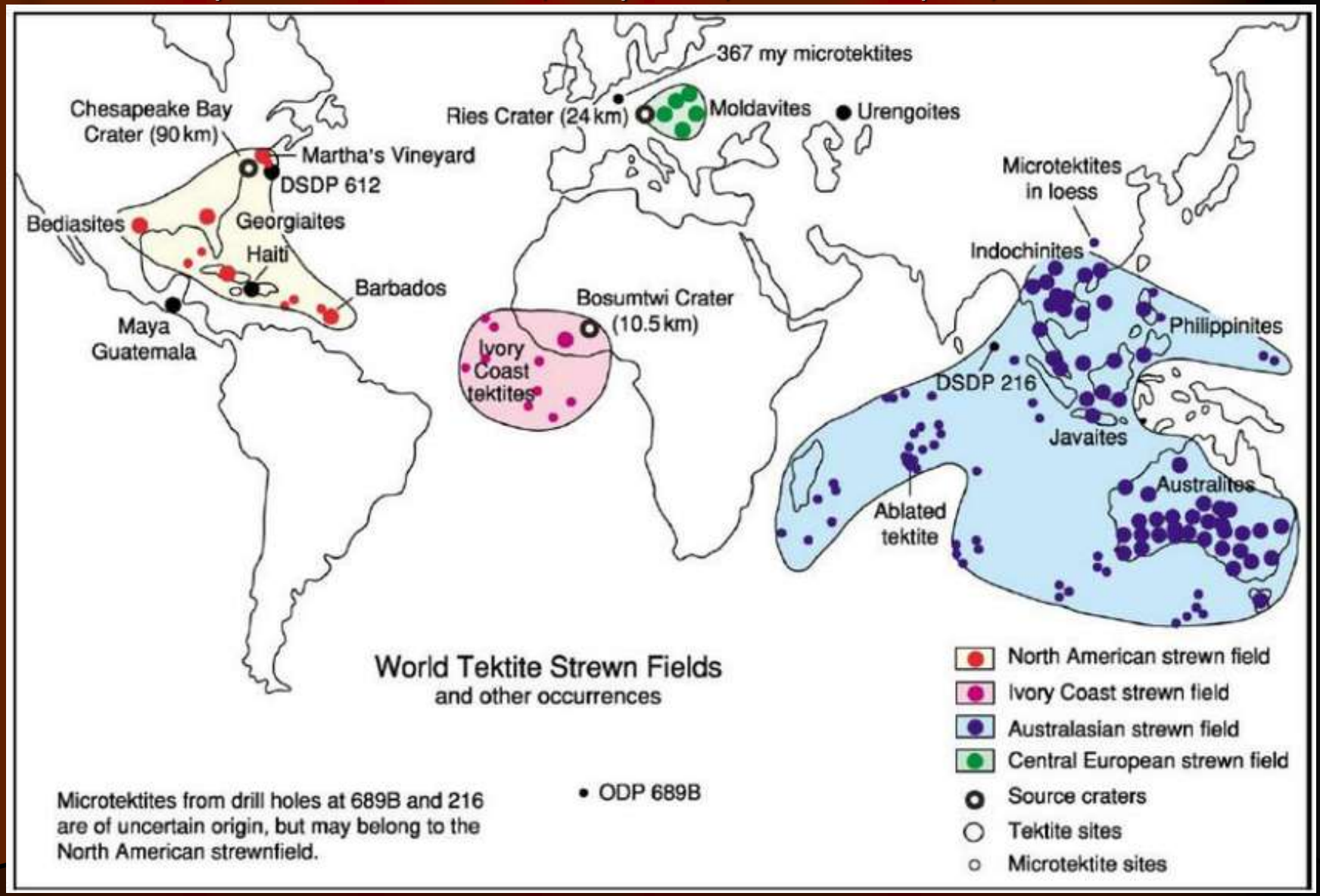
(4) Microtektites are less than 2 mm in size and typically found in deep-sea sediments within the Australasian, Ivory Coast and North American strewn fields. Their silica content can be as low as 50% & they exhibit a variety of shape ranging from spherical to disc, oval and tear drop. Their colours range from colourless to yellowish and pale brown & frequently containing bubbles and inclusions




Microtektites not subject to ablation due to high surface area relative to volume
Rapid solidification
Tektite fully solidifies
Tektite spalls creating cores
Hair-line cracks form on anterior whilst exterior is solid and interior plastic
Spalling occurs along cracks
Ablation creates flanges
Pitting sculpture forms
Anterior shell lost
Tektite may spall and lose flange
Tektite may totally ablate away
Thin solid skin forms
Primary shape forms. Various sizes
Formation of shells by spalling
Tektite is formed
Tektite lands whilst still molten (larger 'blobs' near the source)
Tektite lands and is plastically deformed.
Tektite lands and is dented or bent, occasionally broken.
Tektite lands and retains shape. No significant ablation. Minor flaking/spalling may occur on anterior.
Tektites often demonstrate significant shell loss through spalling.
Tektite has flight-related modifications, sometimes becoming extreme forms
Microtektites
IMPACTITES
MOUNG HONG TEKTITES
SPLATFORMS
DENT-BENTFORMS
SPLASHFORMS
SEMI-PLASTIC-SPLASHFORMS
ABLATED SOLID-SPLASHFORMS
MICROTEKTITES
In the soil, natural chemical etching creates V-grooves and Anda sculpture, principally on the posterior
In the soil, natural chemical etching enhances hair-line cracks into U-grooves, principally on the anterior surfaces

Classification by Strewn Field 撒落場

4 key ones : North America, Ivory Coast, Central European, Australasian



Tektites found in the North American Strewn Field

- Georgiaite : note the star burst rays on the left & the teardrop specimen on the right. It is around 35.4 million years old and only 1,700 to 2,000 pieces have been found in the state of Georgia

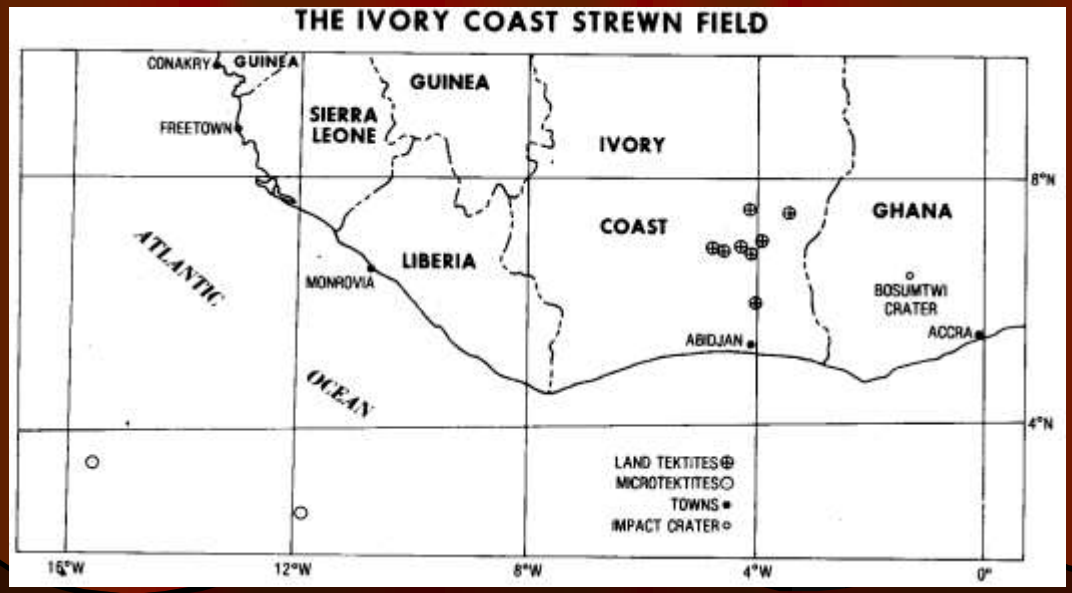


- Bediasites : specimens found in Texas



Tektites found in the Ivory Coast Strew Field

About 1.3 million years old Ivorites. Looks similar to Indochinites



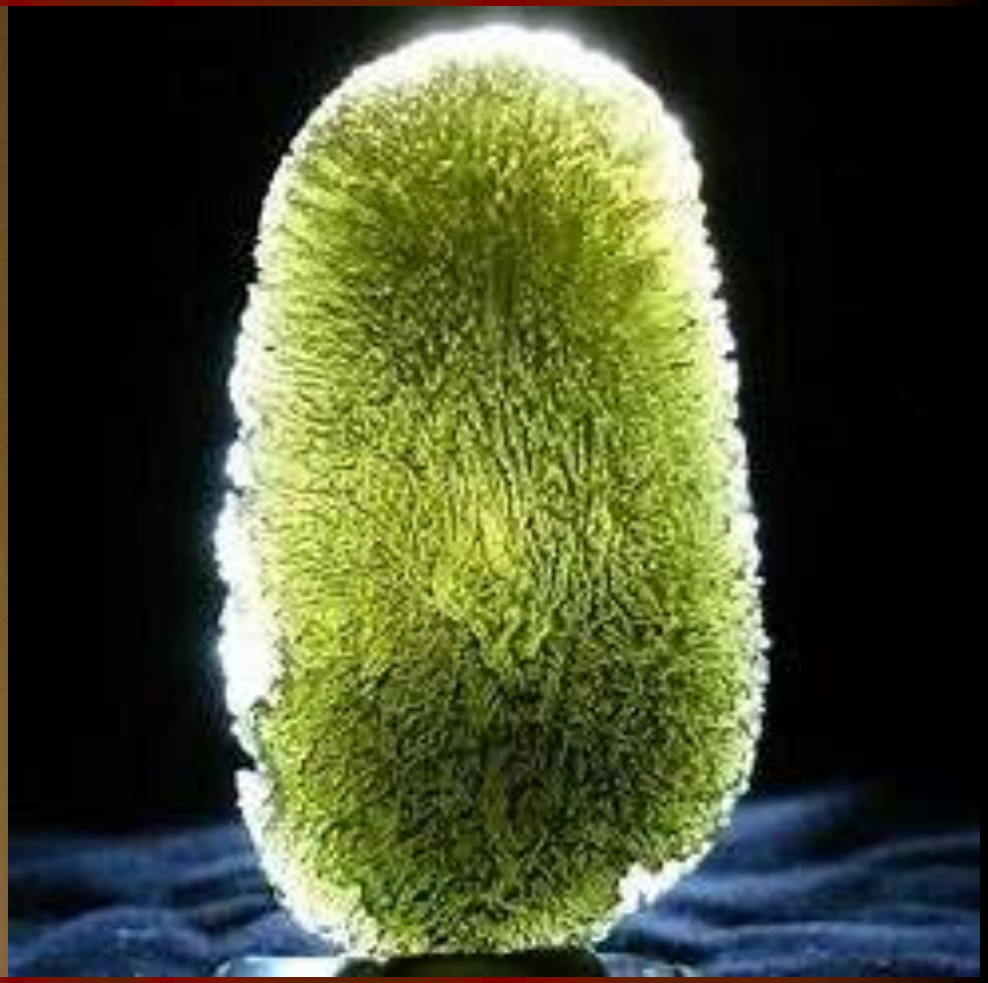
Tektites found in Central Europe Strewn Field

Represented by Moldavite which is a greenish coloured tektite generally believed to have been formed about 14.7 million years ago during the impact of a giant meteorite in the present Nordinger Ries crater. Splatters of material that was melted by the impact cooled while they were actually airborne and most of them fell in Czech and Slovak Republic. Made up mainly of silicon dioxide and aluminium oxide (SiO_2 (+Al_2O_3). The total amount of Moldavite is estimated to be 275 tons



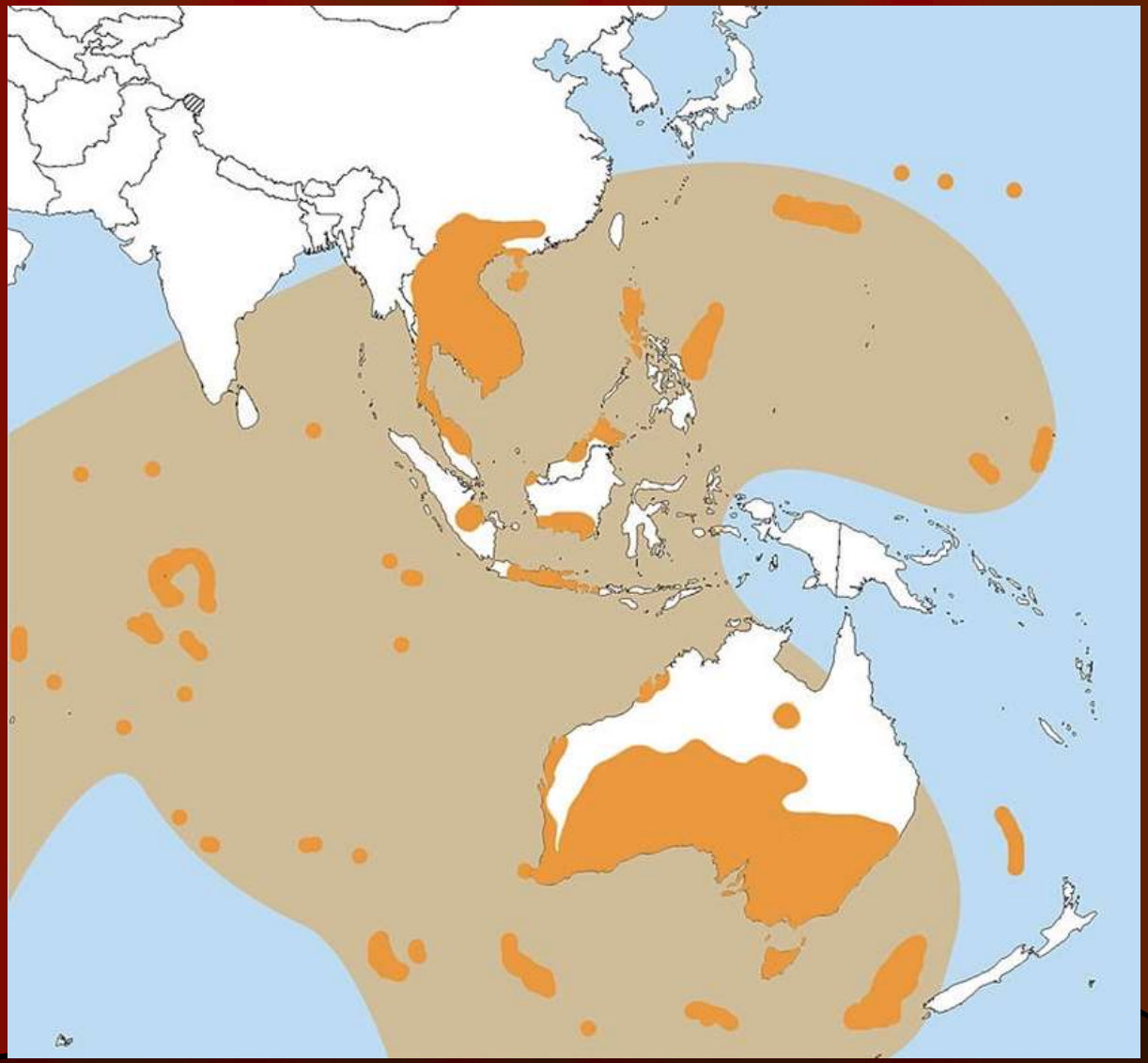



Moldavite is being used for jewellery as Holy Grail Stone with special healing power



Tektites found in the Australasia Strewn Field

0.803 million years old



Strewn field Name	Regional Name	Country Name	Provincial Name
Australasian Tektites (0.803 Ma)	Indochinites (Proximal)	Thailandites	
		Vietnamites	
		Cambodianites	
		Chinites Lei Gong Mo	
	(Medial)	Philippinites (also known as Rizalites)	Bikolites
		Malaysianites	
		Indomalaysianites	Billitonites Satam Stone
	(Distal)	(Indonesia)	Javaites / (Ja-vanites)
		Australites	

Indochinites plastically deformed

Medial tektites from the Philippines

Distal tektites from Australia

A huge Australite Flanged Button ?

Minor tektites & impactites

Minor tektites include South Ural tektite – 1 specimen (6.4 Ma), Urengoite –3 specimens (24 Ma ?), Uruguay Glass (60 Ma ?)

Urengoites



Impactites or impact glass is rock created or modified by the impact of a Meteorite. Argentinean Pampas Glass, Libyan Desert Glass and Darwin glass are considered to be impactites or some way between impactites and tektite

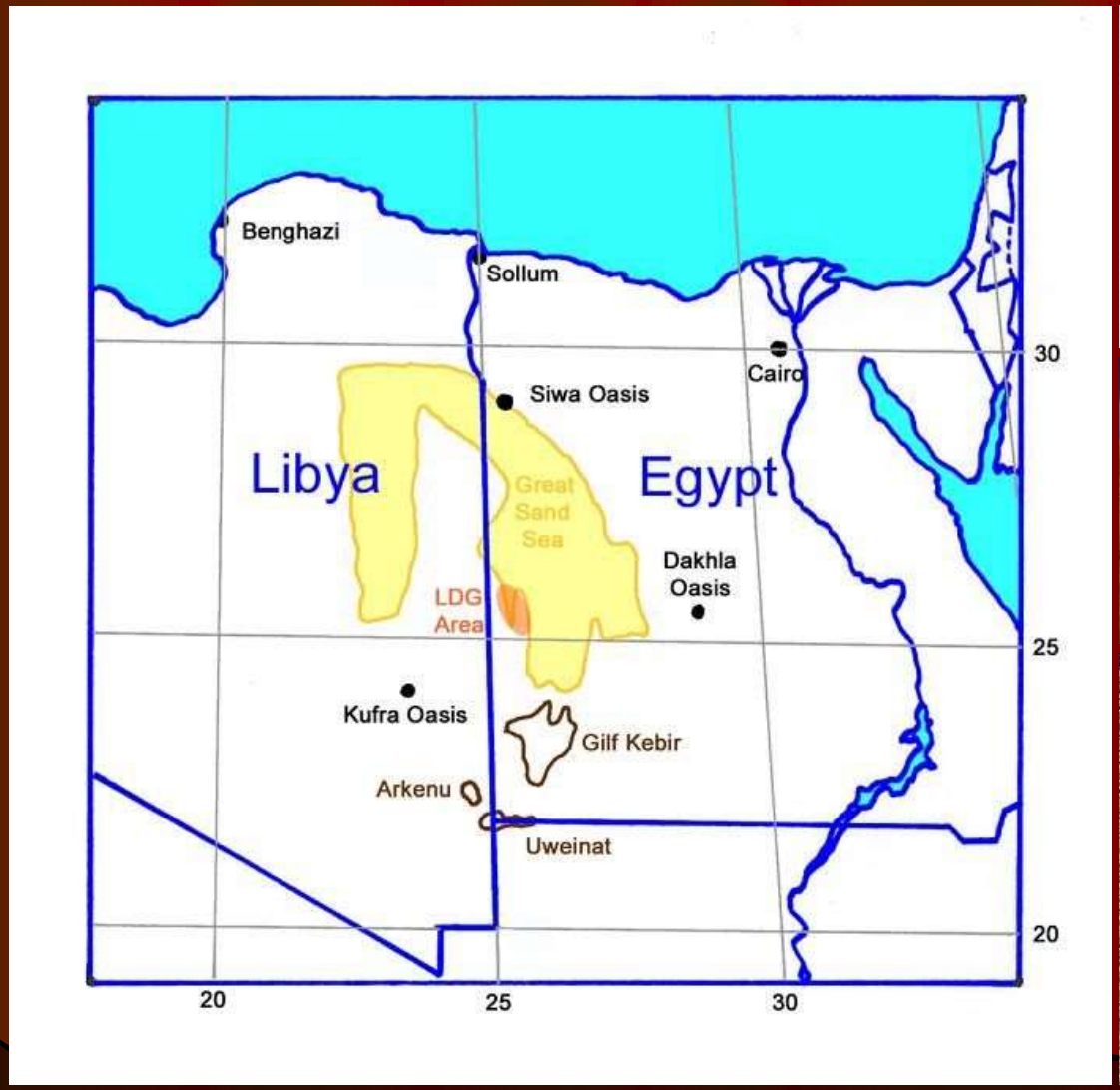
Argentinean Pampas Glass

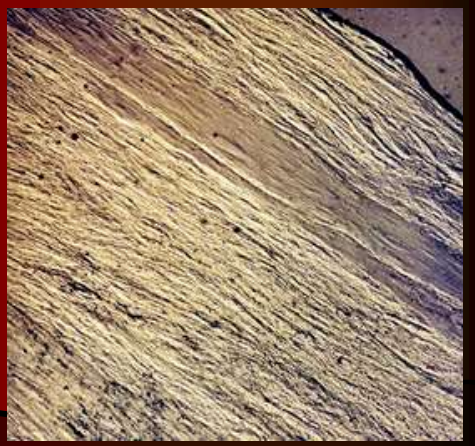
Libyan Desert Glass

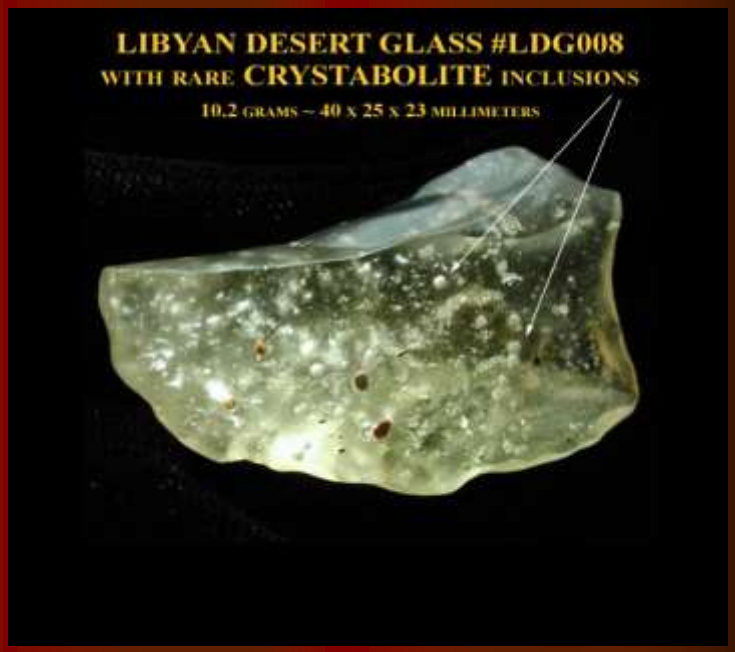
Darwin Glass

- Argentinean Pampas Glass is impact glass found in a strewn field associated with elevendepressions which was probably an impact event that took place 0.48 million years ago. Some scientists however claimed that these might be formed by lightning strikes instead !

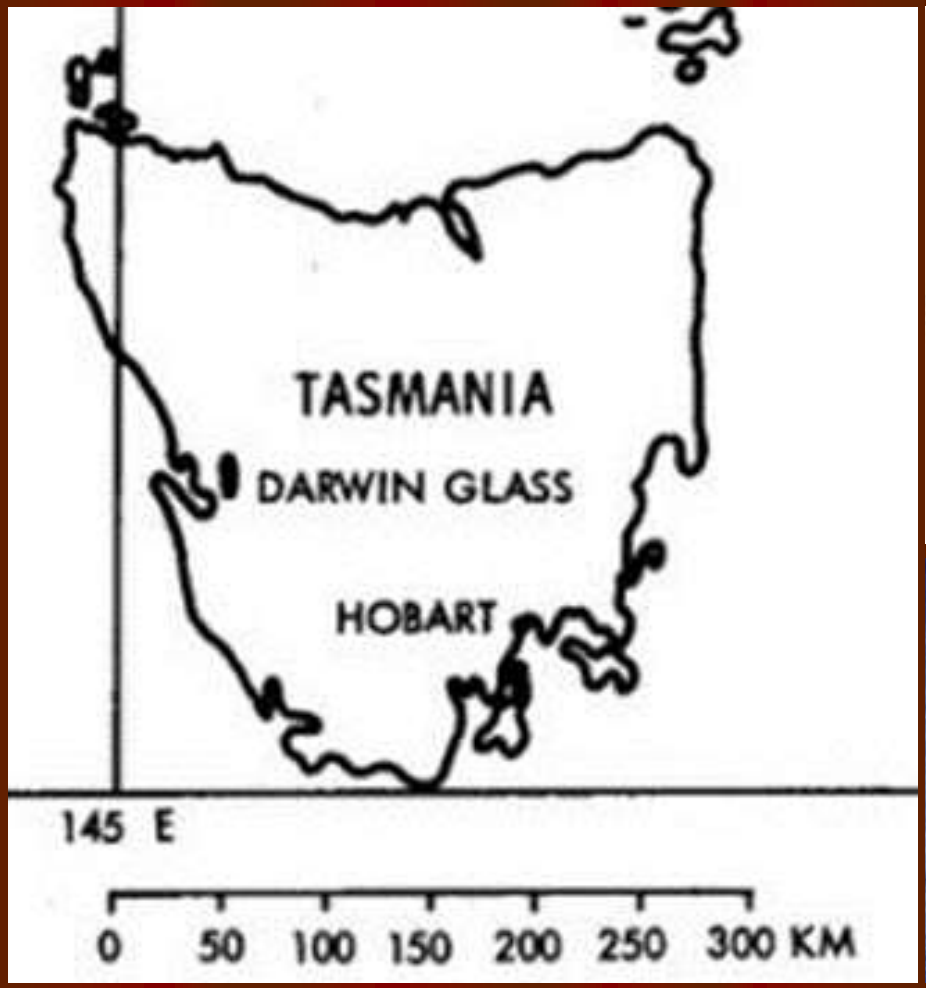
- Libyan Desert Glass (LDG) or Great Sand Sea Glass is an impactite (Impact glass) found in the eastern Sahara in the deserts of eastern Libyan and western Egypt formed as a result of a meteor impact some 28 million years ago






LIBYAN DESERT GLASS #LDG008
WITH RARE CRYSTABOLITE INCLUSIONS
10.2 GRAMS ~ 40 X 25 X 23 MILLIMETERS

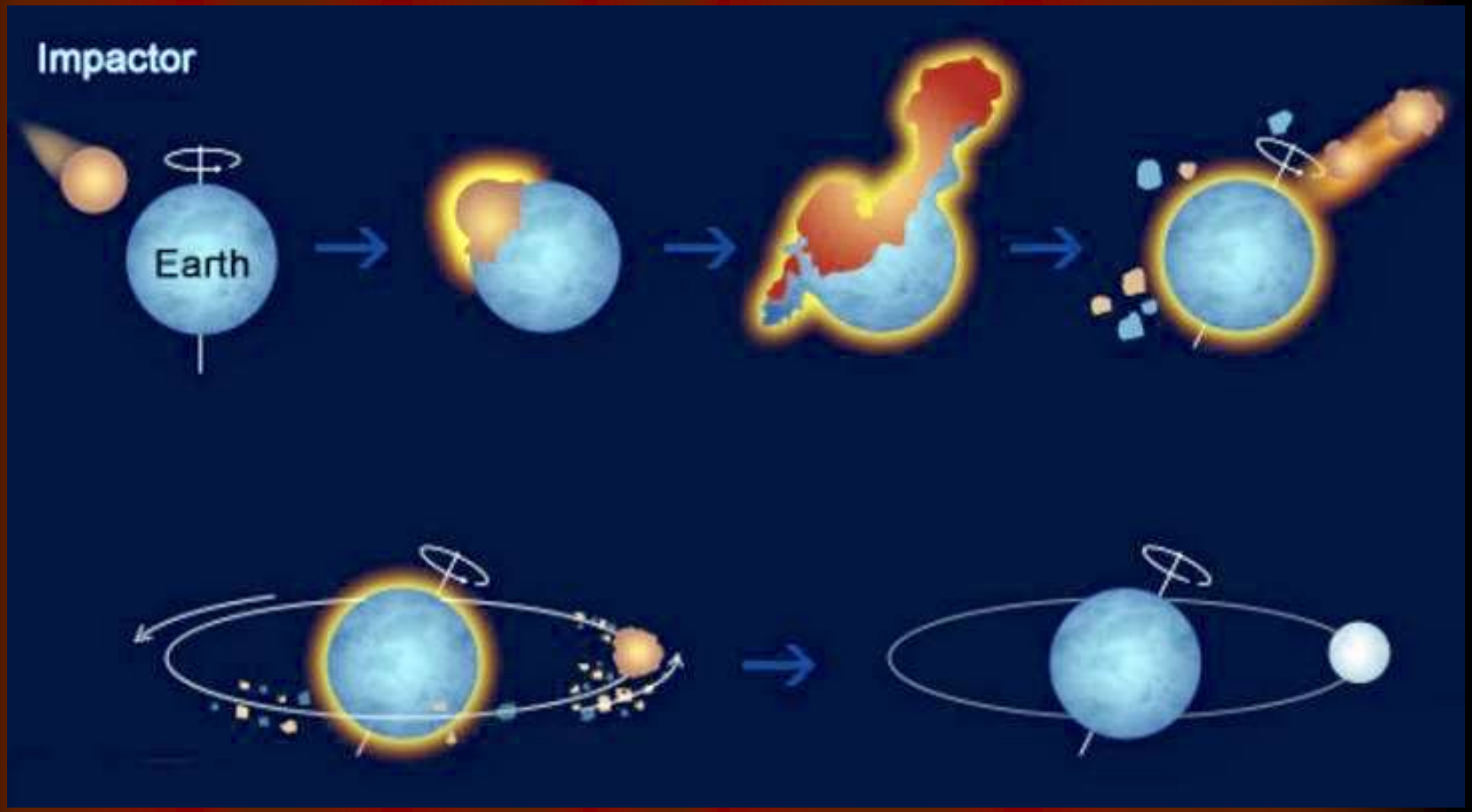
- Darwin Glass is a natural glass found south of Queen's Town at Darwin's Crater at West Coast Tasmania which was formed 770,000 years ago. Some are exposed and some buried below peat and sediments

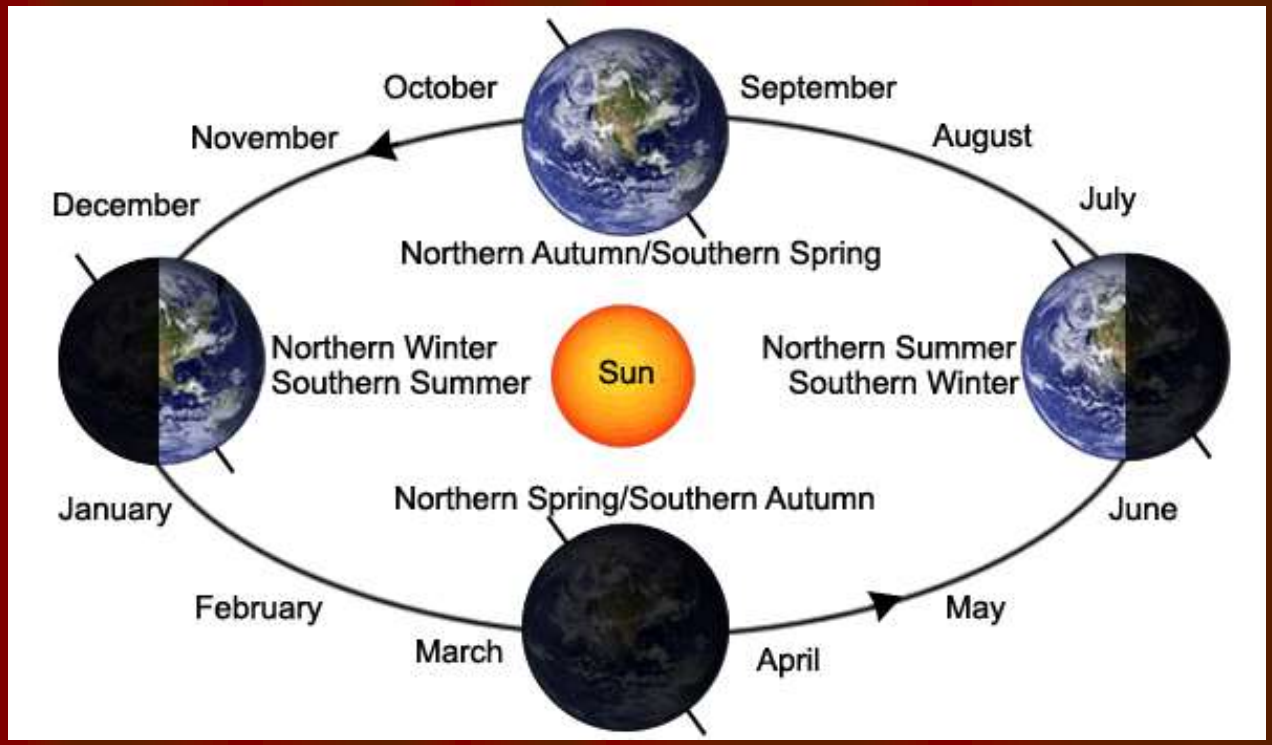


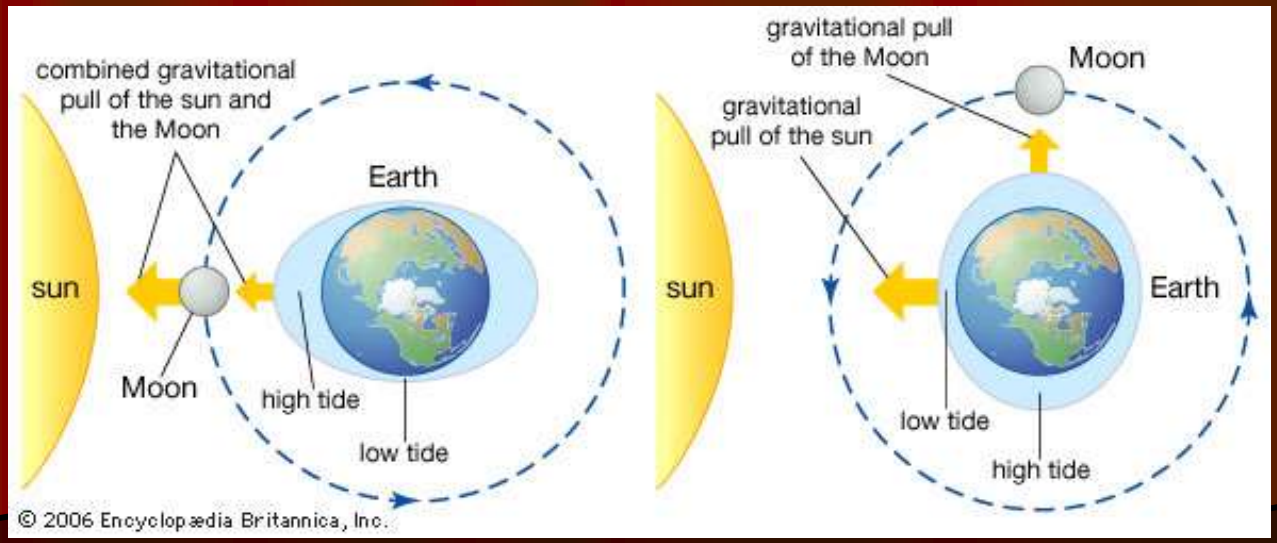
Major historical impact

Theia the "Big Splash"

Also known as the "Big Thwack" its Earth's collision with an asteroid "Theia" at 4.527 Ba led to a 23.5 degree inclination of the earth's axis resulting to four seasons, longer days , the formation of the Moon and Tidal Cycle




October
September
November
August
December
July
Northern Autumn/Southern Spring
Northern Winter
Southern Summer
Sun
Northern Summer
Southern Winter
January
Northern Spring/Southern Autumn
June
February
May
March
April


combined gravitational pull of the sun and the Moon
Earth
sun
Moon
high tide
low tide
gravitational pull of the Moon
Moon
gravitational pull of the sun
sun
Earth
low tide
high tide
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Importance of Tide and Lunar Cycle

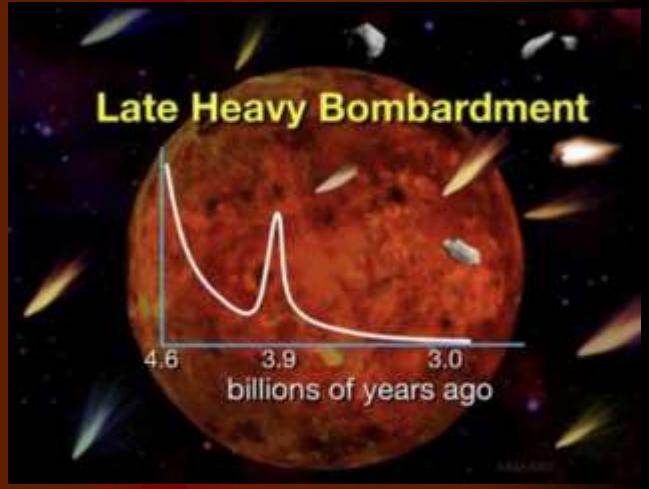
Feeding mangrove with nutrient; sea turtle egg laying; coral & giant clam reproduction & annual surge in Qiantang Jiang 錢塘觀潮



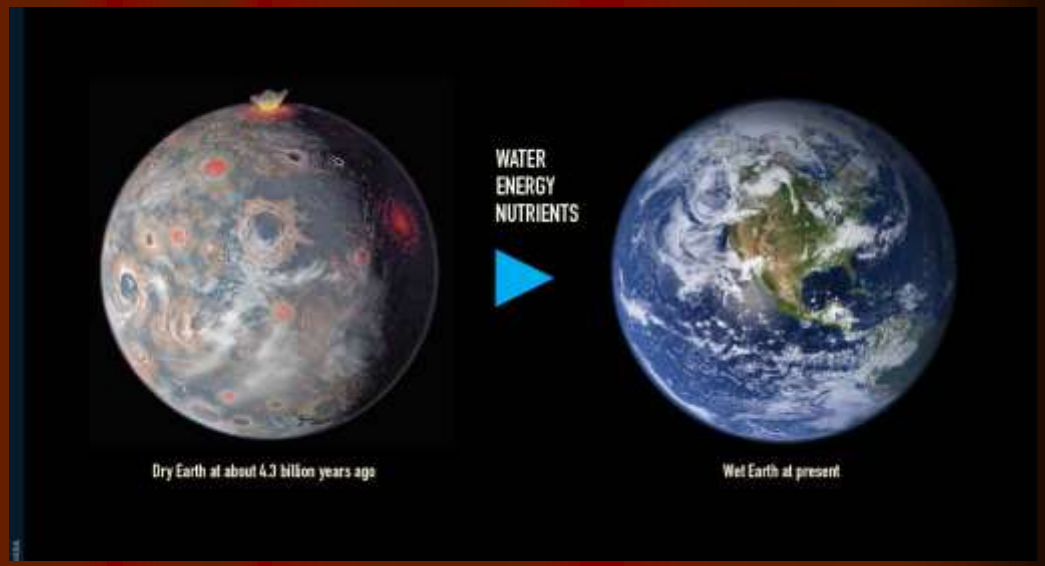


The Late Heavy Bombardment (LHB)

It is an event occurred approximately 4.1 to 3.8 billion years ago during which time a large number of asteroids from left over planet building material and comets collided with the early terrestrial planets including Mercury, Venus, Mars, Earth and Moon. On Earth it created 22,000 or more impact craters with diameter >20 km, 40 more than 1,000 km & several more than 5,000 km. Due to plate tectonic and weathering the Earth bears relatively few scars but they can still be recognised in the other planets



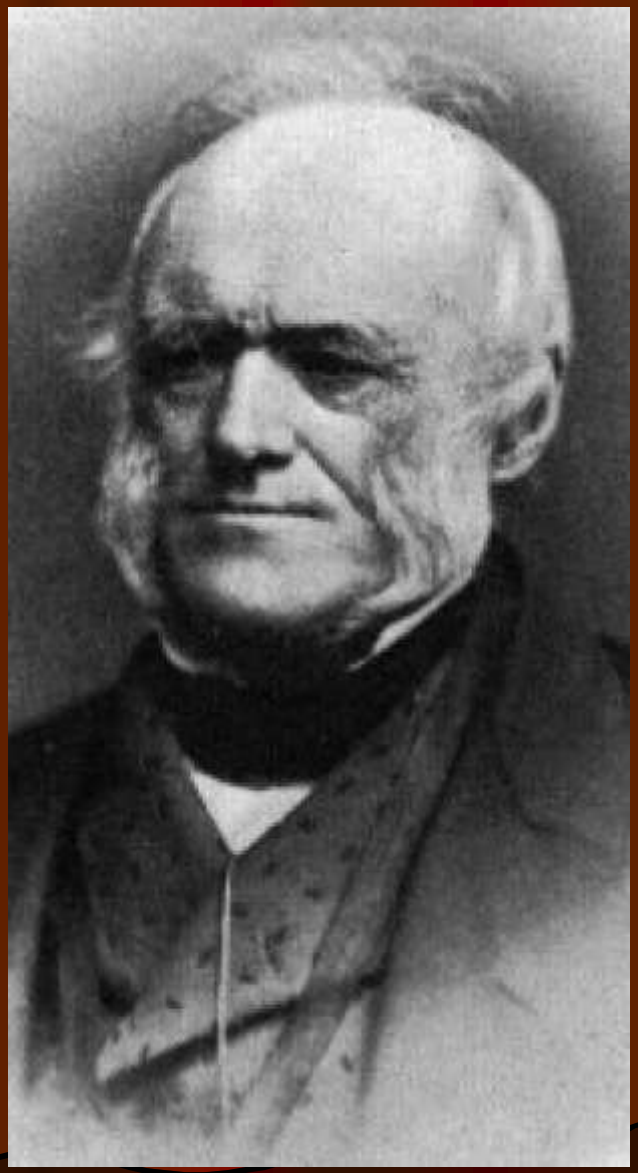
Popular among scientists the Late Heavy Bombardment was caused by the orbital migration of the giant planets namely Jupiter and Saturn which scattered objects in the asteroid and/or Kuiper belts into colliding paths with the terrestrial planets. Dating of the lunar meteorites and the lunar craters confirmed the timing of the event. Earth then was still very hot to hold onto water so the LHB may have been key to delivering water to the planet without which life could not have been formed



Meteorite & Extinction - 26 million years Impact Cycles ?

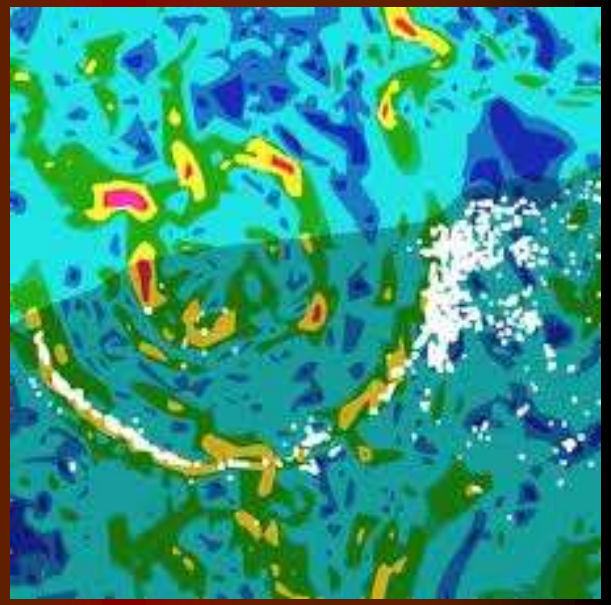
craters found	extinction event (millions of years ago)	age of crater (million years)	fossils	expected 26-million-year cycle
none	11 mya			12 mya
9	36 mya	36 mya	some Eocene mammals	38 mya
8	66 mya	66 mya	Cretaceous dinosaurs, marine life	64 mya
7	94 mya	91 mya	Late Cretaceous marine life	90 mya
6	116 mya	115 mya	Early Cretaceous marine life	116 mya
5	145 mya	145 mya	Jurassic dinosaurs	142 mya
4	168 mya	168 mya	Jurassic marine life	168 mya
3	201 mya	201 mya	Late Triassic reptiles	194 mya
2	225 mya	228 mya	Late Triassic marine life	220 mya
1	252 mya	254 mya	more than 90 percent of life	246 mya

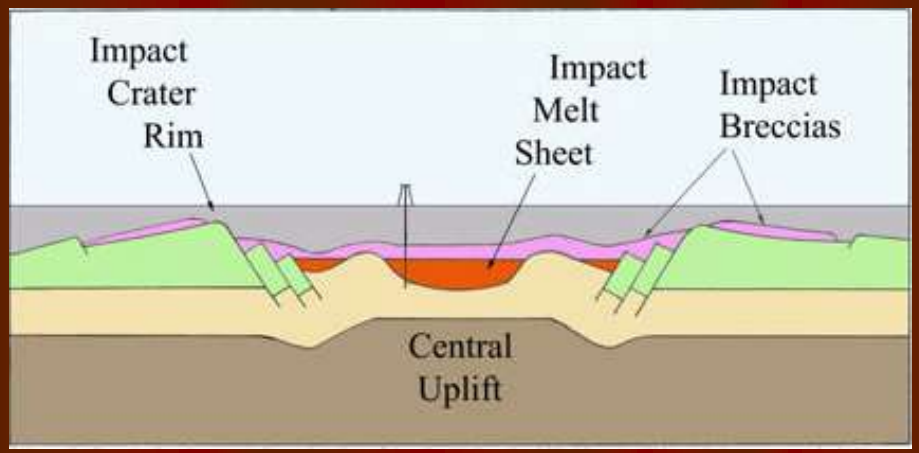
Charles Lyell's Law and Meteorite Strike

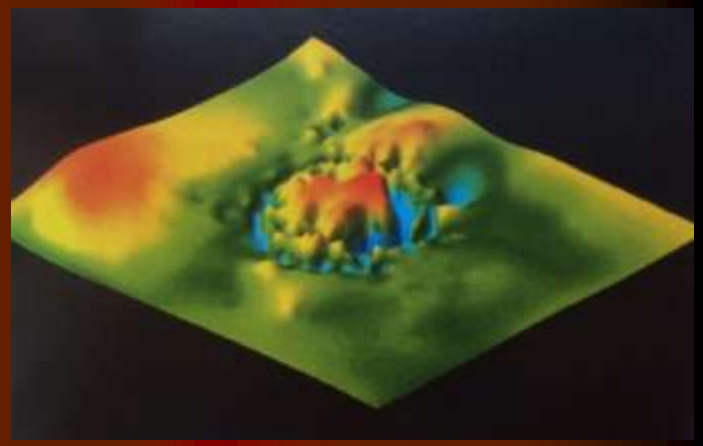


Cretaceous-Paleogene (K-Pg) or KT impact

66 Ma an asteroid 12 km in diameter strike at Yucatan created the Chicxulub Crater

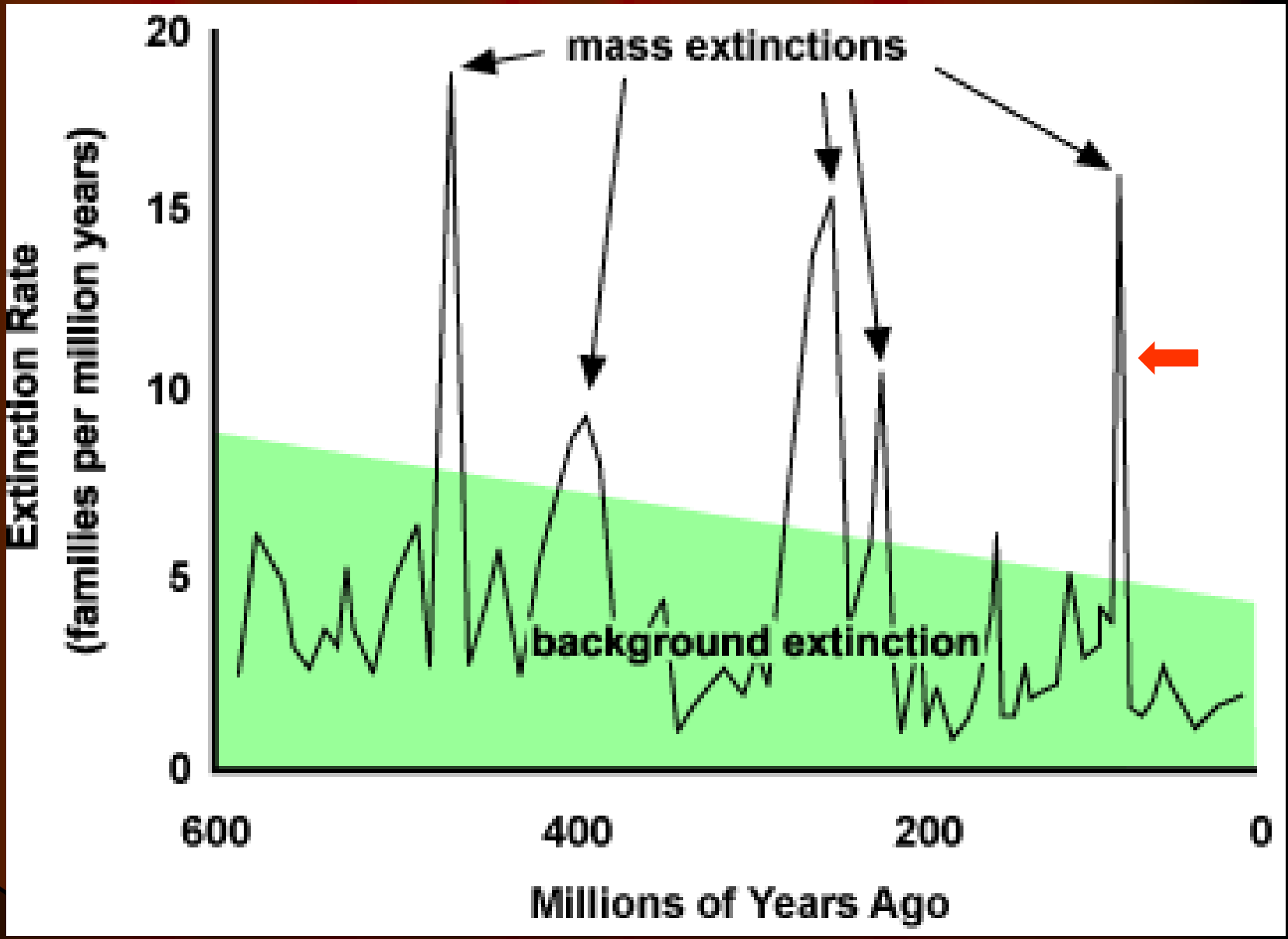




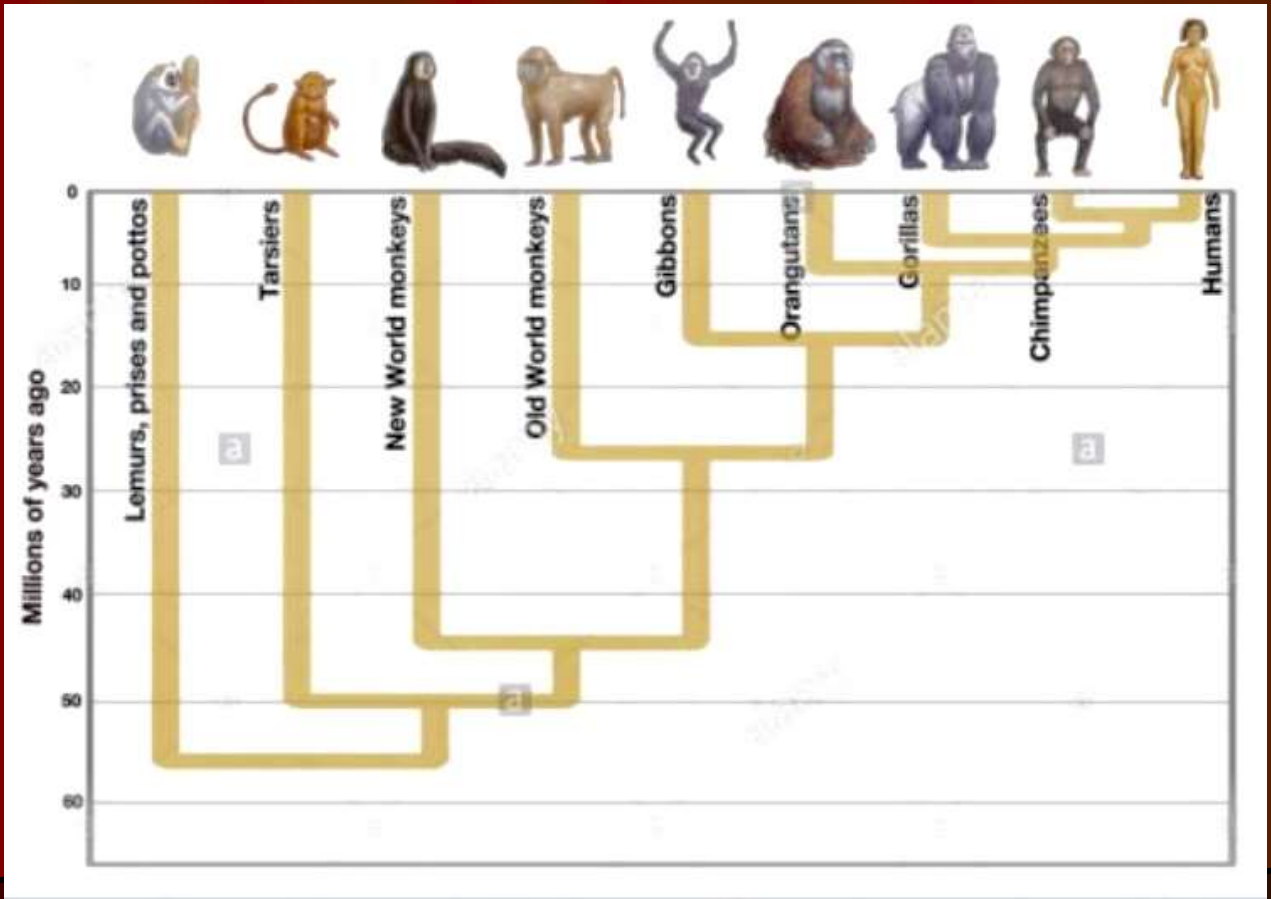


The area was a shallow sea over a sulfur rich shelf. Once vaporized formed a climate altering blanket that envelop the planet & fell as acid rain. All animals larger than 25 kilo could not survive the "Impact Winter". As a result 75% of plant and animal species including the dinosaurs became extinct & changed the course of evolution allowing mammals to prosper

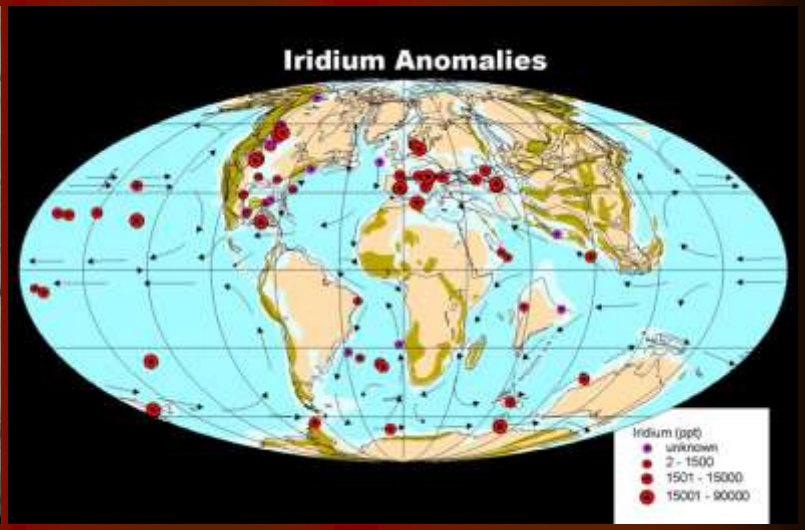
The 5th Extinction - More than 75% of all species vanished



The RISE of mammal



A major evidence is the presence of Iridium 銥 which is a very dense metal rarely found on the Earth's crust but an asteroidal element. A layer of this sediment was located globally at the KT Boundary at 350 sites worldwide



After the impact

Impact: 66 million years ago

Before the impact

Record of Disaster

A slice of rock from Canada, representing a span of 500,000 to 750,000 years, offers clues to what the world was like before, during, and after the meteor struck Earth.

Paleogene: Microfossils in coal indicate that forests collapsed and ferns took over. No dinosaur fossils are found in or above this layer.

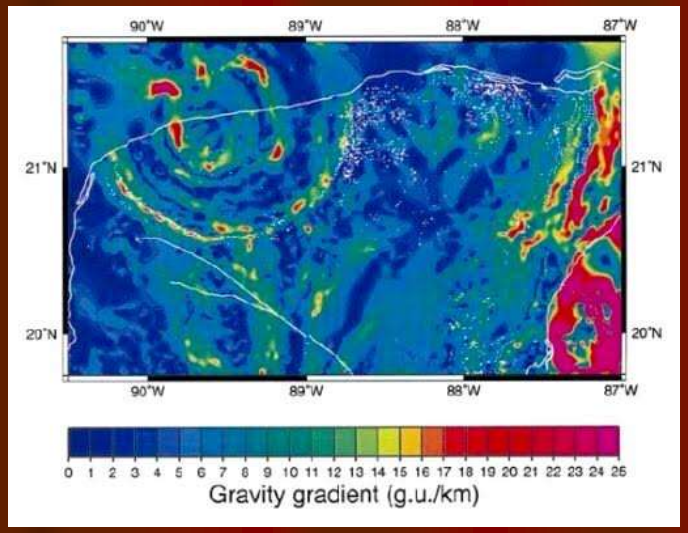
Cracked quartz and rare metals such as iridium (scarce on Earth but plentiful in some meteorites) suggest a meteor strike.

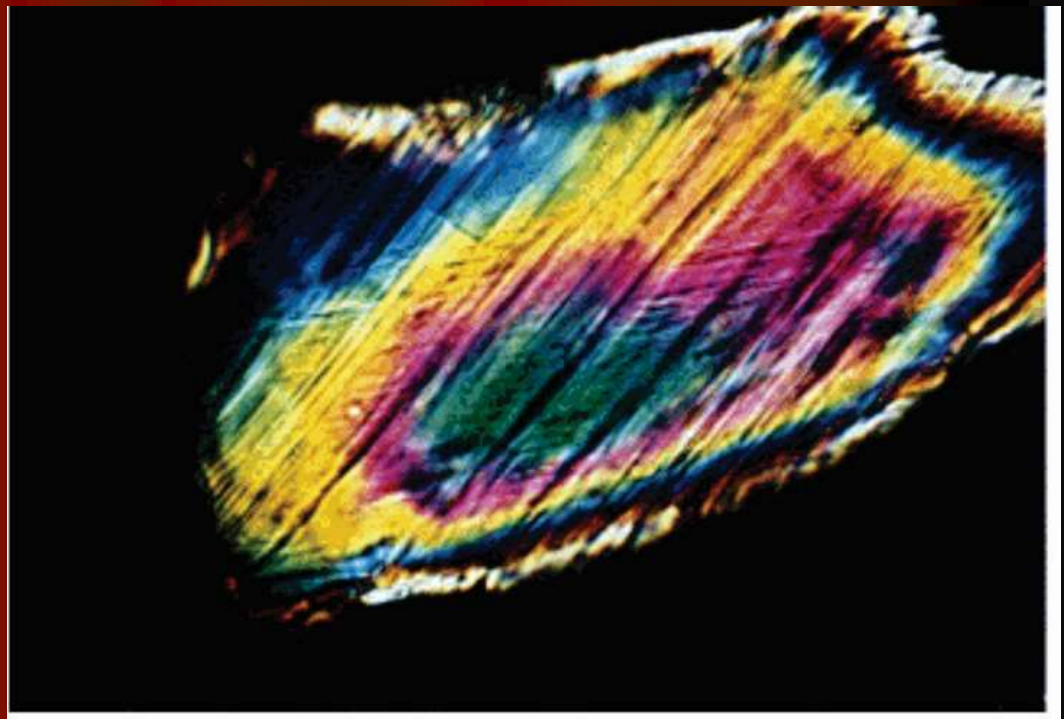
Cretaceous: The transition from pale mudstone to coal shows the climate shifting from dry to wet, perhaps stressing dinosaurs, other fauna, and flora.

PHOTOGRAPHED AT ROYAL TYRRELL MUSEUM OF PALAEONTOLOGY, ALBERTA, CANADA

SOURCE: DENNIS BRAMAN, ROYAL TYRRELL MUSEUM OF PALAEONTOLOGY

On site evidence of the meteor strike included gravity anomaly, tektites, shocked quartz, tsunami sediments & numerous sink holes called cenotes

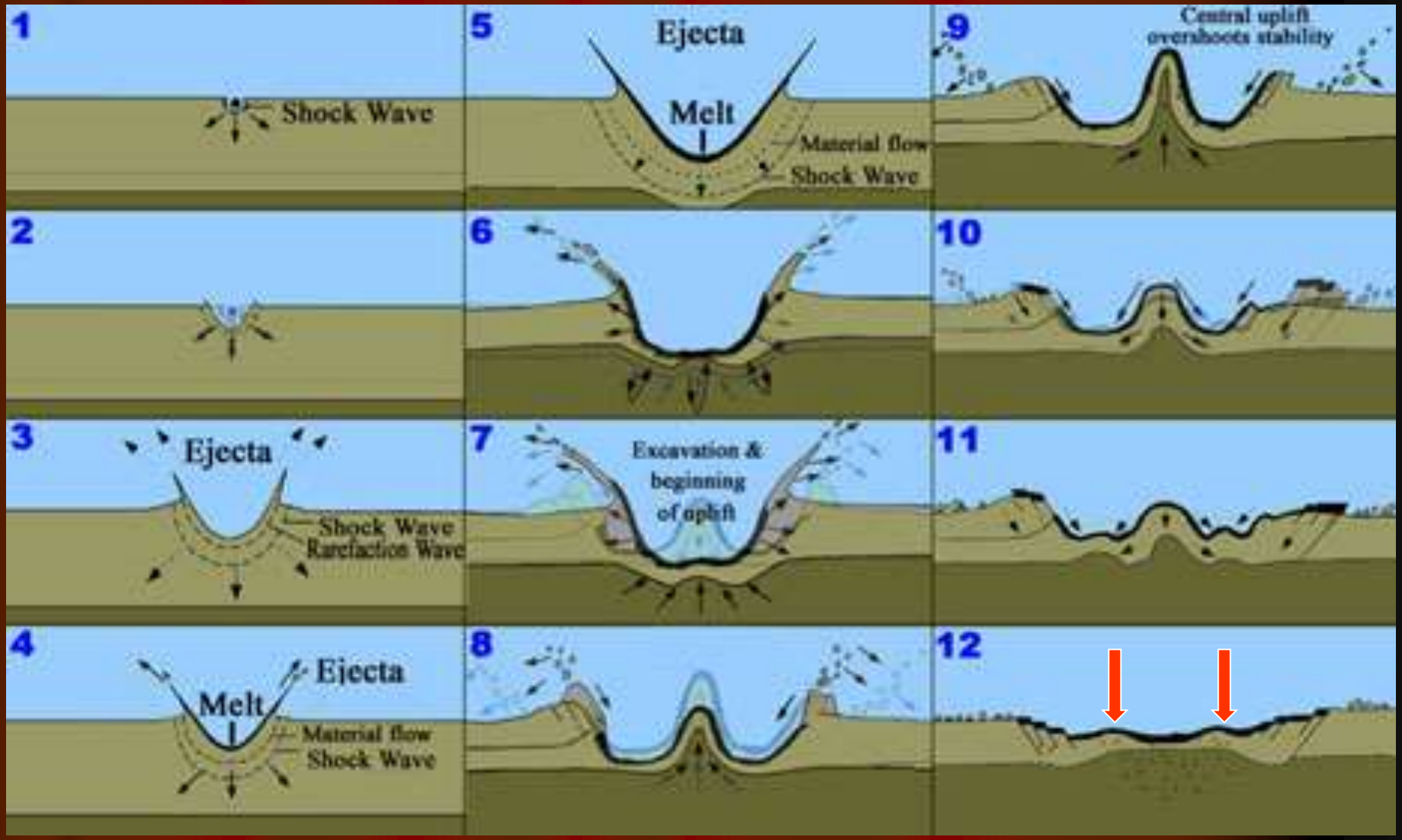




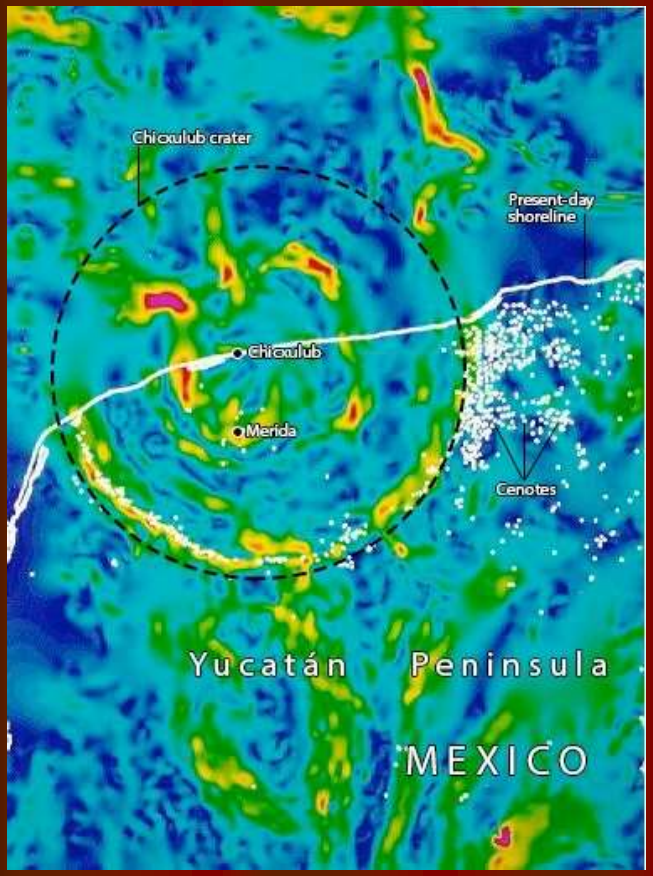
Microscope view of shock lamallae (multiple parallel lines, or planes)in a quartz grain (about 0.3mm across) that formed during impact of the Chicxulub asteroid. This sample is from the Cretaceous-Tertiary boundary clay at Teapot Dome, Wyoming.

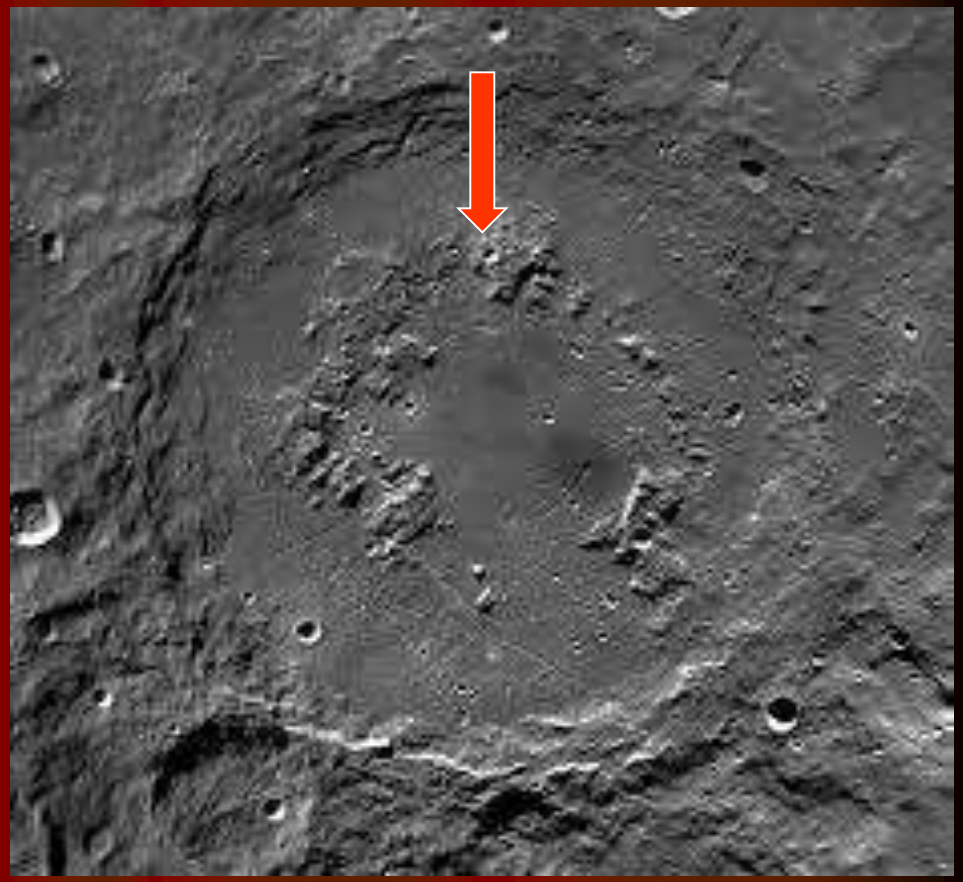
Image http://minerals.cr.usgs.gov/gips/na/space.html

Sequential formation of an impact crater also produce a Peak Ring



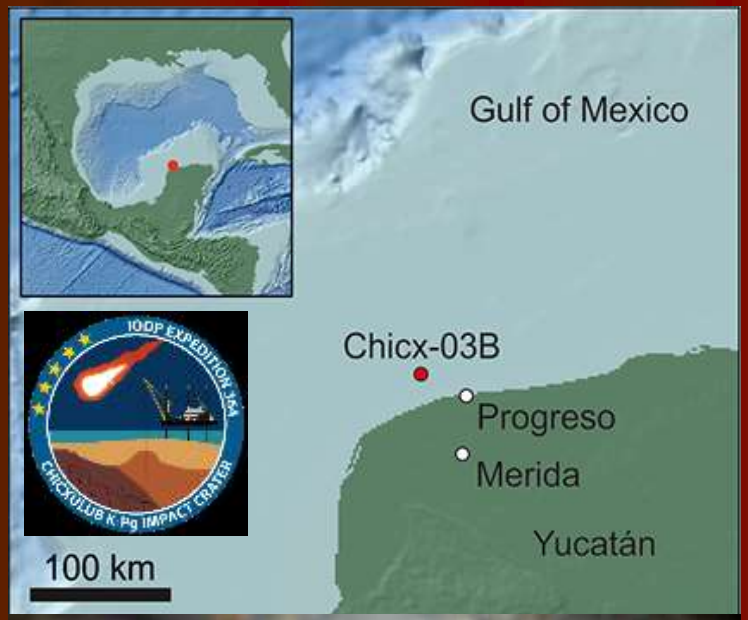
The Peak Ring of the Chicxulub closely resembles the moon's Schrodinger crater confirming its origin from meteorite strike

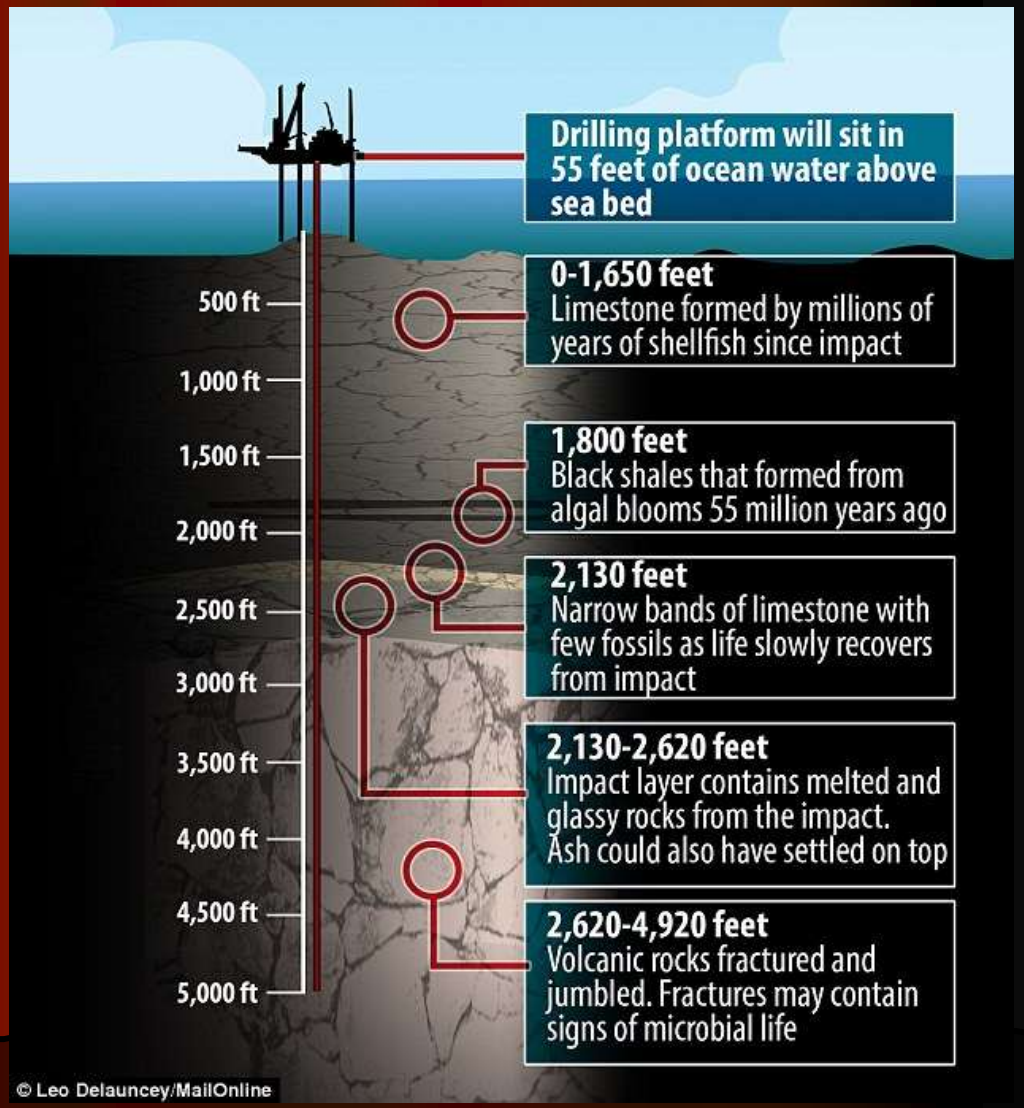




Drilling Chicxulub K-Pg Impact Crator 2016

The International Ocean Discovery Program Expedition (IODP) 364 will drill 1500 m deep to reach a buried peak ring, the Earth's only example

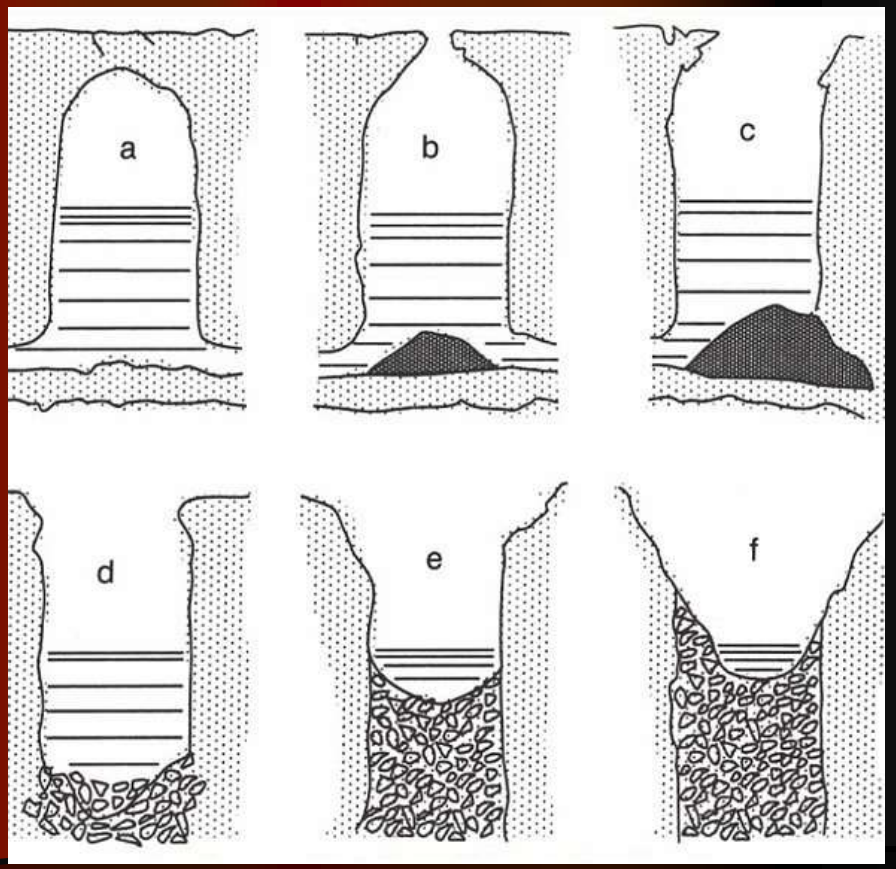




Ring of cenotes : the ring is a circular alignment of sink holes some 170 km in diameter & its formation is evidence of the impact event

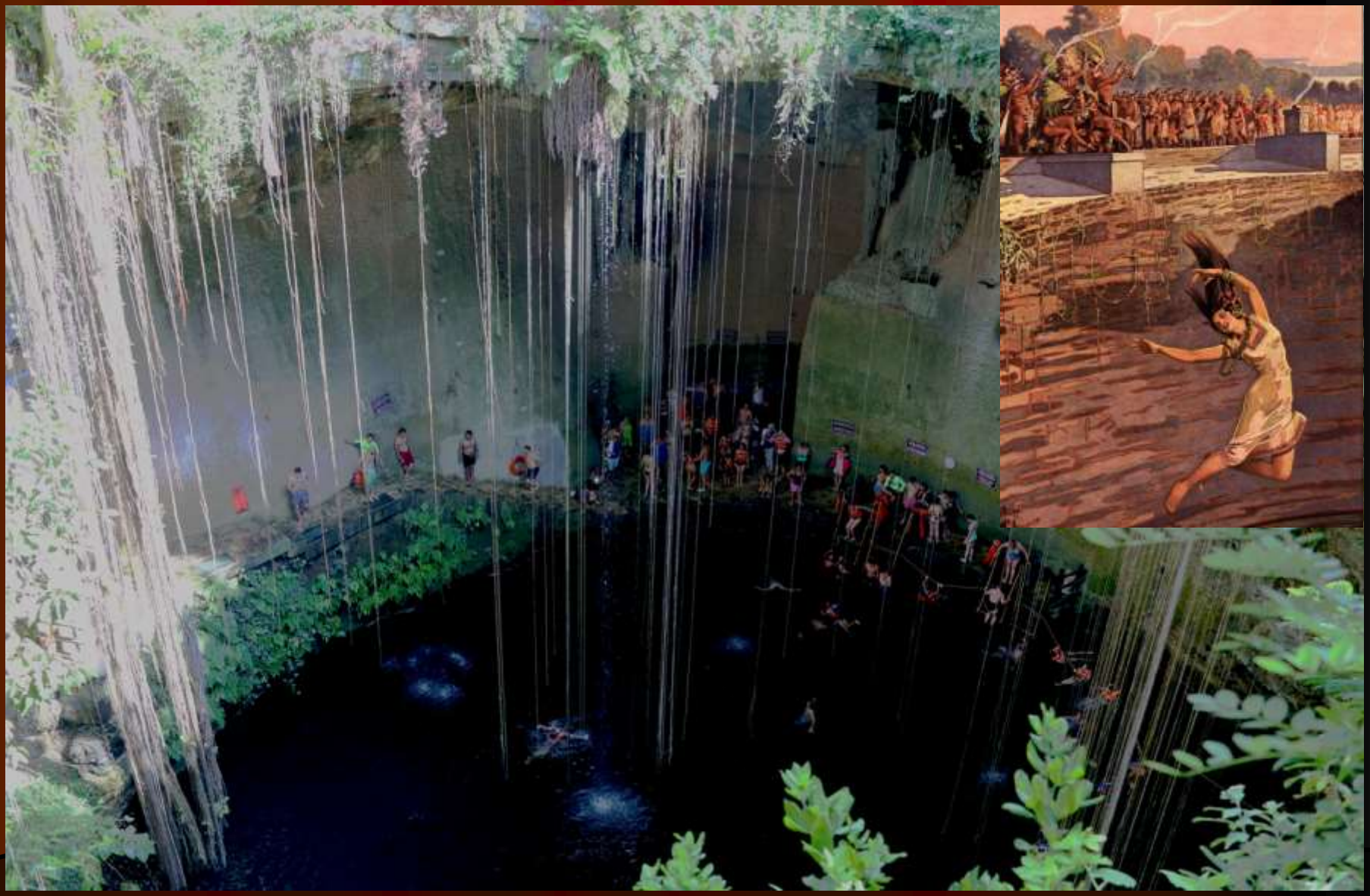
Cenote 溶洞 (cinotay)

The name means "sacred well" in Maya language which is the "passage to heaven". These are sink holes formed by the collapse of porous limestone bedrock which dominated the Yucatan Peninsula. There are around 6,000 to 8,000 cenotes & all have fresh clear water filtered by the rock. Drawing on the right shows the stages of development from young to maturity & drying up



Cenote Ik Kil at Chichen Iza

The water at Cenote Ik Kil Chichen Iza is 50 m deep & there are black catfish living in the cenote water



Hoba Meteorite

The Alte Feste Museum in Windhoek hosts the Hoba Meteorite 霍巴隕石 which is the world's largest measuring 2.95m X2.94m X1m weighing 66 tons. It contains 82.3% iron, 16.4% nickel & traces of cobalt. Fall some 80,000 years ago, it was found in 1920 but without locating any crater due to its table shape which increased the atmospheric drag & decreased the speed of the fall as well as the fact that it landed in a desert covered with thick layers of sand

The Hoba meteorite is classified as an ataxite, a structure-less relatively rare and very dense iron meteorite and shows no Widmannstetter pattern when etching. It is estimated that the meteorite contain sufficient iron-nickel to produce as many as 42,000 automobiles

The Gibeon Meteorite Shower 高抜流星雨

Reported in 1838 this is the largest meteorite shower known on Earth coming from broken asteroid fragments. Its strewn field 撒落場 is probably the largest in the world covering an area of 360 km by 100 km in the Great Nama Land, Namibia. Aged at around 4 billion years, these are iron-nickel meteorites which the Nama people have used to make tools and weapons. More than 25 tons have been recovered, exported & sold in Namibia until recently being banned by government

A total of 77 pieces have been found believed to be part of one large body over 15 tons. Specimens of Gibeon meteorite are being exhibited at the Post Street Mall in Windhoek Namibia. The weight of the 33 pieces in display ranges between 195 kg and 555 kg

Most pieces exhibit Regmaglypts 氣印 which are shallow pits resembling thumb prints formed by ablation when the meteor enter the earth's atmosphere at some 27 km per second

The Gibeon meteorite is classified as a medium Octahedrite which is composed of 91.8% iron, 7.7% nickel & 0.5% of cobalt. The crystal structure of the Gibeon meteorites display classic Widmannstetter pattern (Thomson structure) when cut into slices & etched with acid which is unique in meteorite due to very slow cooling (1C in 1,000 years). Such features are highly appreciated by collectors as well as jewelry designers



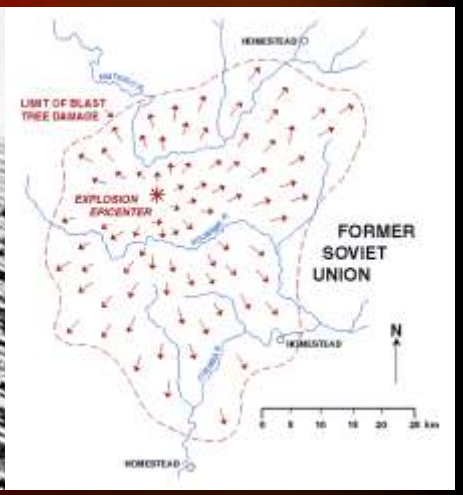




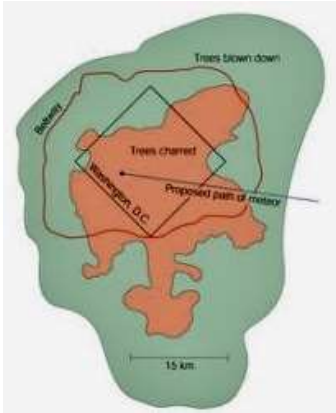

The Tunguska Event

In 30th June 1908 : The huge explosion in Siberia is generally believed to be caused by an Apollo asteroid impact. The explosion force of the airburst is as much as *15 -30 mega ton of TNT resulting in 2,000 km2 of devastation similar in size to Washington DC but no crater. Destroyed 80 million trees. Still no trees after 1,000yrs

(*1000 times Hiroshima)



BAYKIT
STRELKA
MUKHTUYA
STONY TUNGUSKA R.
CHUNYA R.
EXPLOSION EPICENTER
VANAVARA
TETERE
TETERE R.
VITIM
YENISEI R.
KEZHMA
YENISEI
ANGARA R.
LENA R.
VITIM R.
CHUNA (UDA R.)
KIRENSK
BIRYUSA R.
ANGARA R.
TRANS-SIBERIAN R.R.
KOBSK
BRATSK
AREAL EXTENT OVER WHICH THE BOLIDE WAS SIGHTED
PATOM R.
N
OKA R.
LENA R.
LAKE BAIKAL
0 100 200 300 400 Km
IRKUTSK
FORMER SOVIET UNION



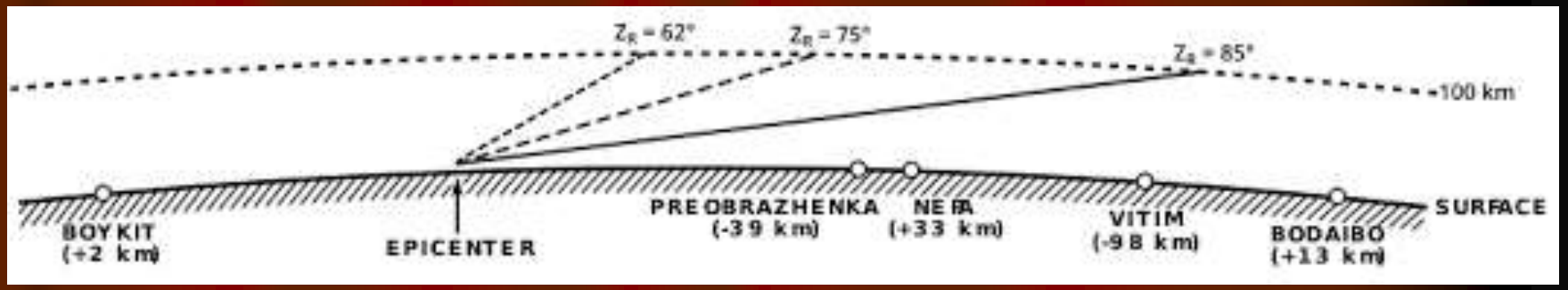


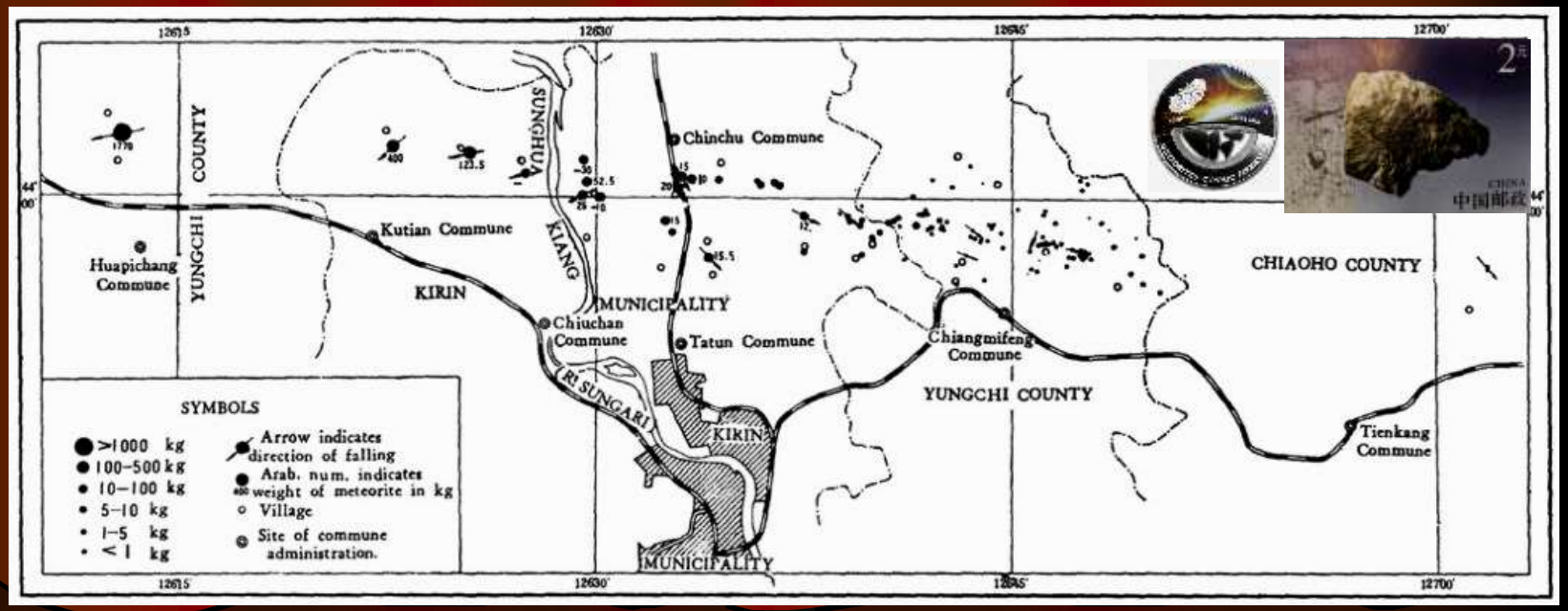
Fig. 3. "Dental crown" stone with spherical depression on convex side and tracks of solidification of couple of liquid vortexes

Fig. 4. Damages on the surface of "whale" stone and melted collar flange on the surface of "boat" stone

- Emerald bought to earth by the asteroid ? Russian scientist suspected that these stones called Kanskite travelled with the Tunguska meteorite. Similar stones but smaller were later found at the epicenter

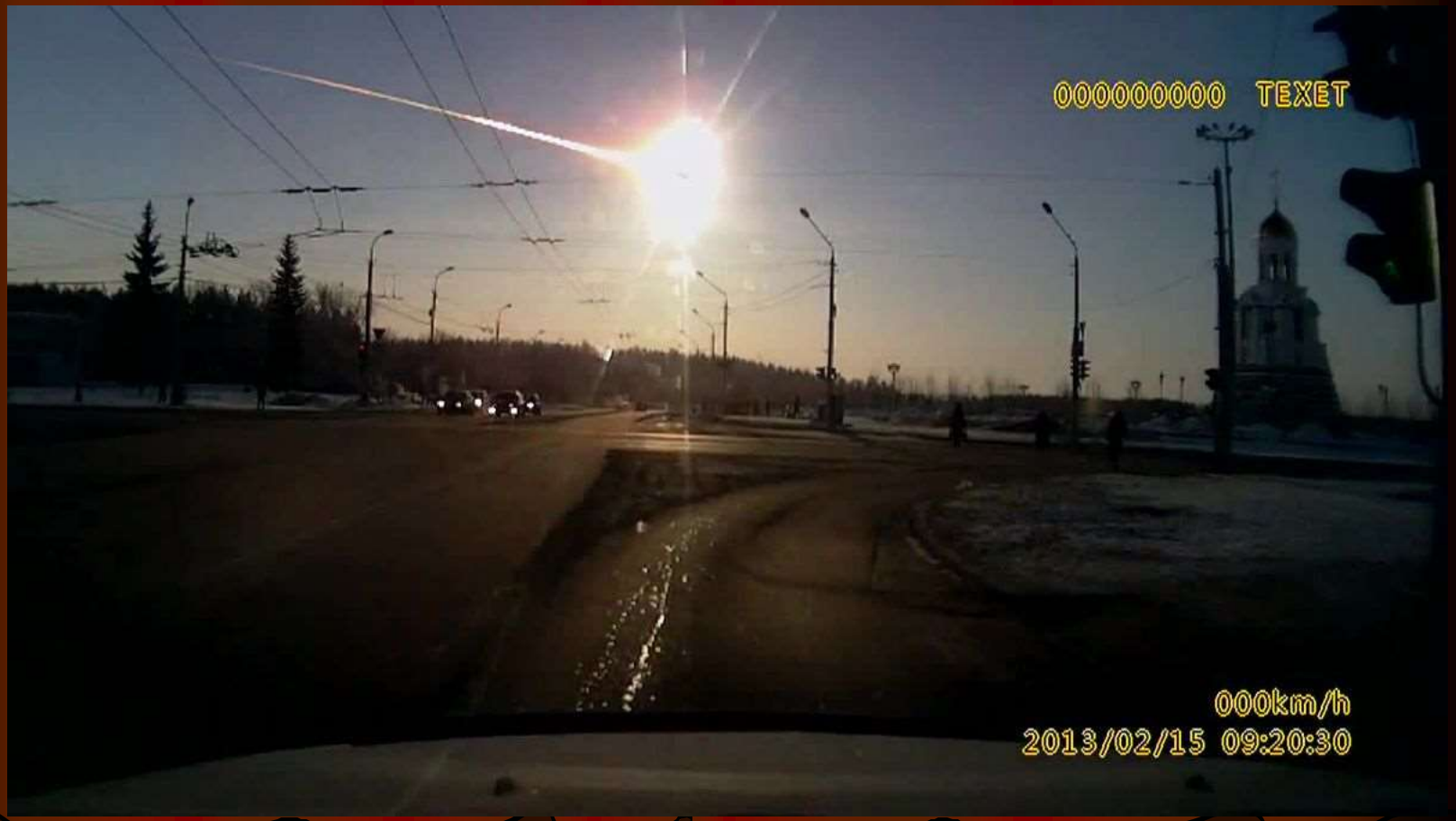
The Jilin Meteor Shower

In March 1. 1976 a 20m a large meteor shower took place in Jilin. Classified as an olivine bronzite chondrites, more than 100 pieces were collected with the largest weighing 1770 kilogram making it the largest stony meteorite in the world

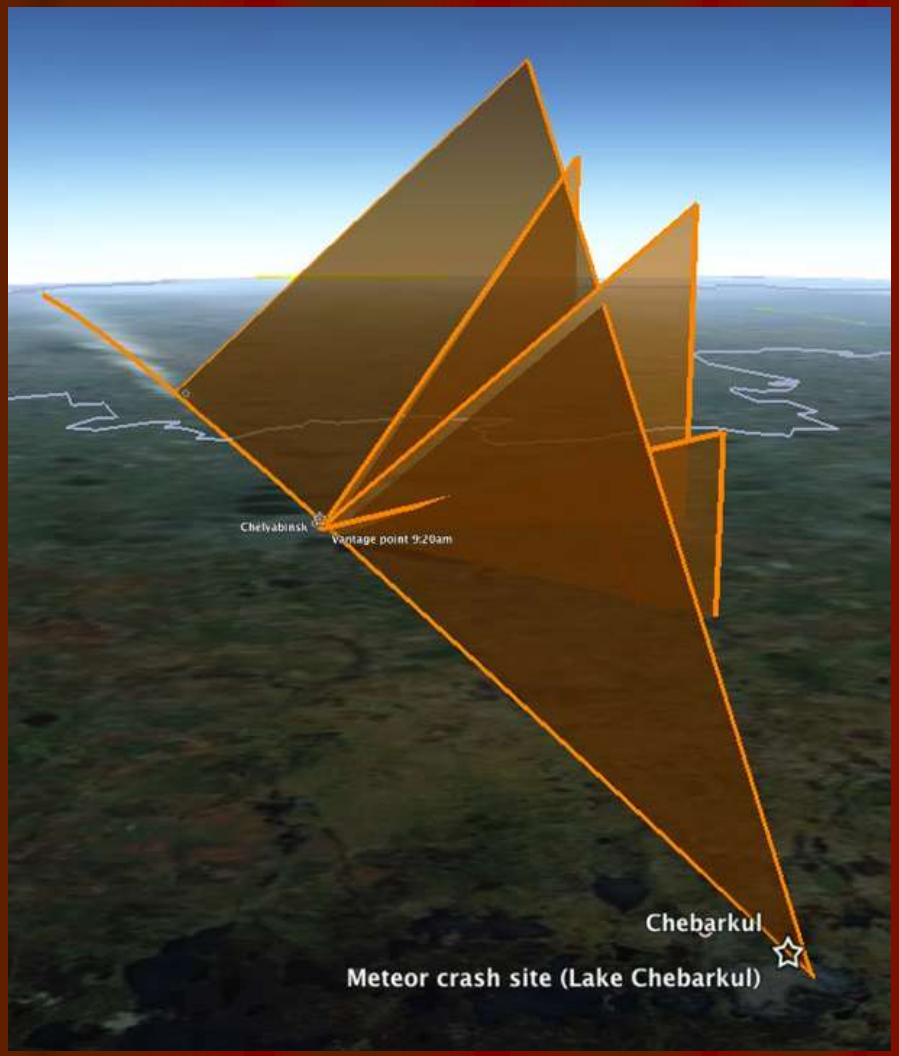


The Chelyabinsk Meteor

In Feb 15. 2013 a 20m asteroid exploded over the Russian city of Chelyabinsk injuring 1,500 people & damaged 7,200 buildings. The blast released the energy equivalent to 30 Hiroshima atom bombs. This occurred on the same day a 30m asteroid called 2012 DA14 missed earth by just 27,000 km !



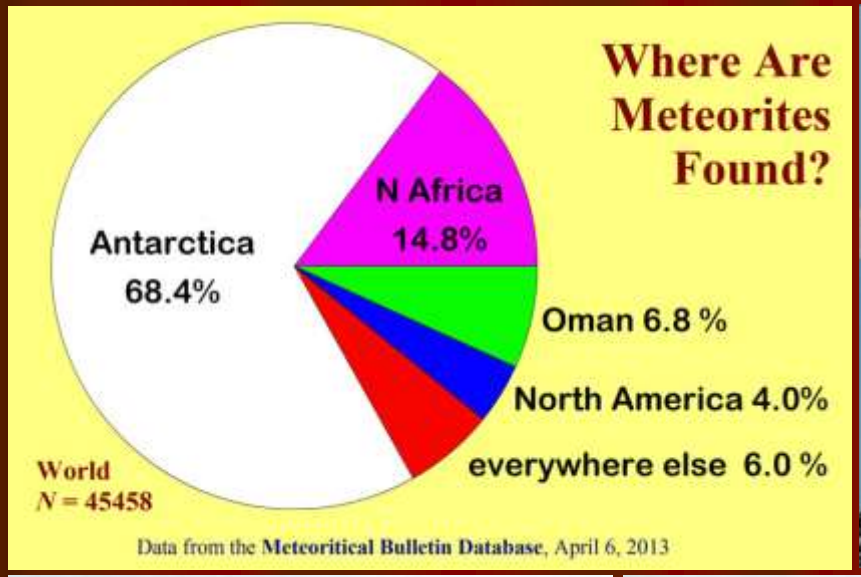
- The 17 m diameter 10,000 ton asteroid hit the atmosphere at 18km/s producing a very bright fireball and exploded before landing

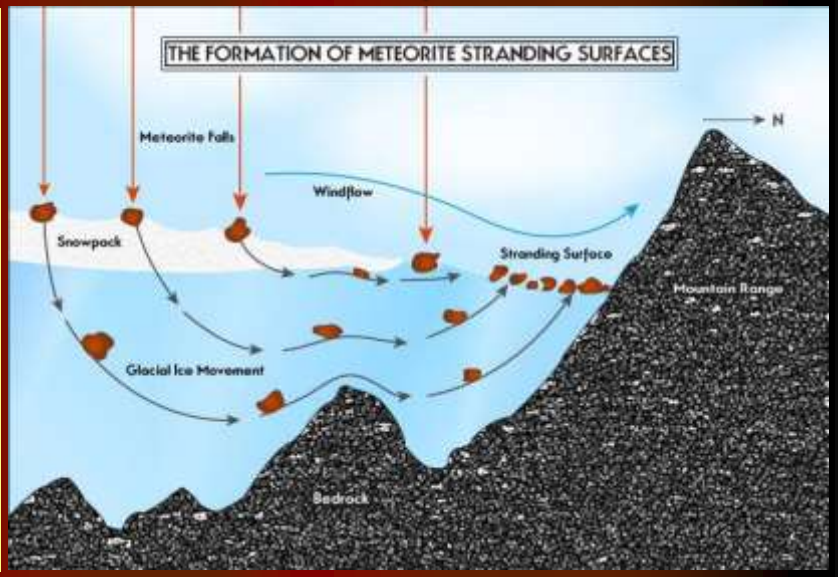


- The blast happened over 23 kilometres above ground so most of the energy was absorbed by the atmosphere and nobody was killed. Still the shockwave shattered 6 Russian cities and the Superbolide temporarily blinded many observers on the ground. 12 fragments of the meteorite have beech recovered. One example has been classified as a chondrite with very low level of iron and made up of silica, nickel and cobalt compounds

Antarctic Meteorite

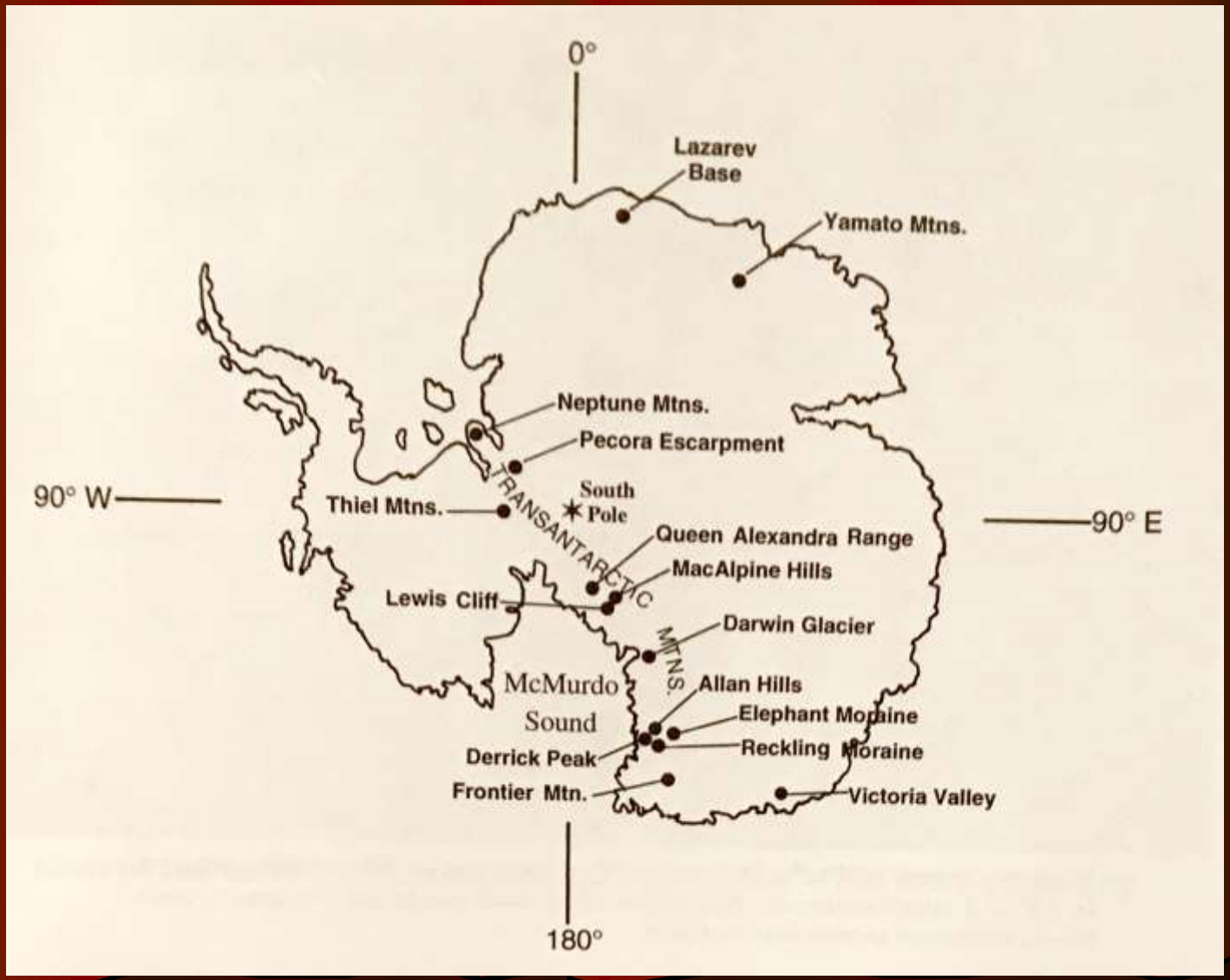
Meteorites are most valuable for the study of the origin and structure of the universe. Up to 68.4% of all meteorites collected totaling 35,000 pieces were from Antarctica with the Japanese National Institute of Polar research (NIPR) having the largest collection totaling 16,000 pieces. USA is second and China third with 12,665 pieces collected





Meteorite finds in Antarctica

Note most of the locations are along the edge of mountain ranges



Project AMLAMP & ANSMET

Meteorite collecting in Antarctica is a major operation

LUNAR & PLANETARY INSTITUTE

AMLAMP

ANTARCTIC METEORITE LOCATION AND MAPPING PROJECT

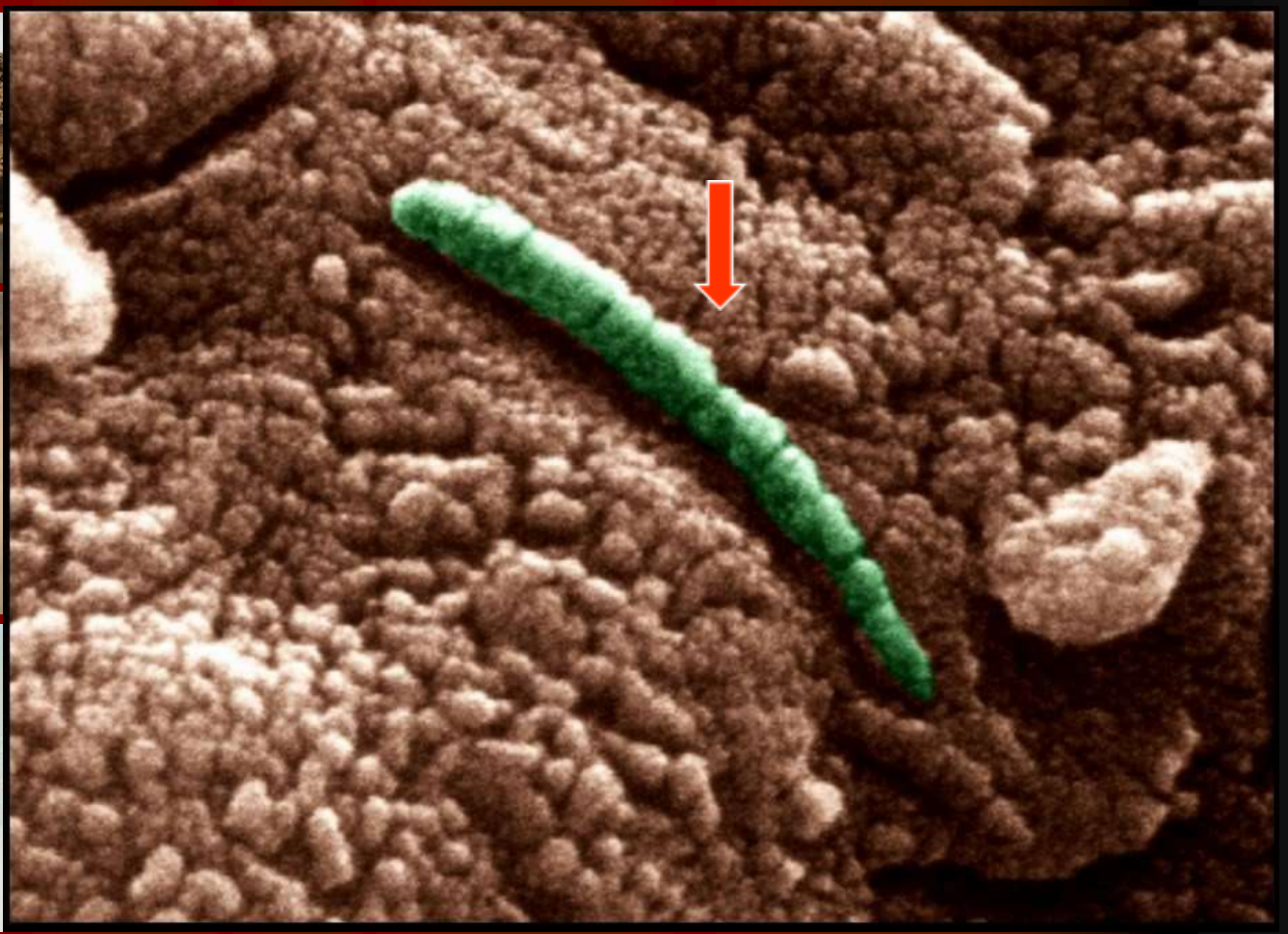
ANSMET

The Antarctic Search for Meteorites

NASA

Smithsonian Institution

- ALH84001 – a meteorite from the Mars surface found in Antarctica in 1984 alleged to contain fossilized bacteria life form !

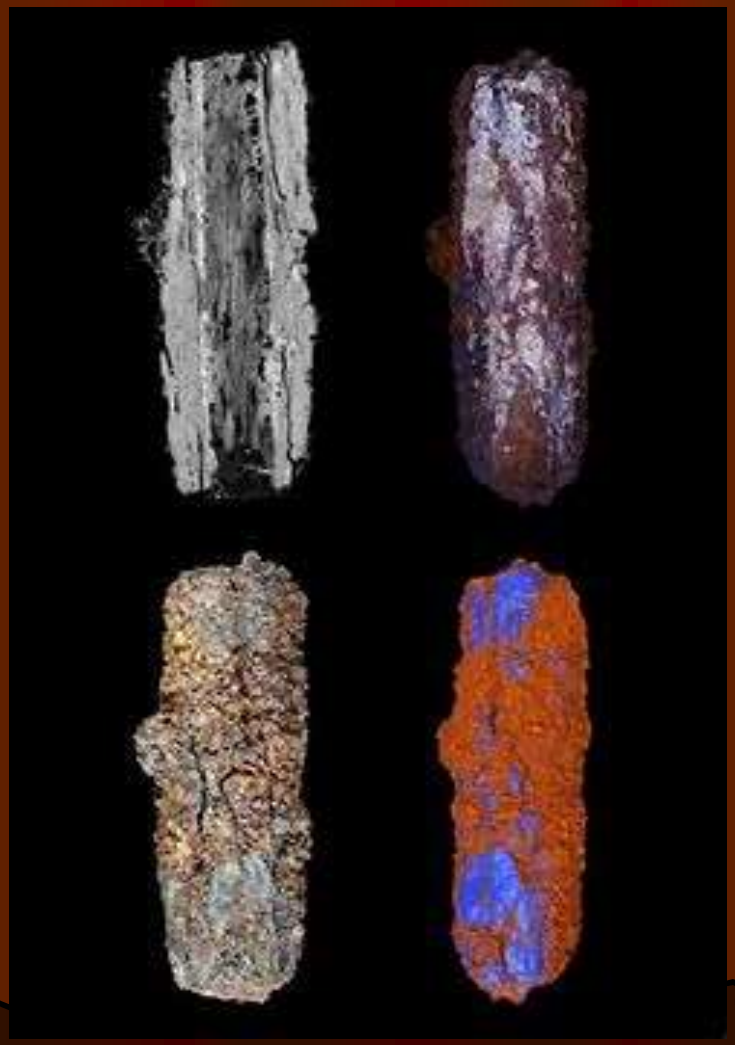


- Two carbonaceous chondrites collected in Antarctica in 1992 and 1995 were found to be abundant in amino acids which are present at concentrations of 180 and 249 ppm (normal content 15 ppm). This could indicate that organic material is more abundant in the Solar System than was previously thought and reinforces the idea that the organic compounds present in the primordial soup could have had an extra-terrestrial origin

- Jan 2013 located a 18 kilo meteorite which is the 5th largest ever discovered and the biggest found in 25 years

Interesting Objects

- Meteoric iron was already used before the arrival of the Iron Age to make tools and weapons. The term "ba-en-bat" in Egyptian means "metal from Heaven". Ancient Egyptians were known to forge iron beads and trinkets from meteoric iron. The beads below left were 5,000 years' old



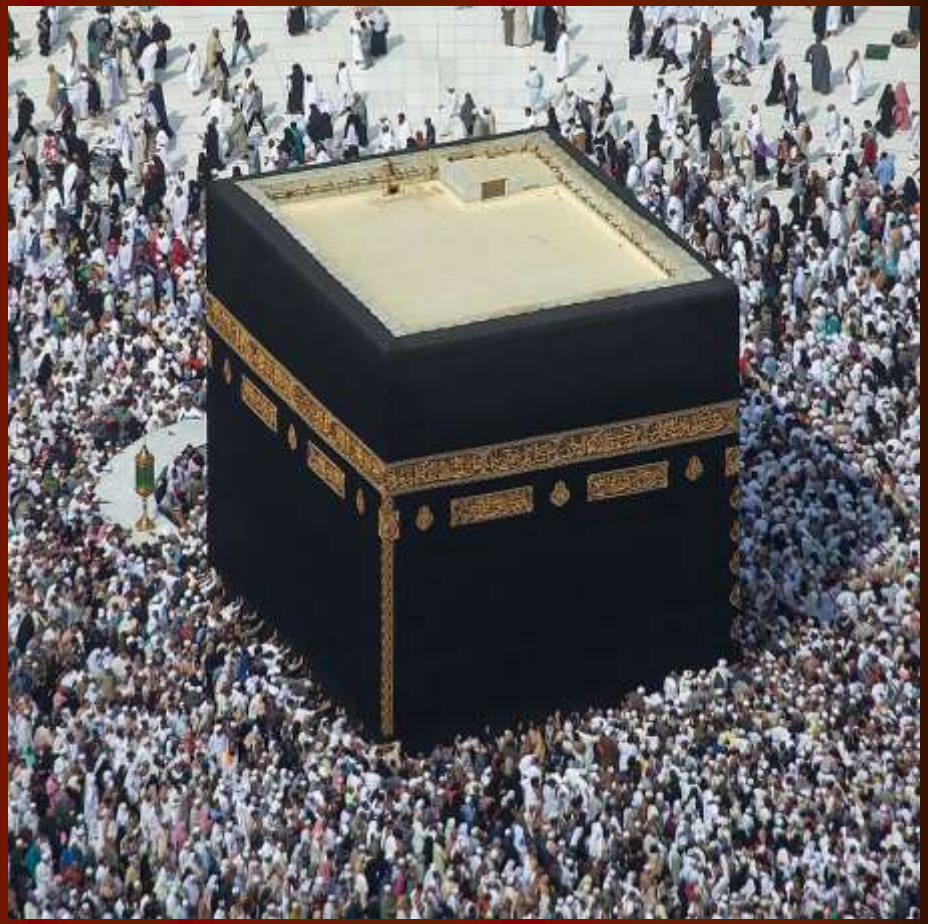
- King Tutankhamm's dagger was made with iron from a meteorite. The dagger's metal has not rusted. It was supposed to be a gift from the gods. Probably forged from a meteorite called Kharga (1341-1323 BC)

The 13th C Egyptian hieroglyph at upper right means "iron from the sky"

- Libyan Desert Glass (LDG) from the Sahara Desert was used to make tools during the Pleistocene and ancient Egyptian also used it to make jewellery including this Tutankhamen's scarab pendant

- The mysterious magnetic stone ball at Ahe Te Pito Kura meaning the "navel of the world" is a meteorite alleged to be bought to the Easter Island by King Hotu Matu which had supernatural power and served as a symbol of his authority

- The Black Stone of Islam 20 cm by 16 cm it is attached to the east corner of the Kaaba which is located at the center of the Grand Mosque in Mecca, Saudi Arabia. The stone has never been analyzed scientifically but some believed it is a meteorite or impactite that fell 6,000 years ago at Wabar



- The "Iron Man" is an ancient Buddhist statue brought back by a Nazi expedition from Tibet shortly before World War II. It was probably carved from an ataxitre meteorite called Chinga which crashed on Earth thousands of years and discovered in Russia in 1913

- A bracelet crafted from stone meteorites recovered in the Sahara

- A knife made for Mughal emperor Jahangir, partially made of meteoric iron with gold inlay, 1621, India

- A dragon tanto knife with the blade also made from the Gibeon iron -nickel meteorite

- A Russian letter opener with a Damascus meteorite blade

- A meteorite knife forged from the Breham Gibeon, Henbury and Chinga meteorites

Apart from making tools and weapons the Thomson structure of the Gibeon meteorite when cut into slices & etched with acid are highly appreciated by collectors as well as jewelry designers but there are fake ones produced in China by plating on rusty Muonionalusta meteorite. Gibeon meteorite were used for jewelry such as watches, rings, cuff links, ear rings and ball pens





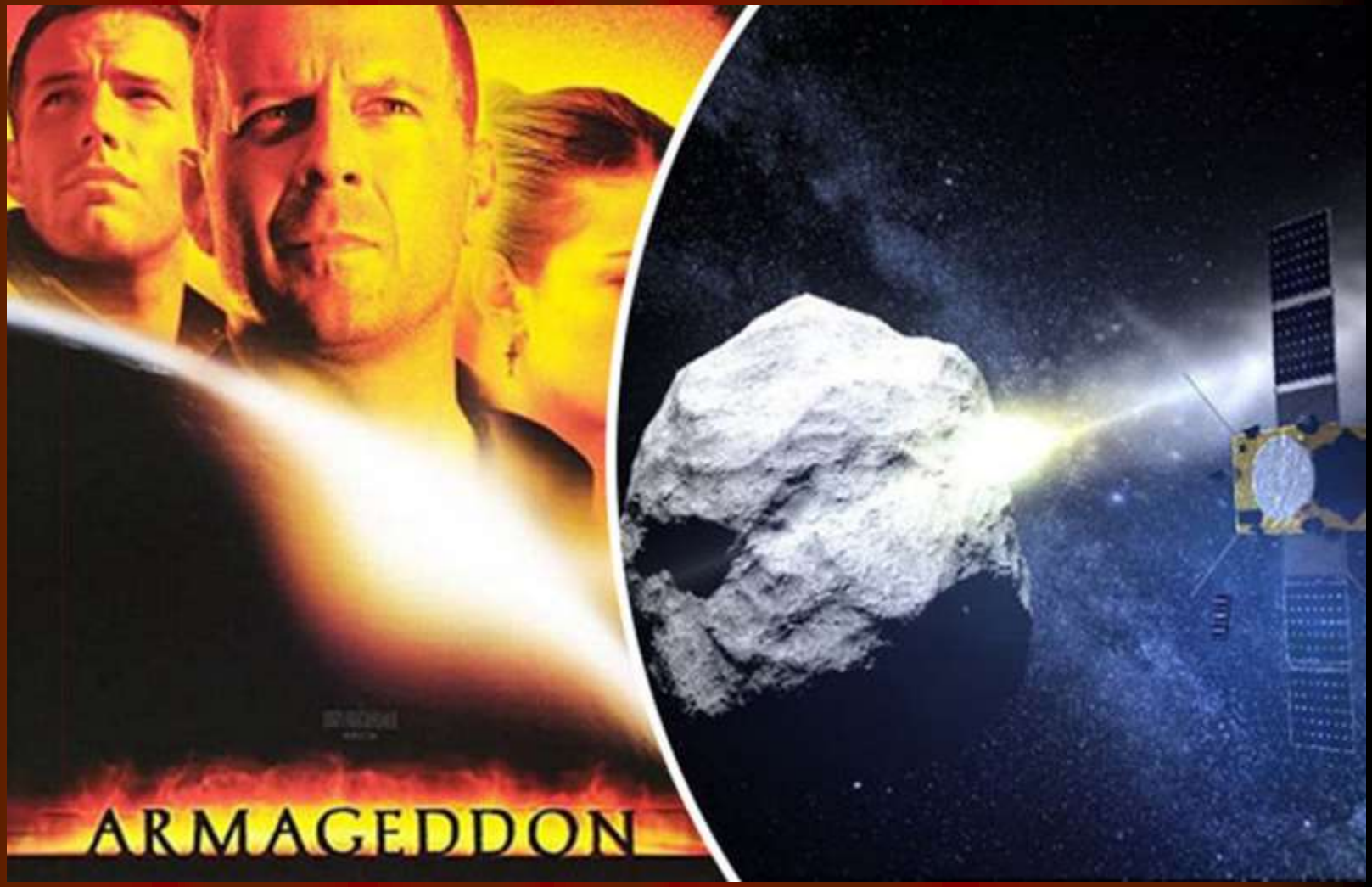

- A matching set of silver earrings and pendant made from the Muonionalusta meteorite each containing a piece of the meteorite and a cabochon of Moldavite

- Pendants, brooch and cuff links made from pallasite meteorite tablet containing natural peridot crystals

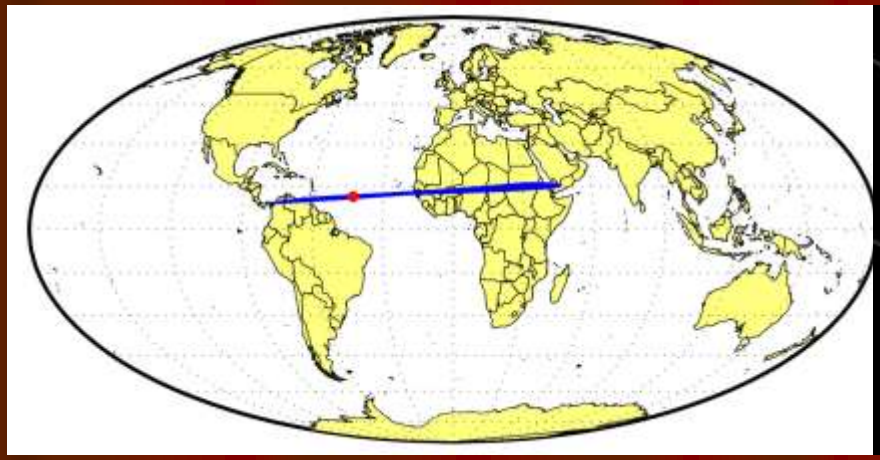
Protection from future impact

"An asteroid collision is considered to be the biggest threat to our planet !"

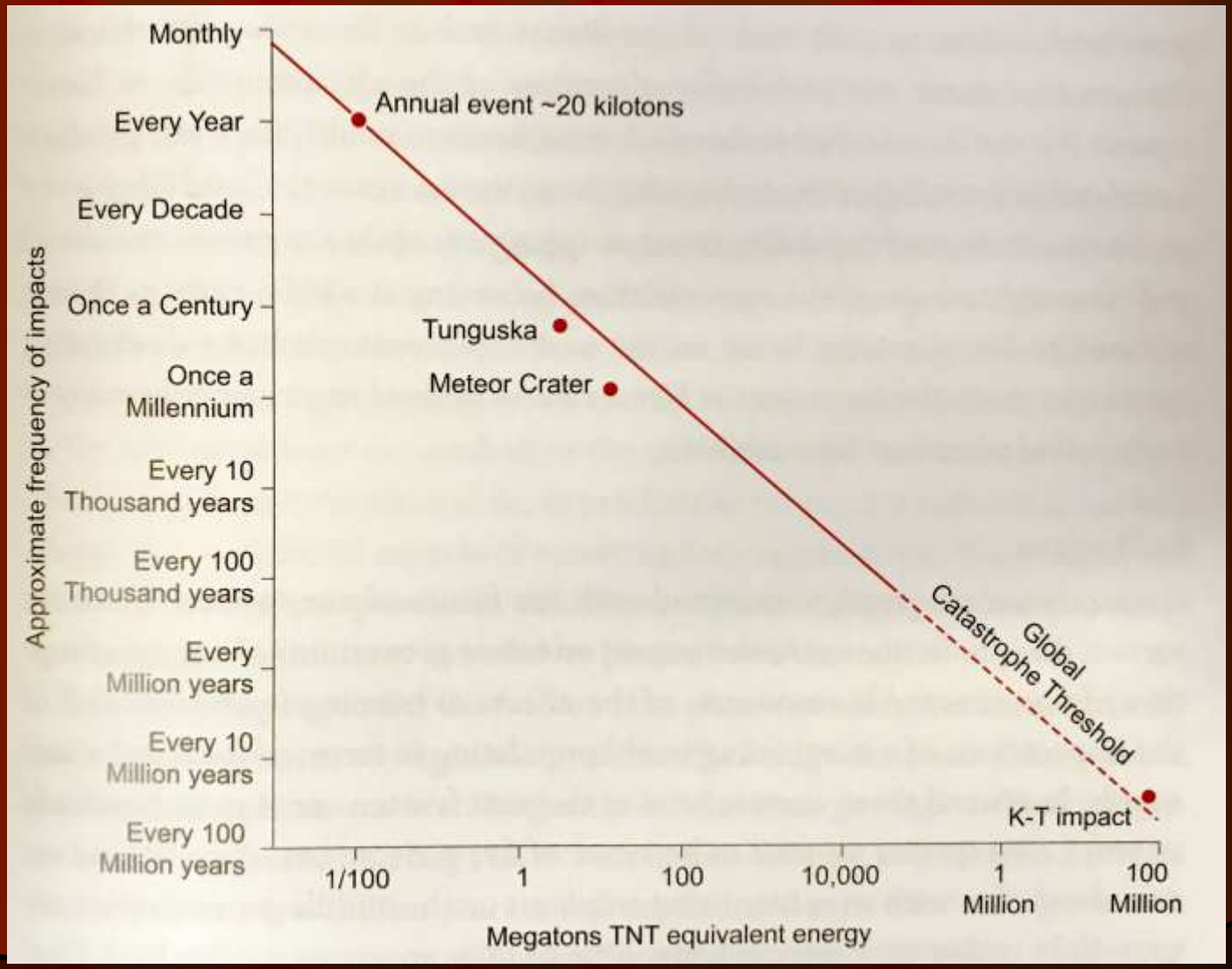
Physicist Stephen Hawking



On March 5th 2014 Asteroid 2014 DX110 of the Apollo Group approximately 30m in diameter passed Earth with the closest approach at about 9/10 of the distance between the Earth and the Moon which is really quite close !



Scientists estimated that it seems likely Earth will be struck by a 10 km object approximately once every hundred million years, a 1 km object once every 200,000 years and a 10-100 metre object once a century



Study, Locate, Track, Analyse, Neutralise

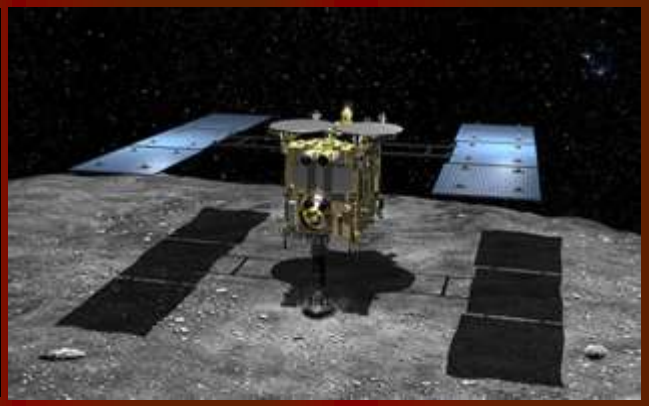
Study using space crafts

1997-2001 NEAR Shoemaker landed on 433 Eros

1999 Deep Space 1 studied 9969 Braille

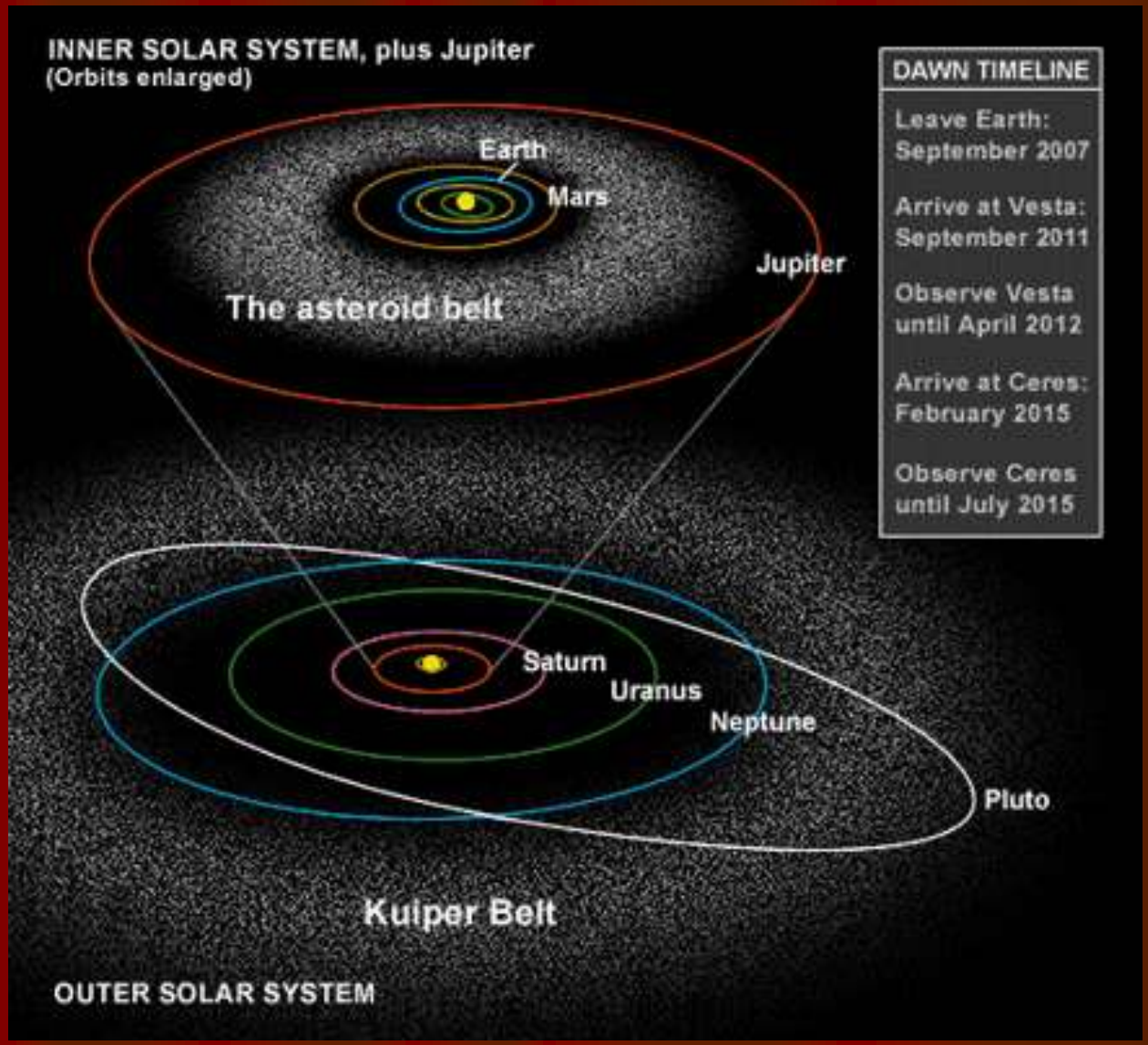
2002 Stardust studied 5535 Anne frank & comet 81P/Wild

2005 Japanese Hayabusa studied 25143 Itokawa

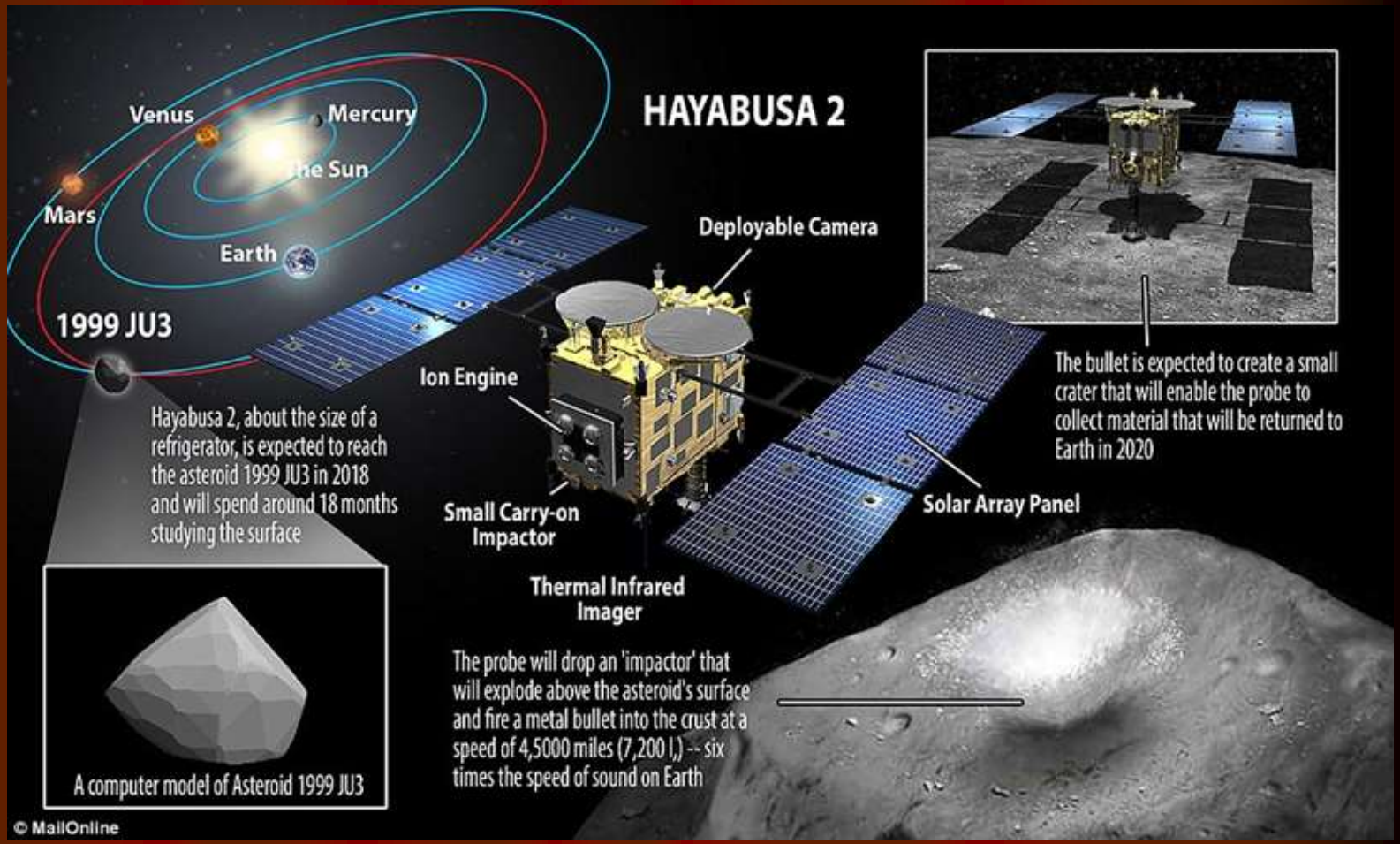


2006 NASA Stardust the first spacecraft that has bought comet dust to Earth

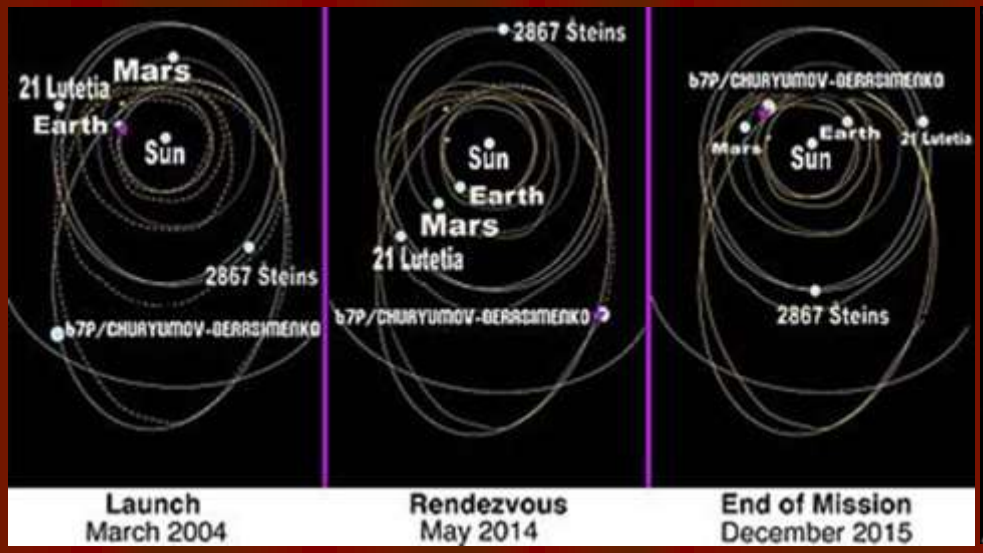
2011/15 NASA Dawn space craft orbited 4 Vesta & 1 Ceres



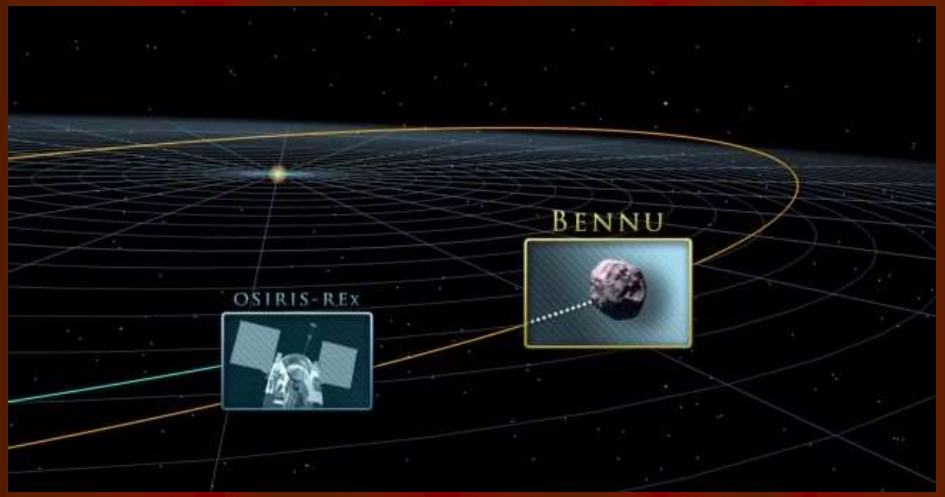
2014 Japanese Aerospace Agency launched Hayabusa 2 and plans to return samples from 162173 Ryugu in 2020

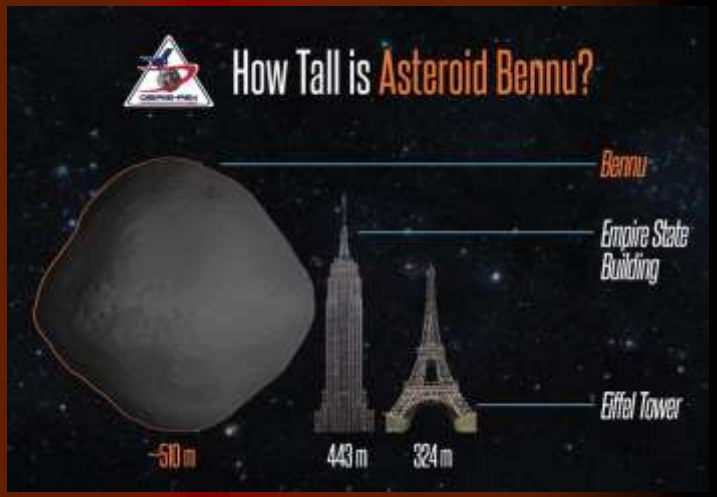


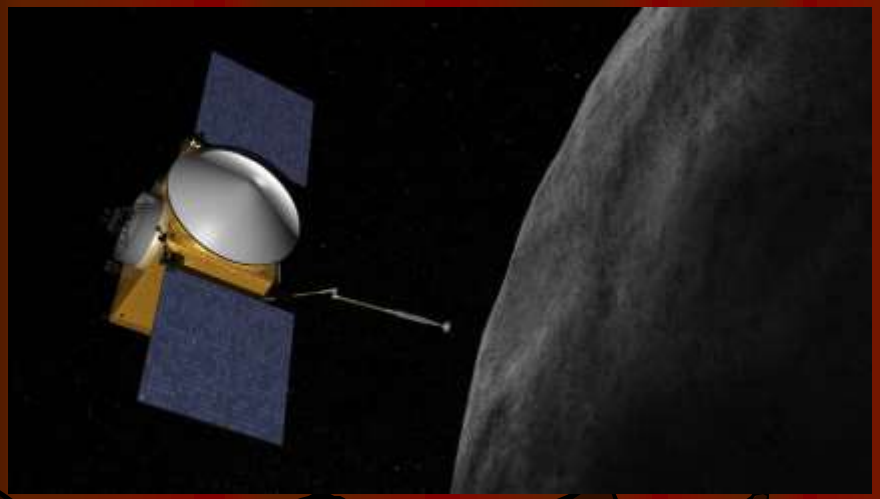
2015 Rosetta spacecraft completed exploring asteroid 21 "Lutetia", asteroid 2867 "Steins" and comet 67P. It crashed onto 67P on 30th September 2016



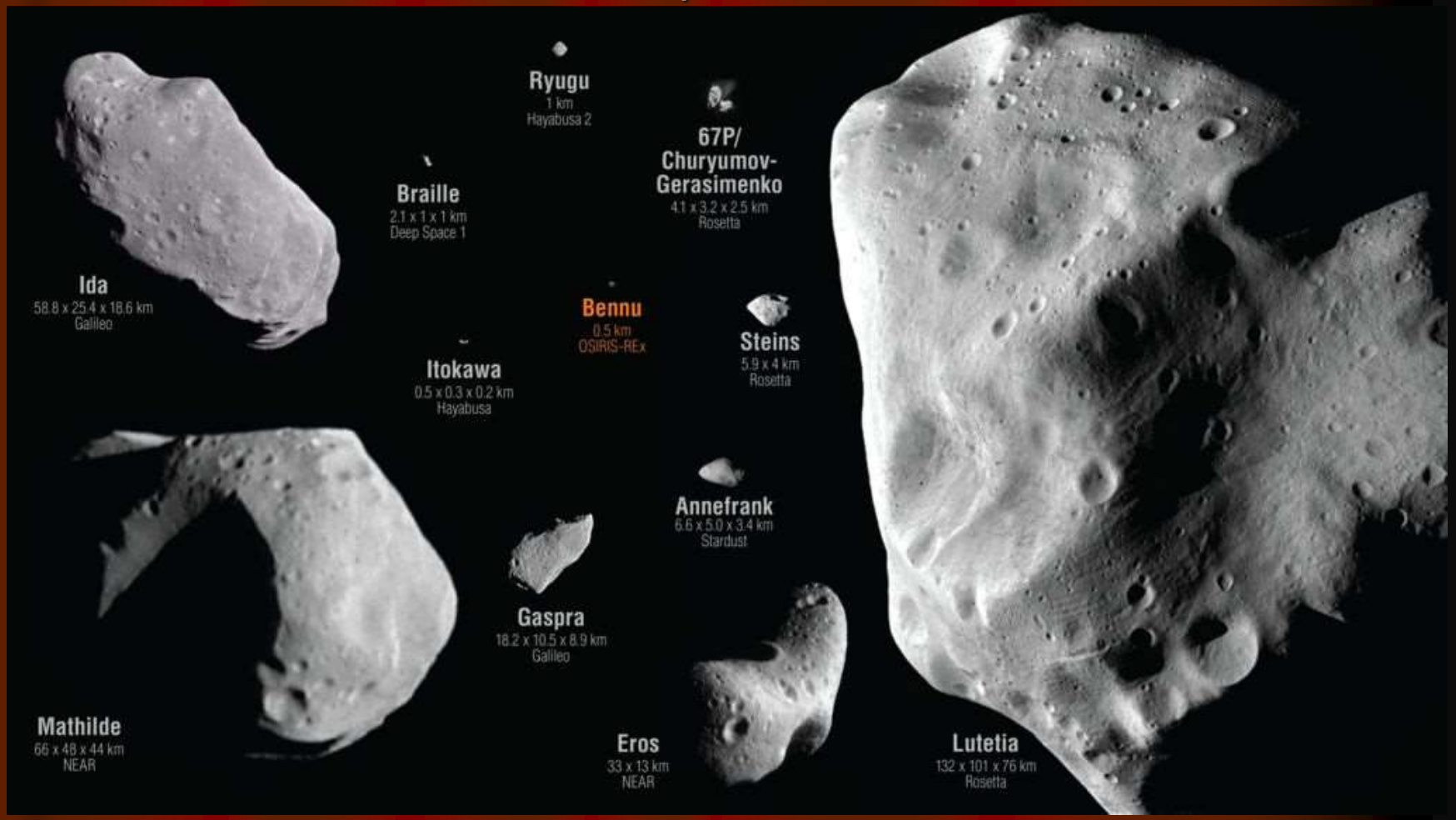
2016 the Regolith Explorer (Osiris-Rex) was launched by NASA to study asteroid 101955 Bennu & to return a sample on earth in 2023. The chance for Bennu to strike Earth in 2175 is 1/2700. The project will cost US$800 million







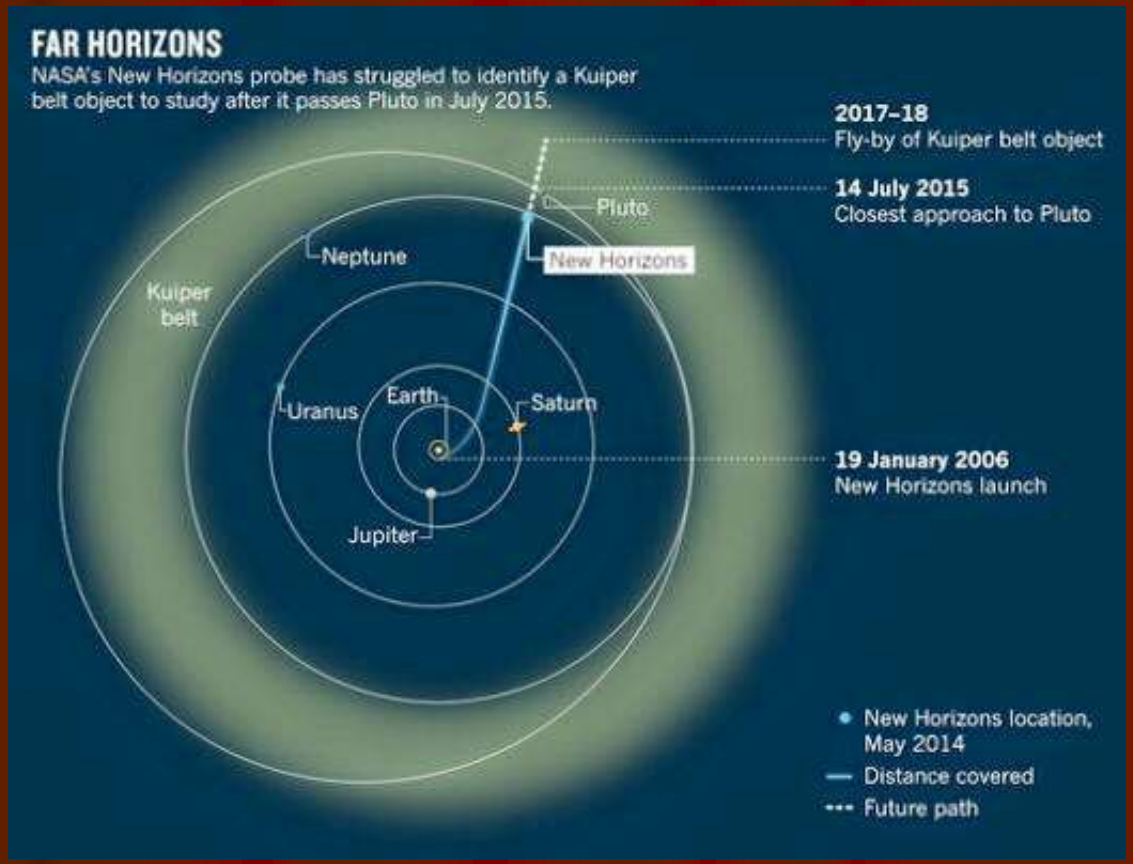
Size of Bennu compared to other asteroids



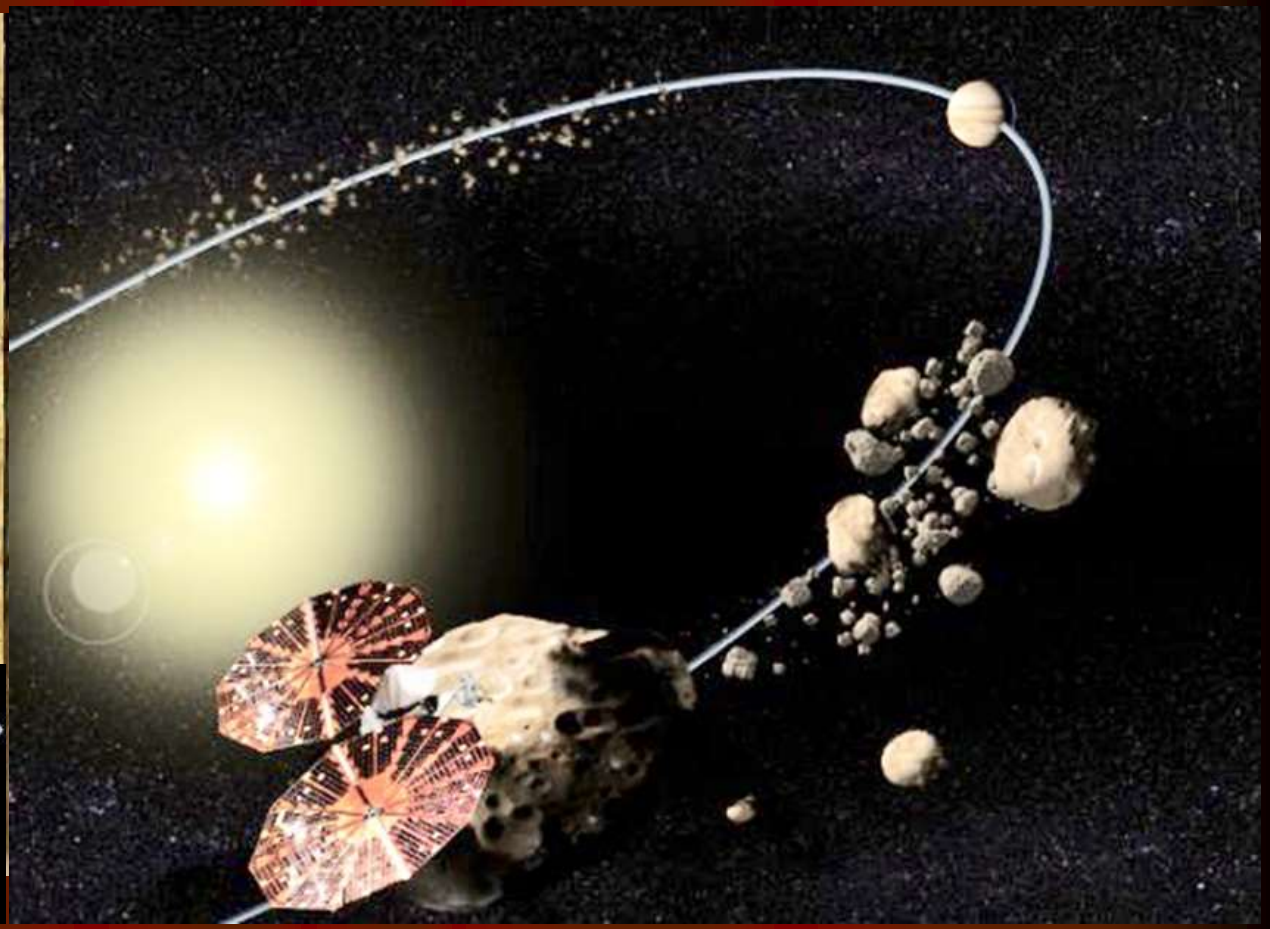
- Asteroid Psyche – a US$750 million NASA project to build and send a spacecraft also called Psyche in 2022 to investigate this asteroid which is probably the dead metallic heart of an ancient obliterated planet

Artist rendering of Asteroid Psyche surface

- NASA New Horizon – May 2019 flyby MU69 nicked name Ultima Thule which is about 36 km long located in the Kuiper Belt making it the farthest exploration of an object in history – 4 billion miles from Earth

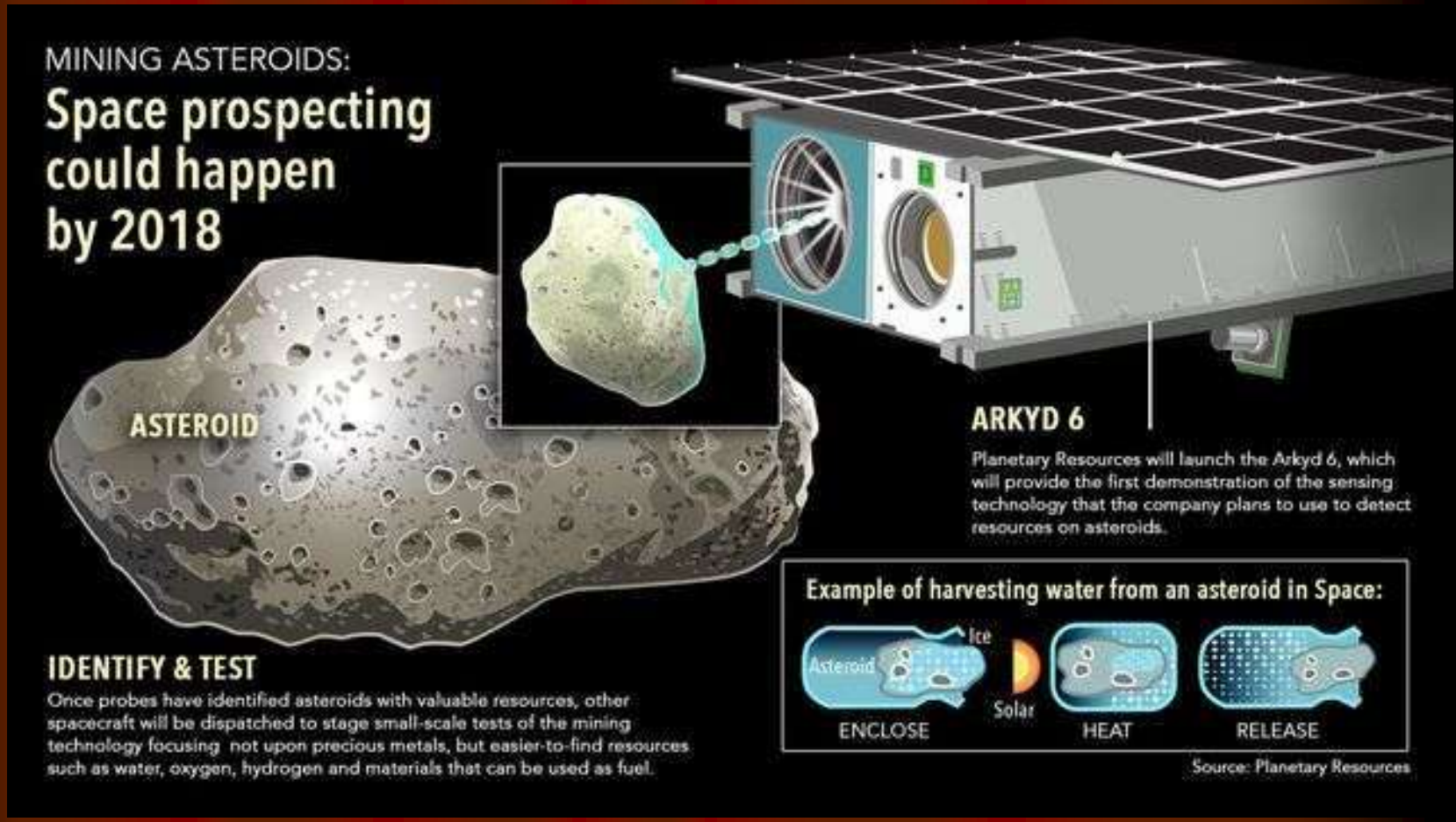


- NASA planned Lucy spacecraft to orbit 6 Jupiter Trojans. Launched 2021

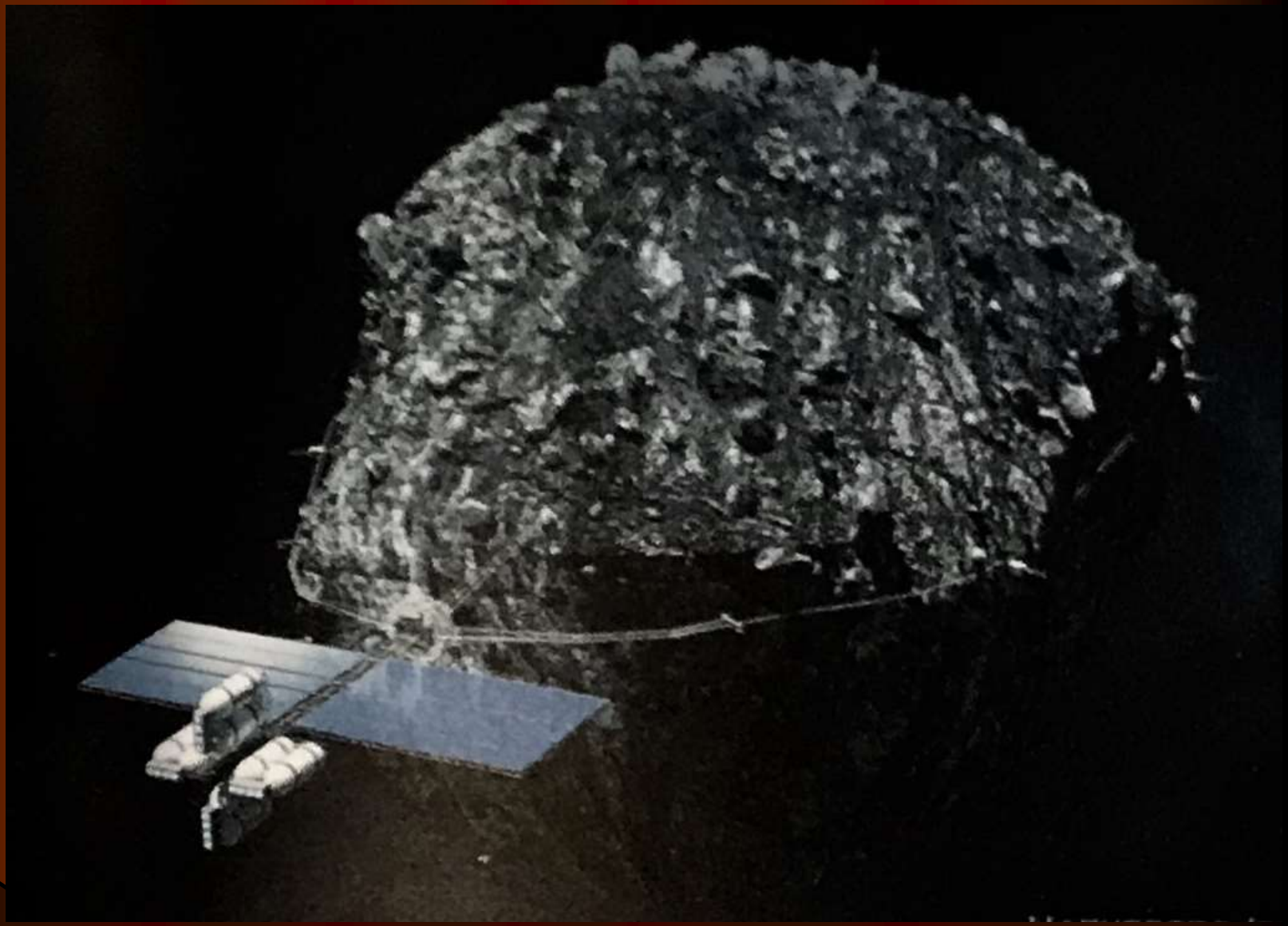


- NASA planned to capture an asteroid 2011 MD in the early 2020s and move it into lunar orbit where it could be visited by astronauts and later impacted into the Moon

- Asteroids can be very useful as a gateway for man's future space exploration by providing drinking water, fuel, breathable air and also a source of rare minerals such as platinum and iridium

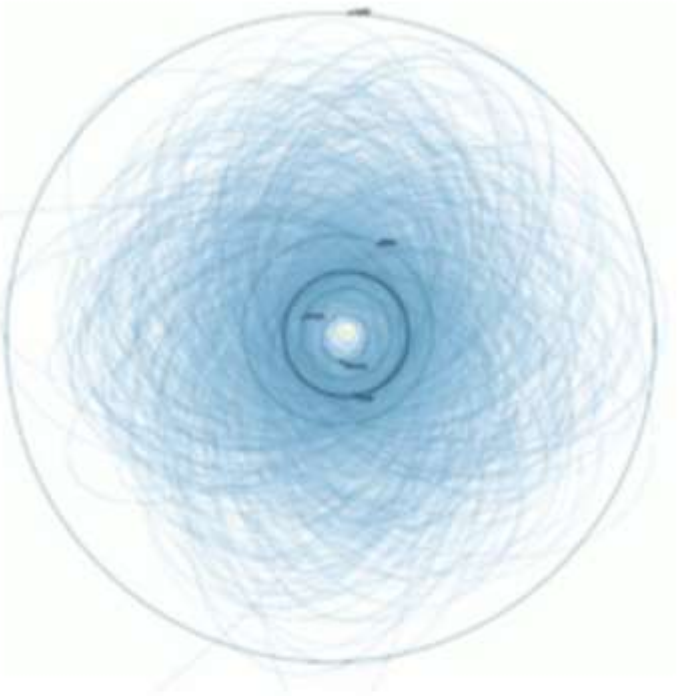


- Artist conception of how a solar powered robotic vehicle would lock onto a small asteroid and extract the ore

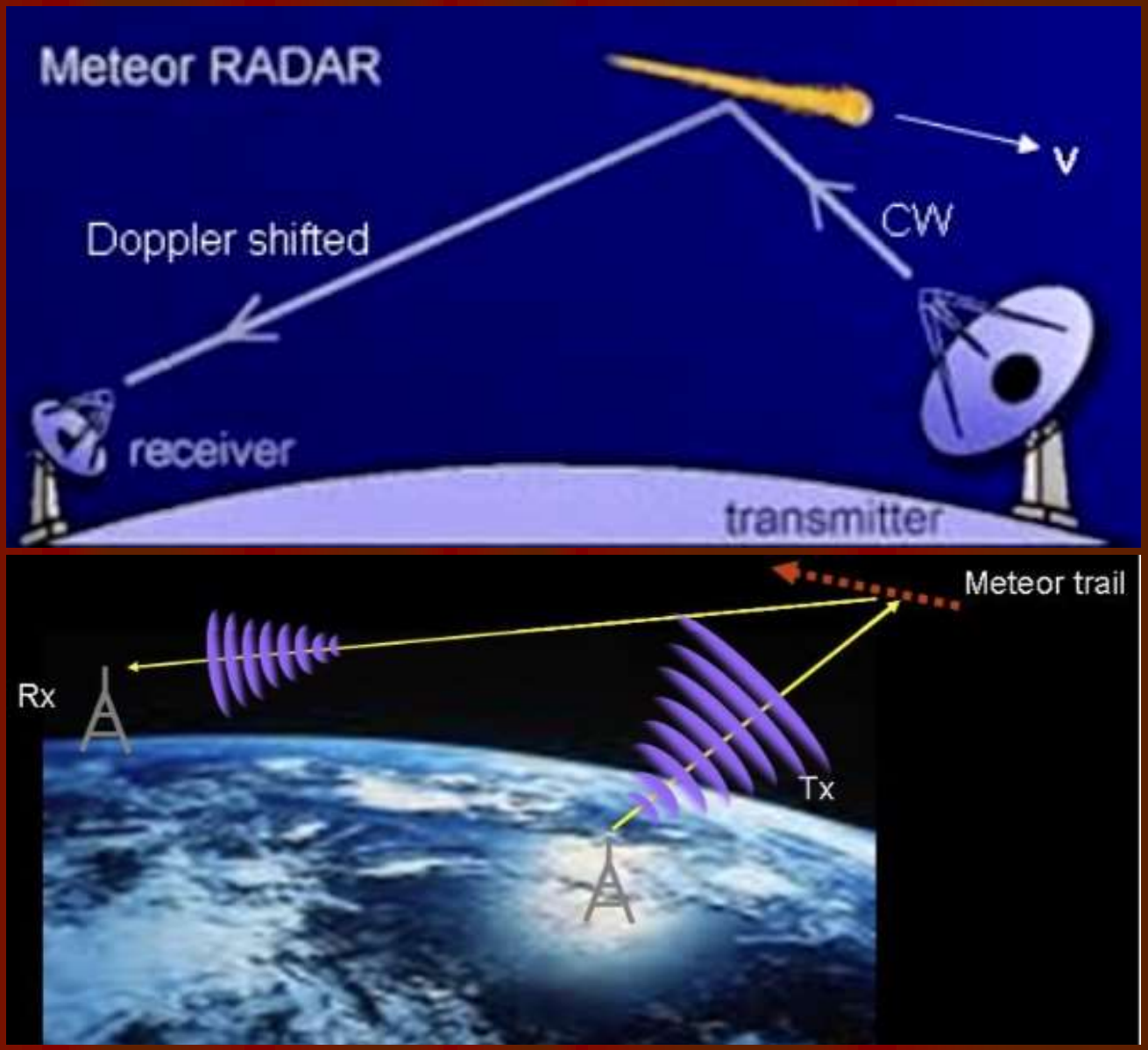


Find, Track, Analyse, Neutralise

NASA's NEOs (Near Earth Objects) Observation Program is tasked with finding, tracking, characterizing NEOs and identifying those that may pose a hazard to Earth

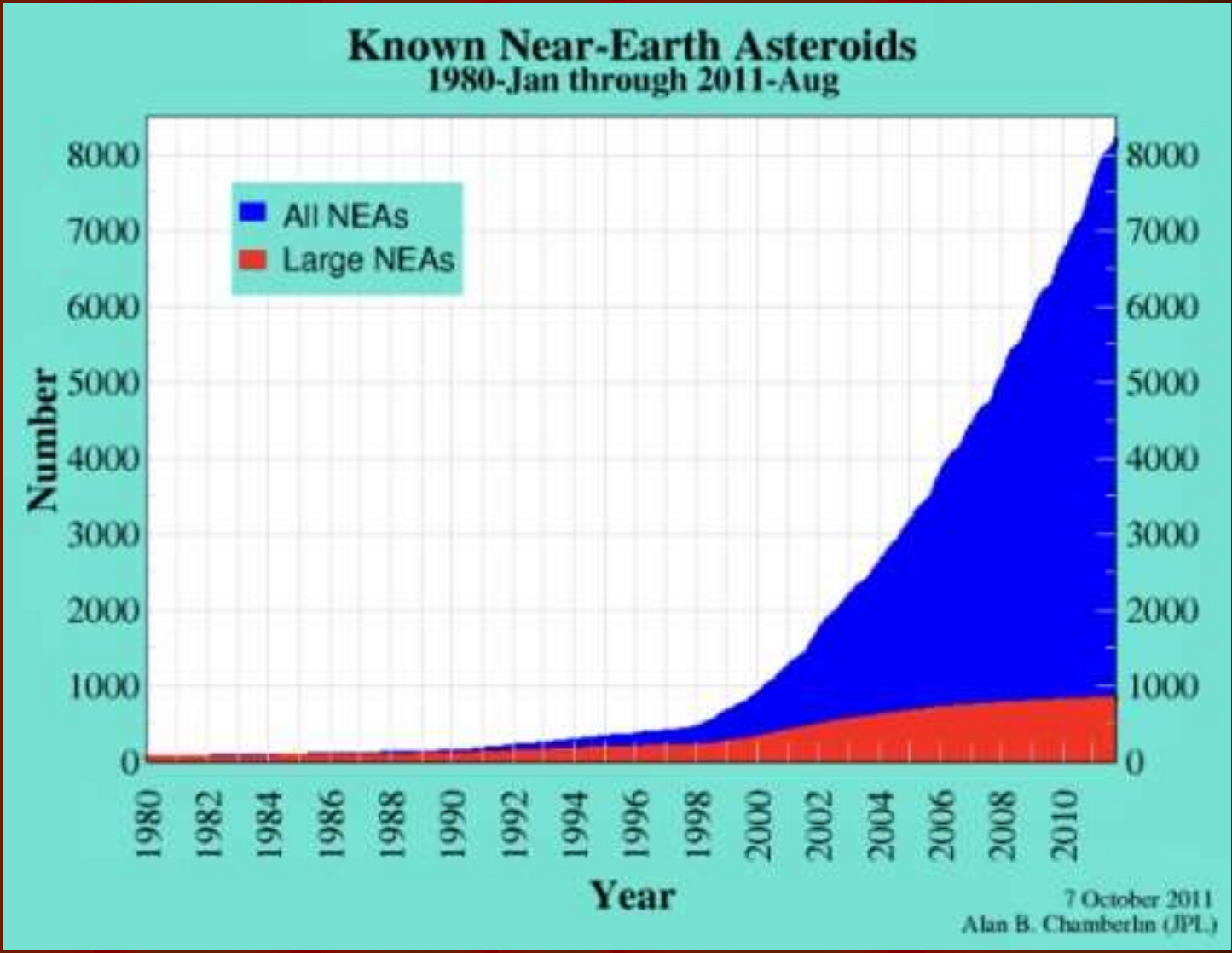


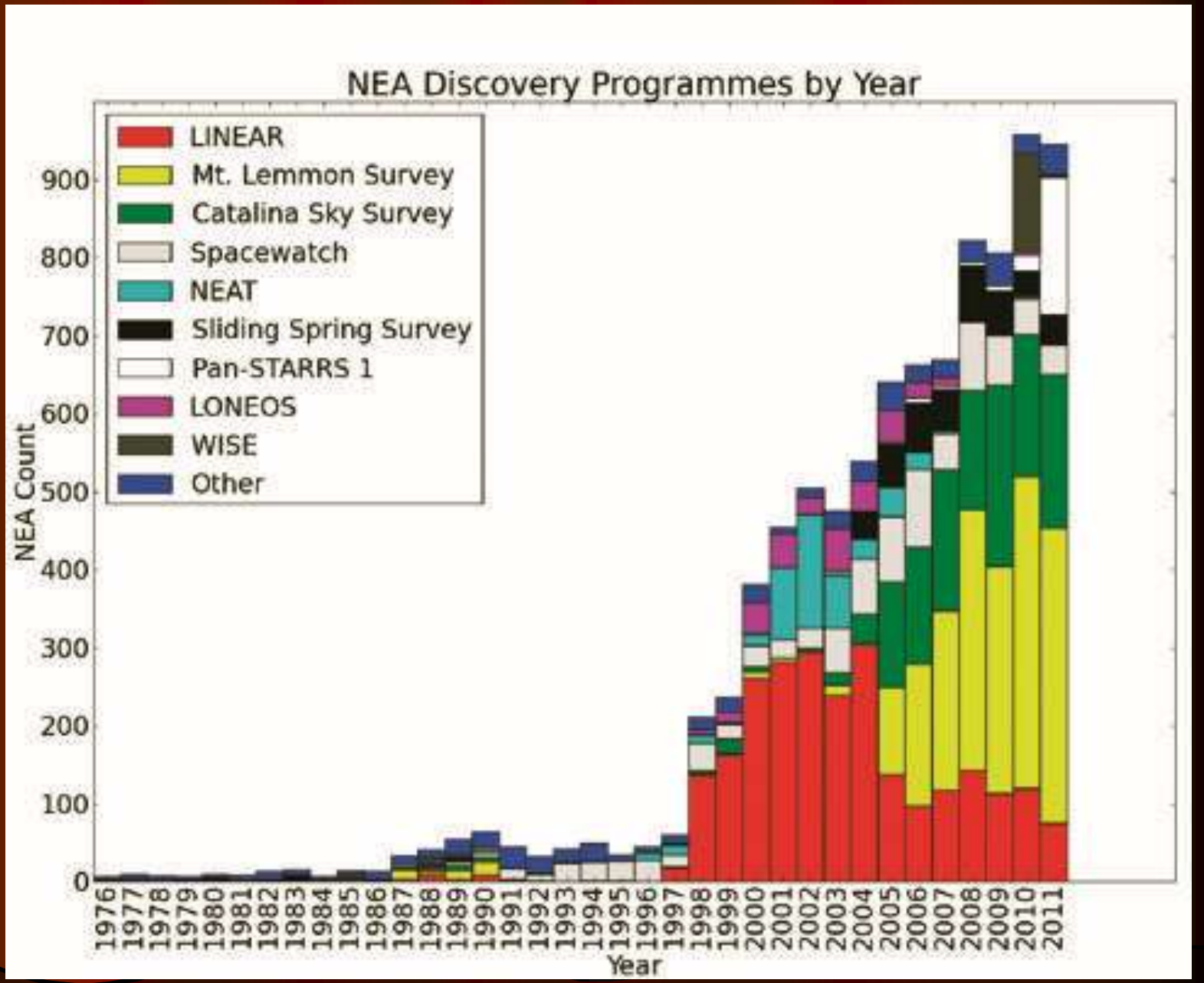
Plot of orbits of known potentially hazardous asteroids (size over 460 feet (140 m) and passing within 4.7 million miles (7.6×10^6 km) of Earth's orbit) as of early 2013


Meteor RADAR
v
CW
Doppler shifted
receiver
transmitter
Meteor trail
Rx
Tx

- NASA's Wide-Field Infrared Survey Explorer (WISE) orbiting Earth to identify NEOs as part of the NEOWISE project

There is a marked increase in numbers identified due to better technology




NEA Discovery Programmes by Year
LINEAR
Mt. Lemmon Survey
Catalina Sky Survey
Spacewatch
NEAT
Sliding Spring Survey
Pan-STARRS 1
LONEOS
WISE
Other
NEA Count
0
100
200
300
400
500
600
700
800
900
1976
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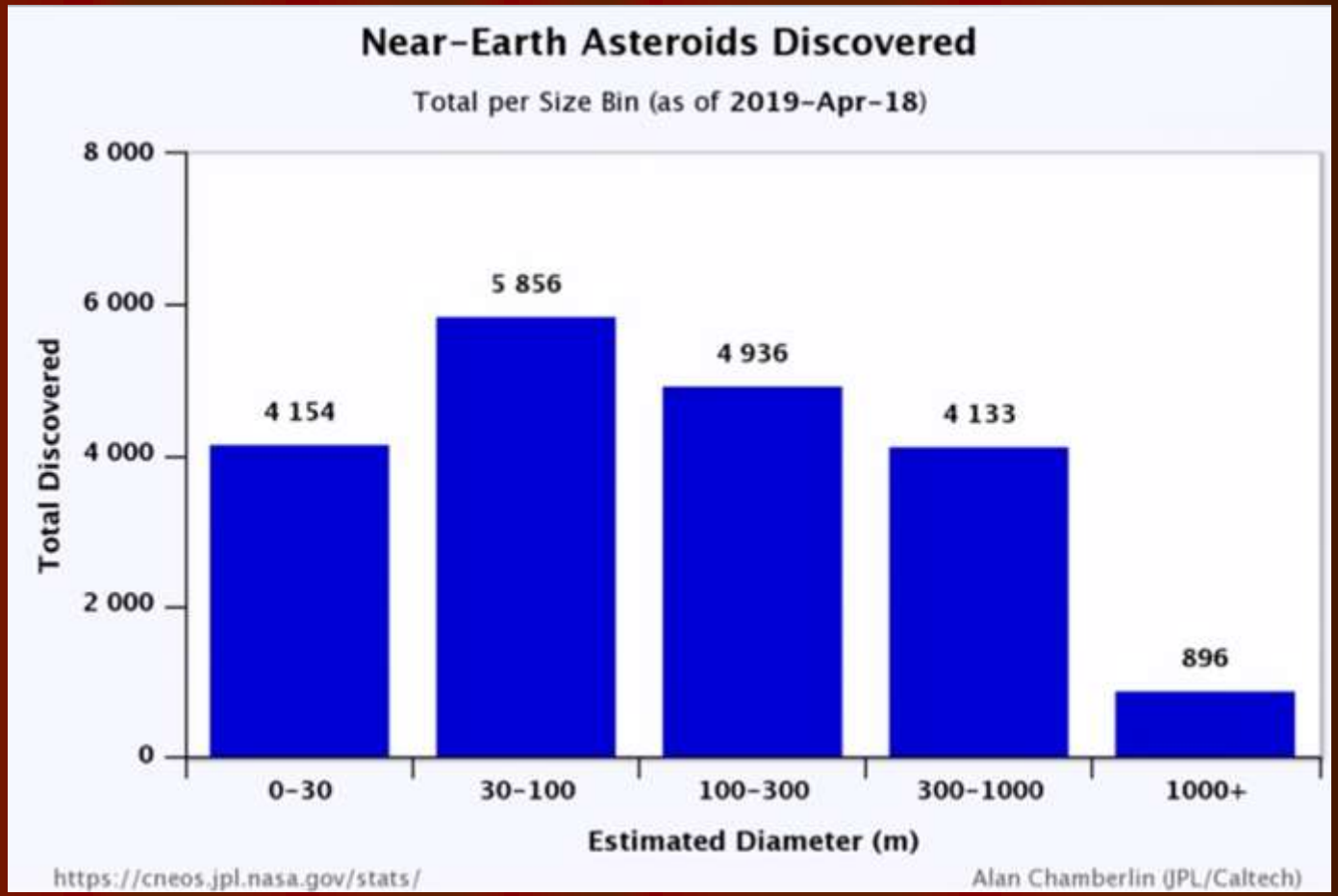
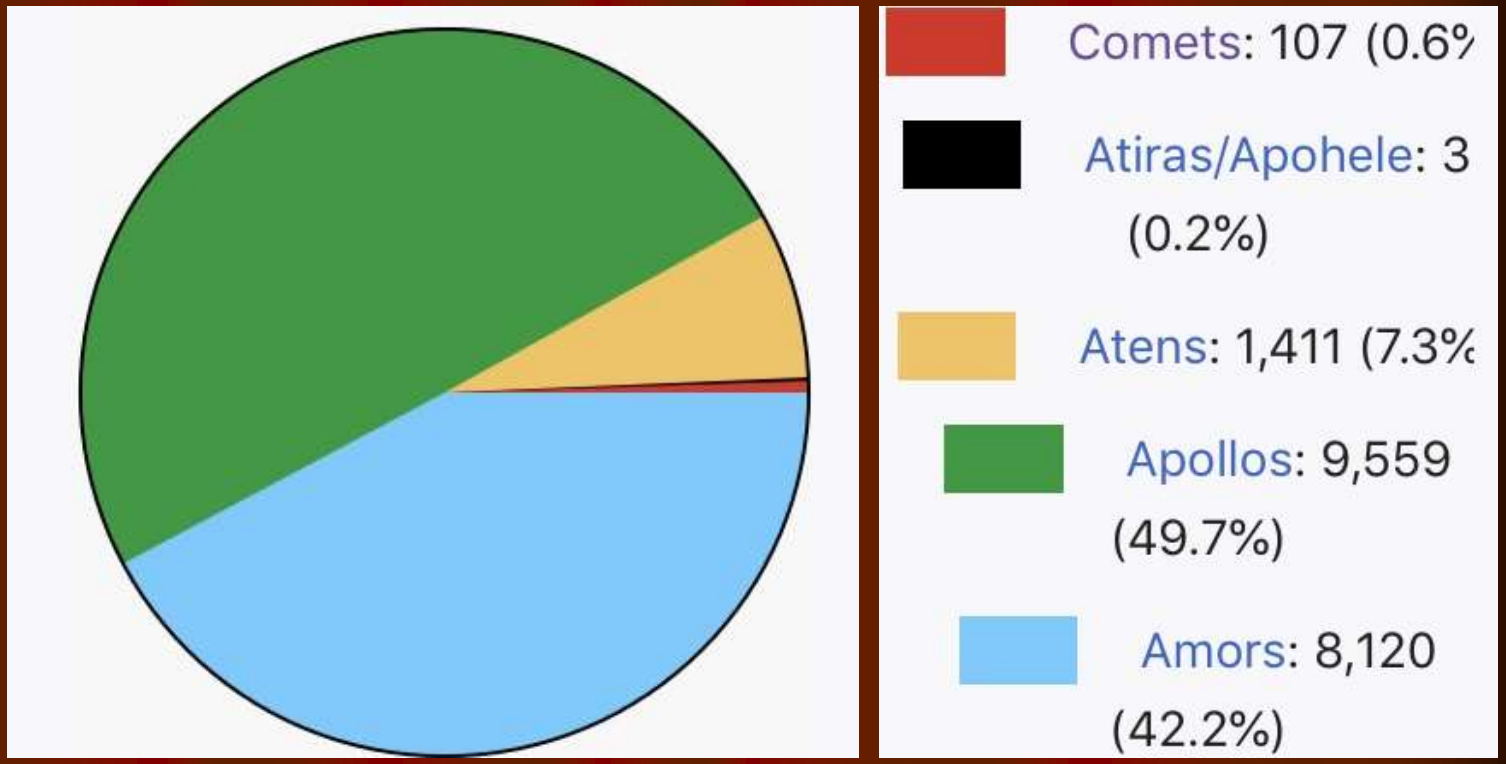
2009
2010
2011
Year

Known Near Earth Objects

In Jan 2019 19,470 NEOs have been discovered 19,363 (99.45%) being asteroids and 107 (0.55%) are comets

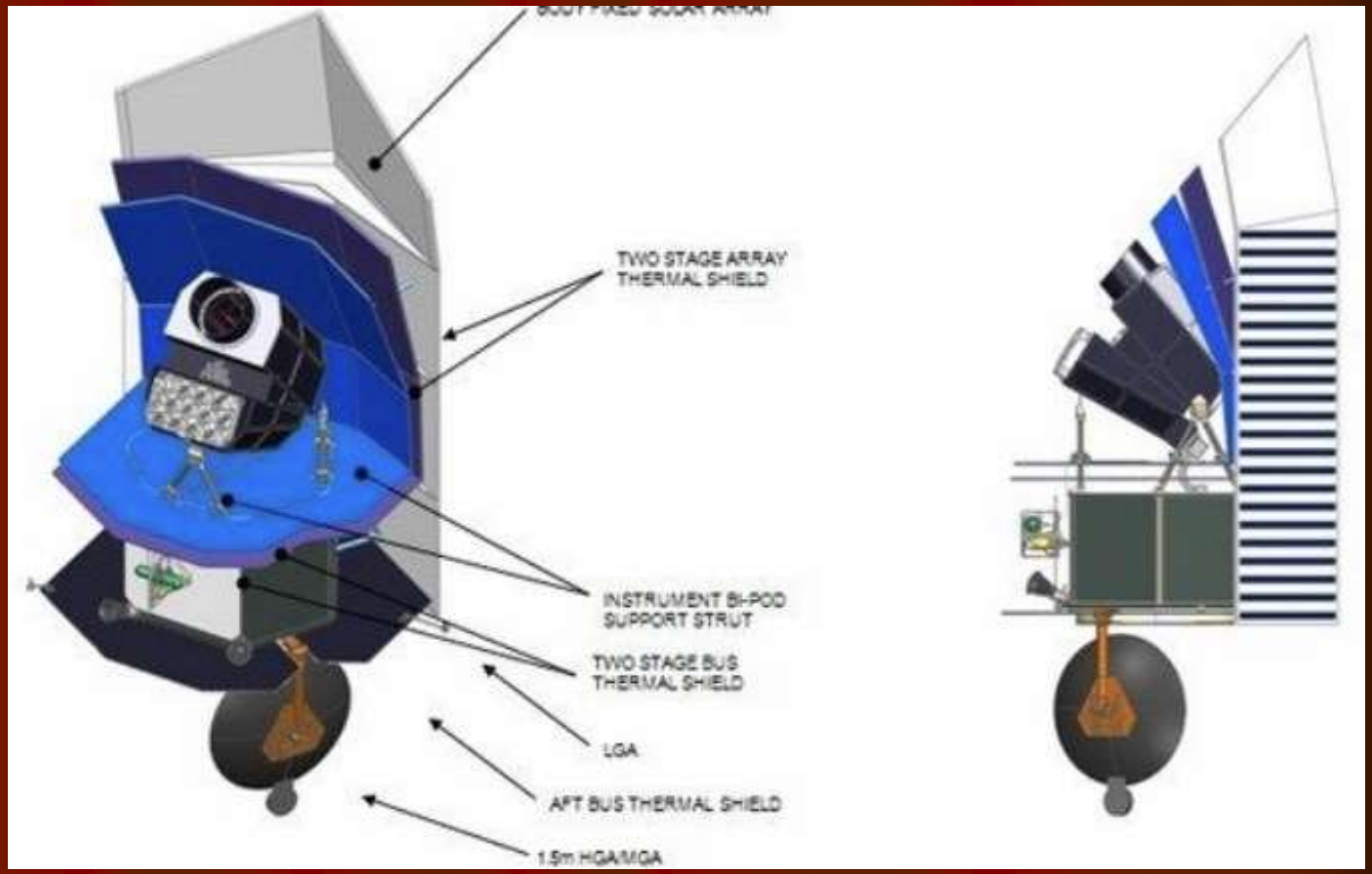


- The known NEOs can be divided into several orbital groups



- If a NEO's orbit crosses the Earth's and the object is larger than 140m across, it is considered a Potentially Hazardous Object (PHO)

- NASA scientists, astronomers around the world and amateur observers all participated in seeking out hazardous NEOs. New technology/equipment such as a Near Earth Object Survey Spacecraft shown below are also being developed



Neutralise

A. Destruction

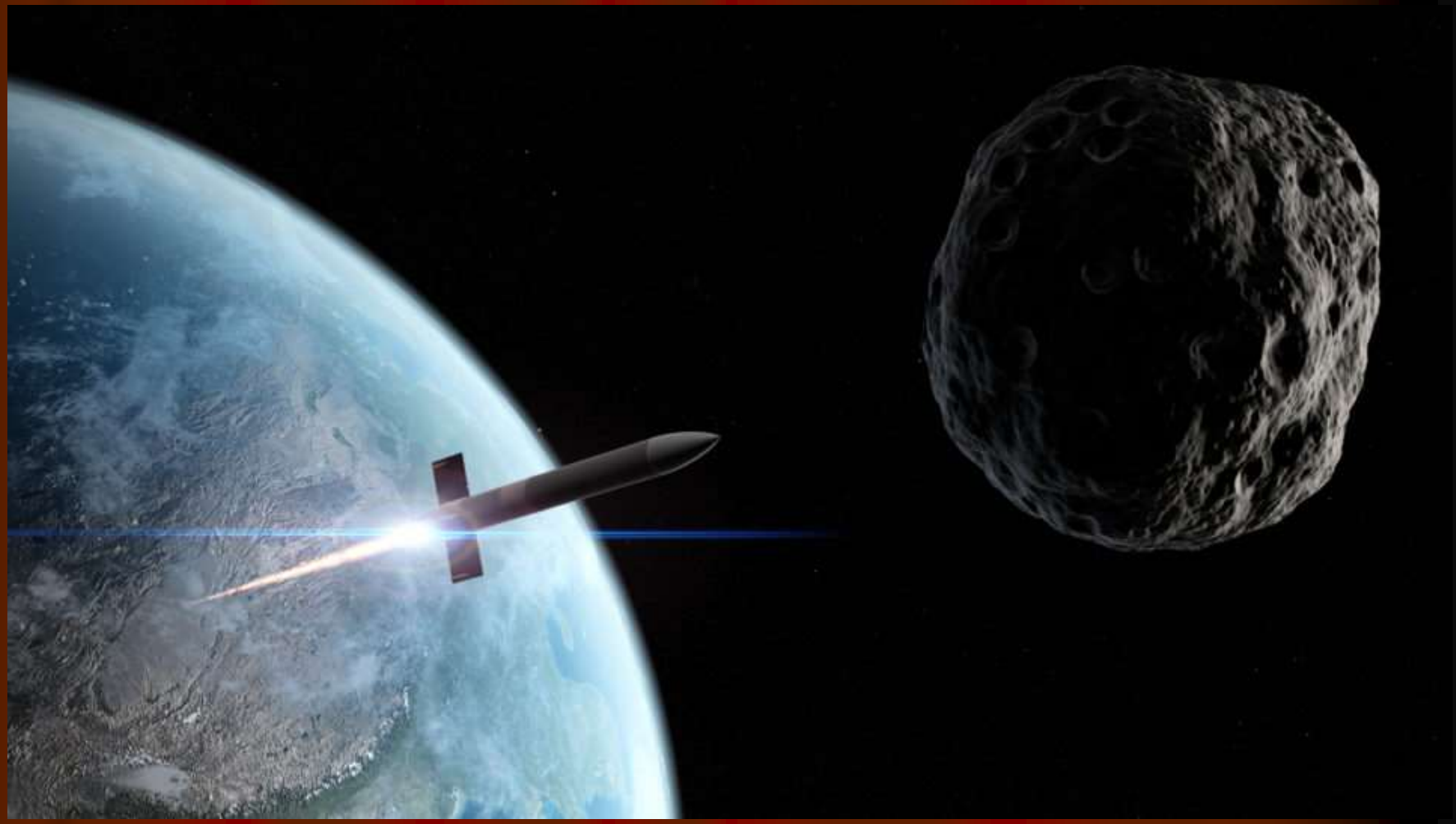
Blast the asteroid with a nuclear missile or a Hypervelocity Asteroid Interceptive Vehicle (HAIV) but resulting fragmentation could create a "shotgun effect" producing many more pieces to hit earth

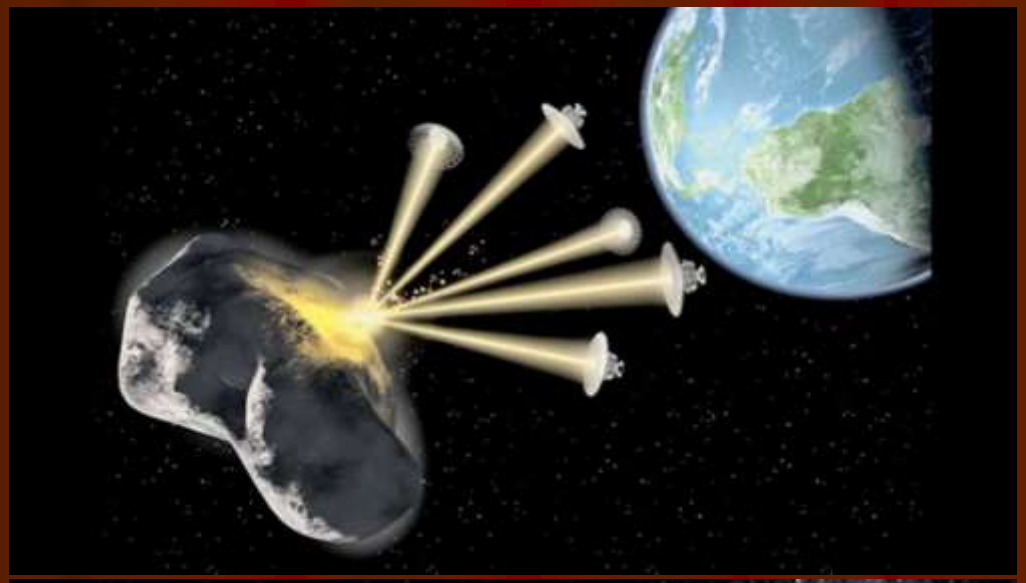
B. Course alteration either away from Earth or to a nonpopulous area

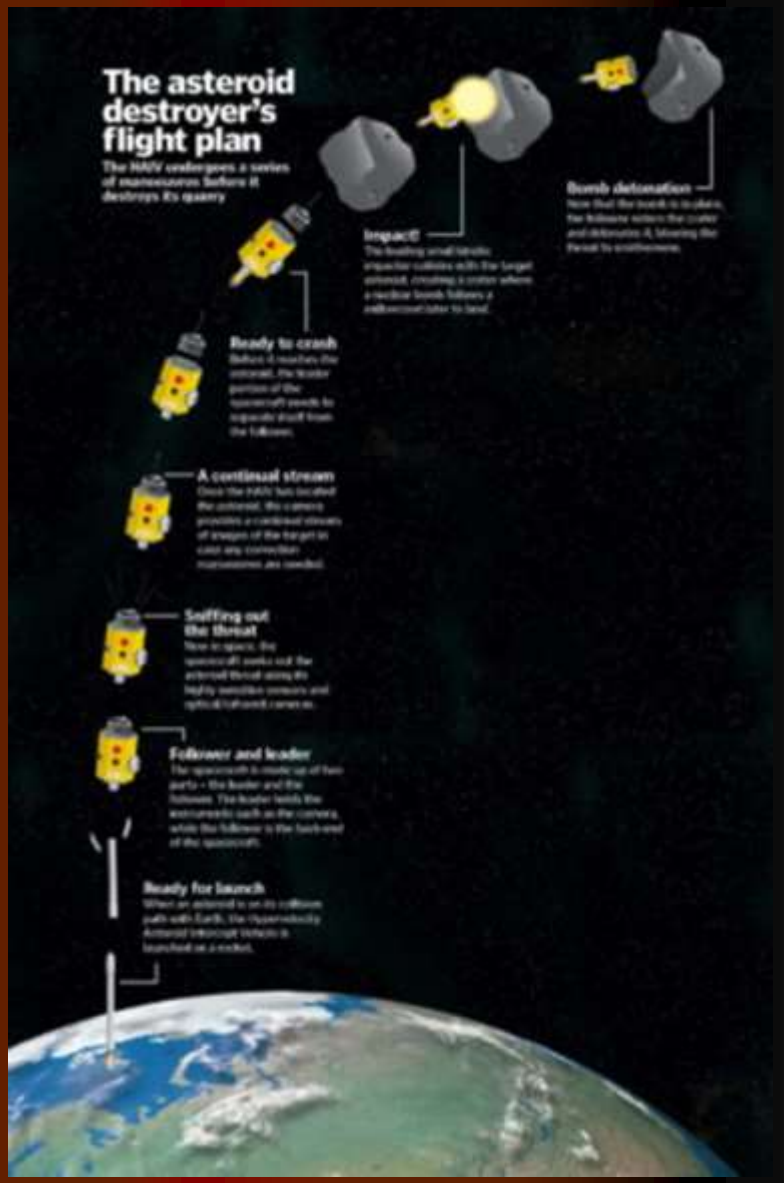
Kinetic impactor technique : to alter the course of the asteroid with man made object to alter its course –NASA's DART Project (Double Asteroid Redirection Test Spacecraft) to try on the Didymos asteroid in 2022/2024

Gravity Tractor : use a spacecraft flying alongside an asteroid for decades in order to generate enough gravity to change its course

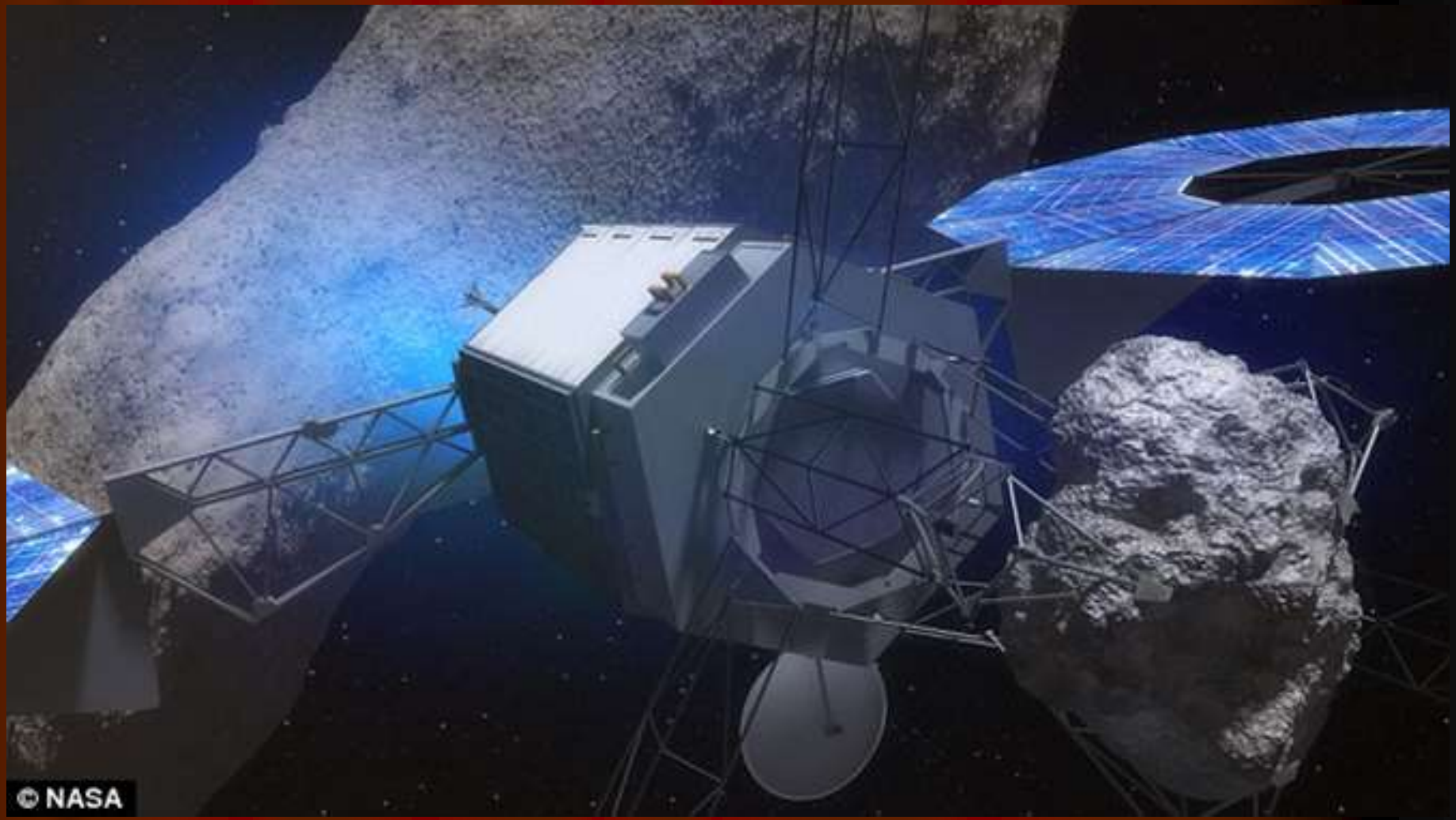
Landing and installation of rocket engines, solar sails on the asteroid






The asteroid destroyer's flight plan
The NAV undergoes a series of manoeuvres before it destroys its quarry
Impact!
Bomb detonation
Ready to crash
A continual stream
Sniffing out the threat
Follower and leader
Ready for launch


DART launches
Dec. 2020 to May 2021
Didymos
(65803)
DART
Impact event
October 7, 2022
"Didymoon"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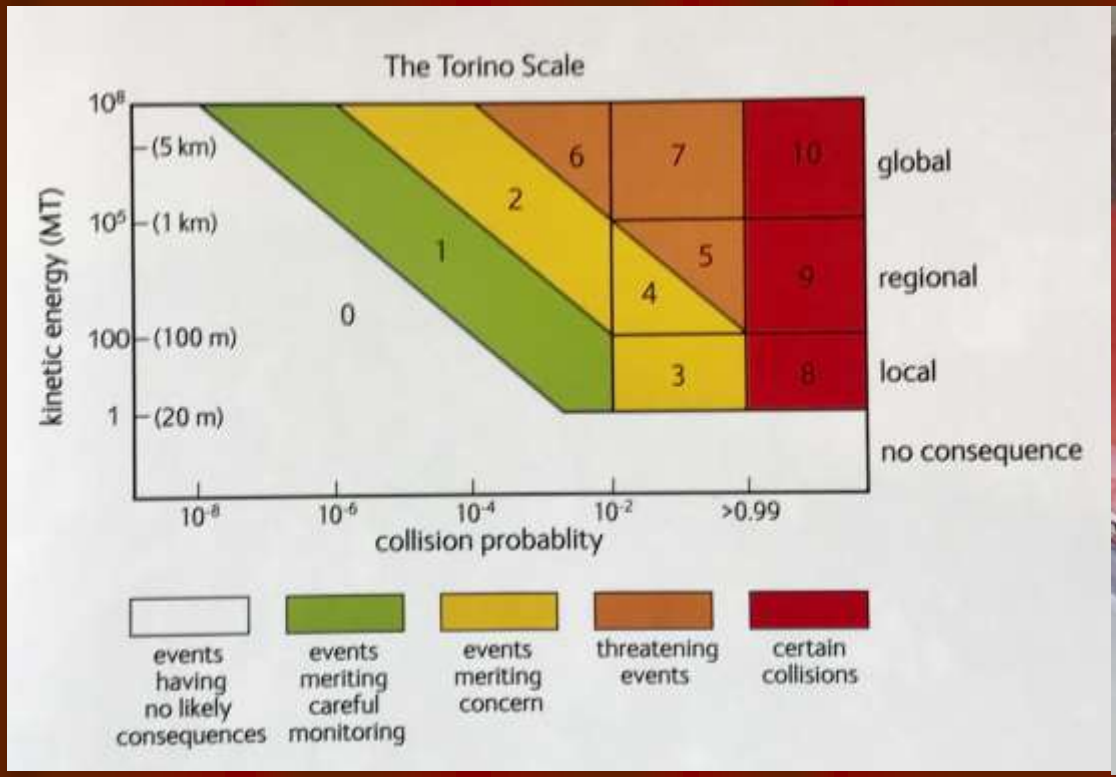
About 95% of the 980 potential civilization-enders ie. rocks at least 1 km wide have been found and none pose a threat to Earth in the near future. However that still leaves thousands of unseen and unknown asteroids. The good news is NASA predicts there is less than a 0.01% chance for a potential hazard asteroid making an impact in the next hundreds of years !



The End