U3A Planetary Geology

Lecture 7

Samples of the Solar system

Central Goldfields Excursion Itinerary

Sunday 10th November

Garfield waterwheel

Eureka Reef (optional walk)

Forest Creek walk

Overnight Castlemaine

Monday 11th November

North British Mine, Maldon

Mt Tarengower

Molaigul – Welcome Stranger site (walk)

Overnight Bendigo

Tuesday 12th November

Central Deborah Mine Tour

Afternoon free - Bendigo tourist spots

Overnight Bendigo

Wednesday 13th November

Victoria Hill mine walk

Melville Caves (optional)

Return Melbourne

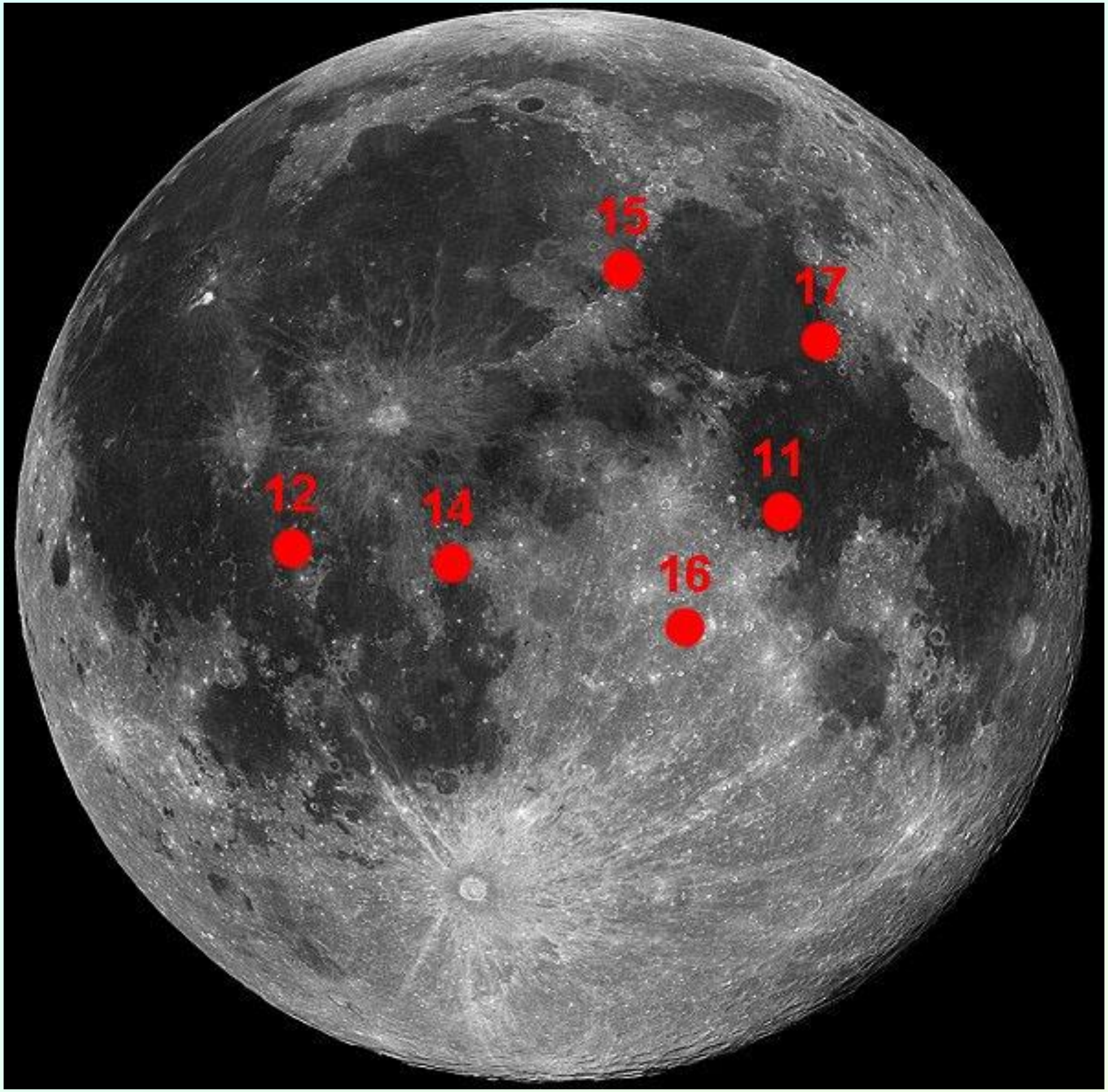
Introduction

Detailed studies of extraterrestrial material from meteorite impacts and planetary surfaces have enabled us to gain considerable knowledge of how planetary bodies have formed and how they have modified over time

Rocks from the moon

- The Apollo Program
  - rocks collected from six landing sites from 1969 to 1972
  - 380kg of rock and soil returned
  - representative of both highlands and maria
- Igneous rocks
  - mare basalts, lava rocks are typical of lunar maria
    → consist mostly of plagioclase feldspar, pyroxene & olivine
  - anorthosites, typical of highlands
    → consist mostly of Ca-rich plagioclase feldspar (anorthite)
- Impact breccias
  - shattered rocks produced by impact processes
  - most abundant in the highlands

Apollo landing sites



A11 Sea of Tranquility

A12 Ocean of Storms

A14 Fra Mauro

A15 Hadley Rille

A16 Descartes

A17 Taurus-Littrow

Lunar basalts

- Fine-grained, dark coloured, igneous rocks can be massive or vesicular

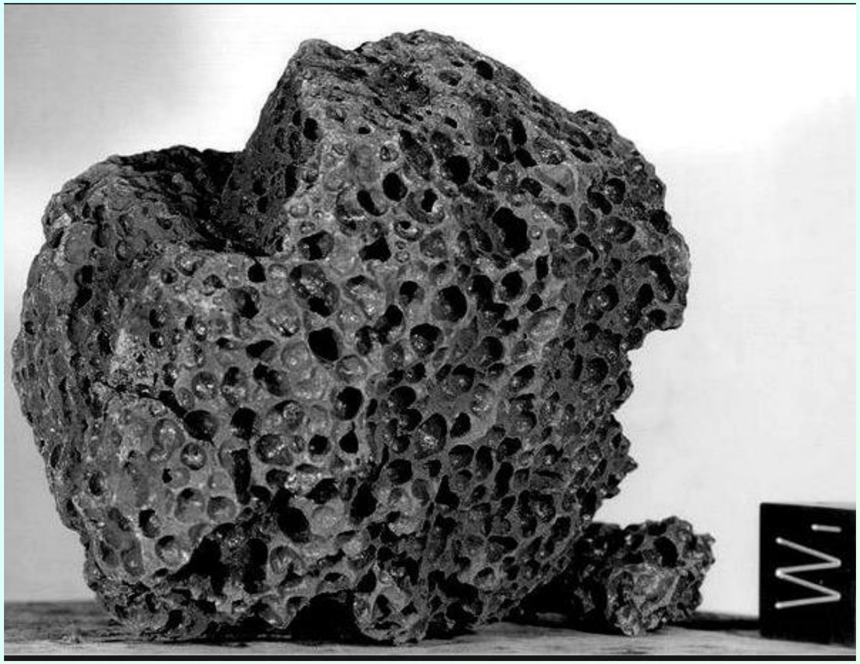
- composed of:

Ca-plagioclase	$CaAl_2Si_2O_8$
clinopyroxene	$Ca(Mg,Fe)Si_2O_6$
olivine	$(Fe,Mg)_2SiO_4$
ilmenite	$FeTiO_3$
magnetite	Fe_3O_4

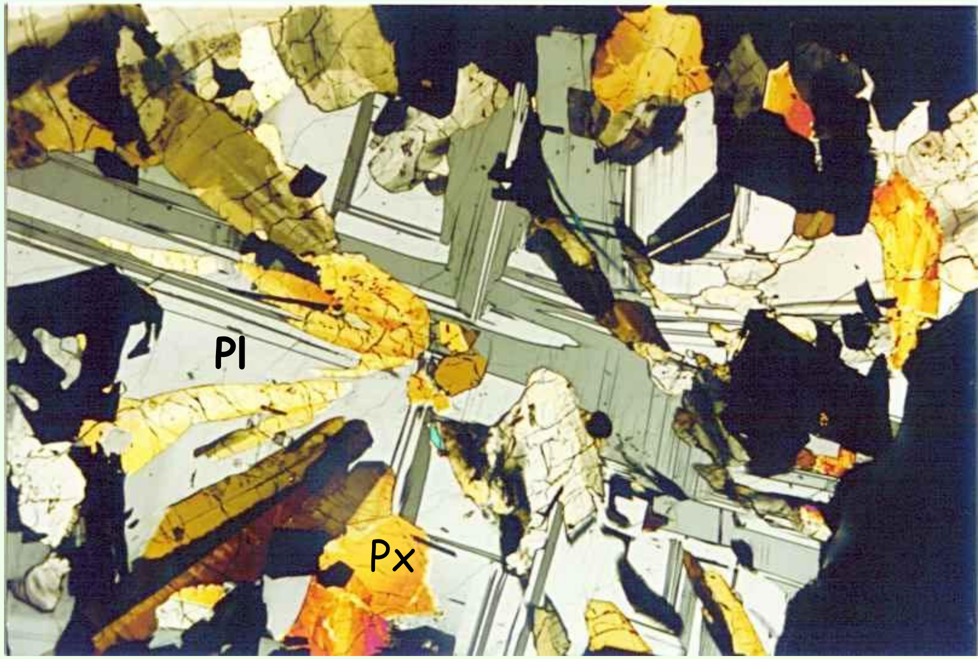
- differ from terrestrial basalts → higher Fe, Mg and lower Na, K, Al

- some mare basalts have high Ti (9–12 wt%) c.f <4wt% (terrestrial) → no terrestrial equivalents

Lunar basalts



Lunar vesicular basalt, hand specimen (from Apollo 15 mission)



Lunar basalt in thin section, crossed polars

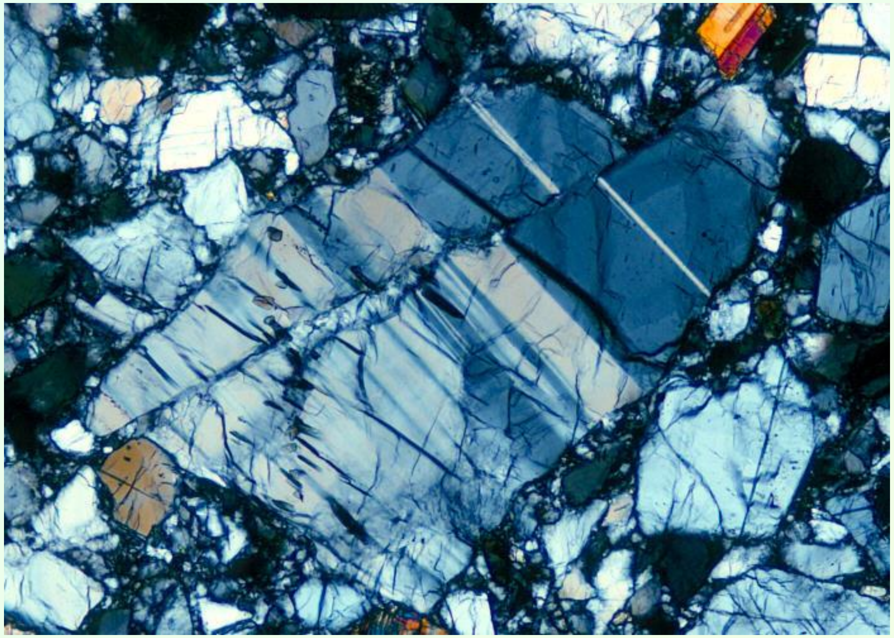
Lunar anorthosite

- Fine to medium-grained, light coloured rock (form light coloured areas of lunar highlands)
- predominantly Ca-rich plagioclase (anorthite) → 90 -100%
- minor pyroxene, ilmenite, magnetite and olivine
- mineral grains shocked → meteorite impacting

Lunar anorthosite

Lunar anorthosite, hand specimen (from Apollo 16 mission) 4.2 billion years old

Lunar anorthosite, thin section



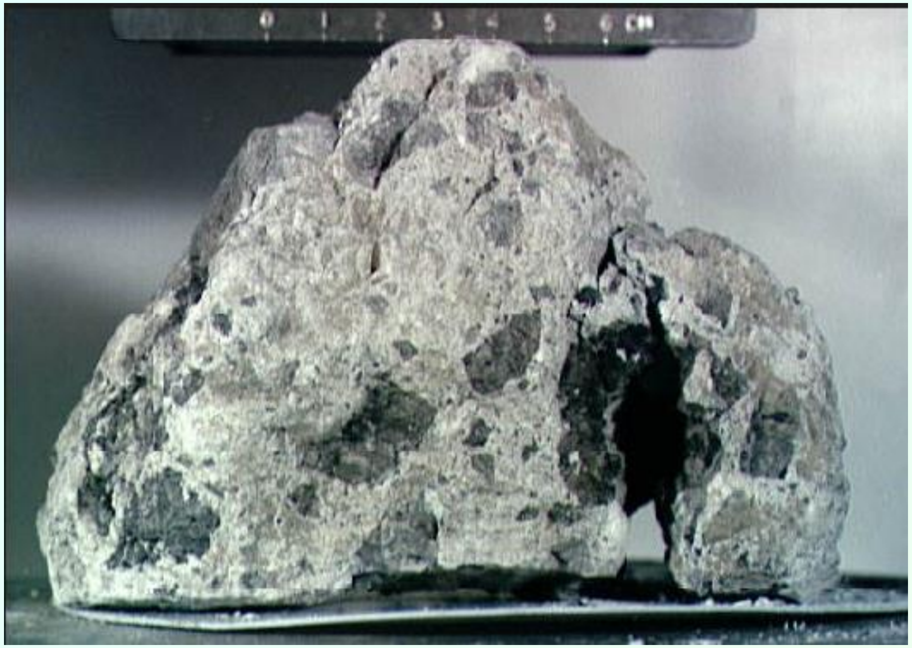
Chemical analyses of lunar basalt, anorthosite and terrestrial alkali basalt

	lunar mare basalt	high-Ti lunar basalt	lunar anorthosite	terr. alkali basalt
SiO_2	45.33	38.54	44.08	49.58
TiO_2	2.25	12.99	0.02	2.74
Al_2O_3	8.17	8.65	35.49	13.61
FeO	22.17	18.25	0.23	12.17
MnO	0.27	0.25	0.00	0.17
MgO	12.27	9.98	0.09	7.09
CaO	8.98	10.28	19.68	11.35
K_2O	0.06	0.05	0.01	0.52
Na_2O	0.27	0.39	0.34	2.40
Cr_2O_3	-	0.50	-	0.03
P_2O_5	0.12	0.05	-	0.27
S	-	0.16	-	0.01

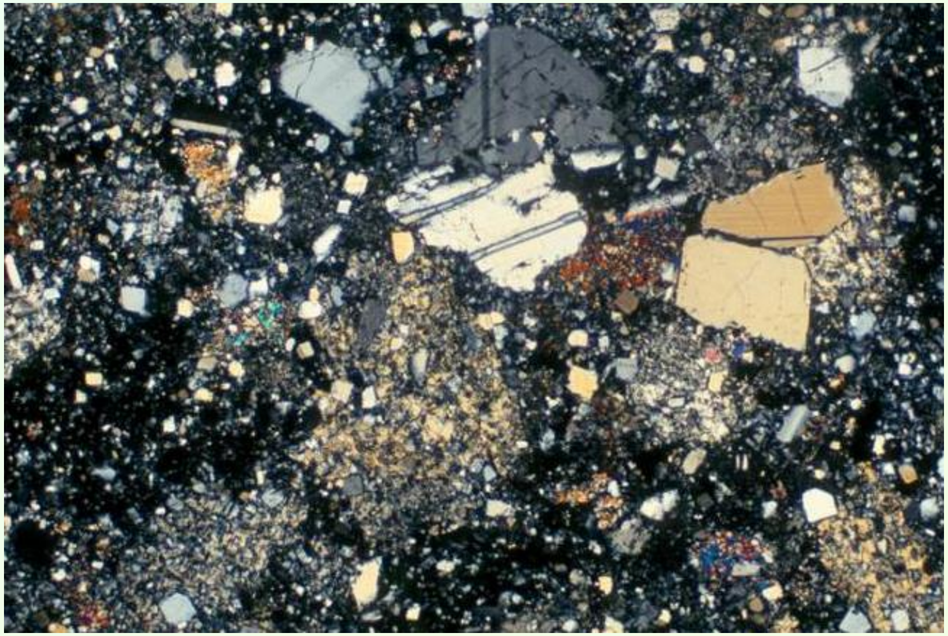
Impact breccia

- Impact breccias are fragmental rocks lithified by shock pressure of an impact
- impact breccias are ubiquitous on the lunar surface → particularly in the lunar highlands
- debris produced by the impact is fused together by melted glass caused by the release of heat resulting from the impact

Impact breccia

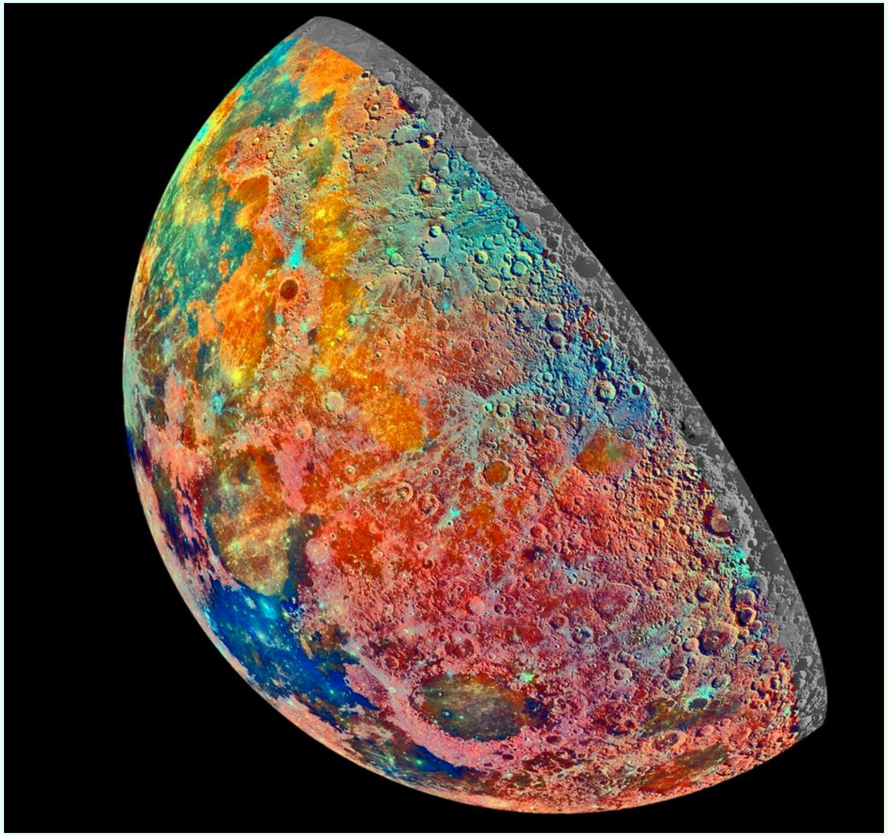


Impact breccia hand specimen



Impact breccia thin section, crossed polars
Apollo 16 mission

Compositional variation of lunar surface



False colour image of lunar surface

- Blue, green and orange shades indicate volcanic lava flows
- dark blue of Mare Tranquilitatis is due to Ti-enrichment
- pink shades represent Al-rich, Fe-poor anorthosites and breccias of lunar highlands

Radiometric ages of Moon rocks

The Moon rocks have a range of ages.

Radiometric dating performed using U-Pb, Rb-Sr and K-Ar

- Age of formation of Moon
  - 4,600Ma (calculated)
- Highlands anorthosites and breccias
  - 4,400 to 4,000Ma
- Mare basalts {flood lavas)
  - 3,800 to 3,200Ma
- Younger impact breccias
  - most analysed 100 to 1,000Ma

Meteorites

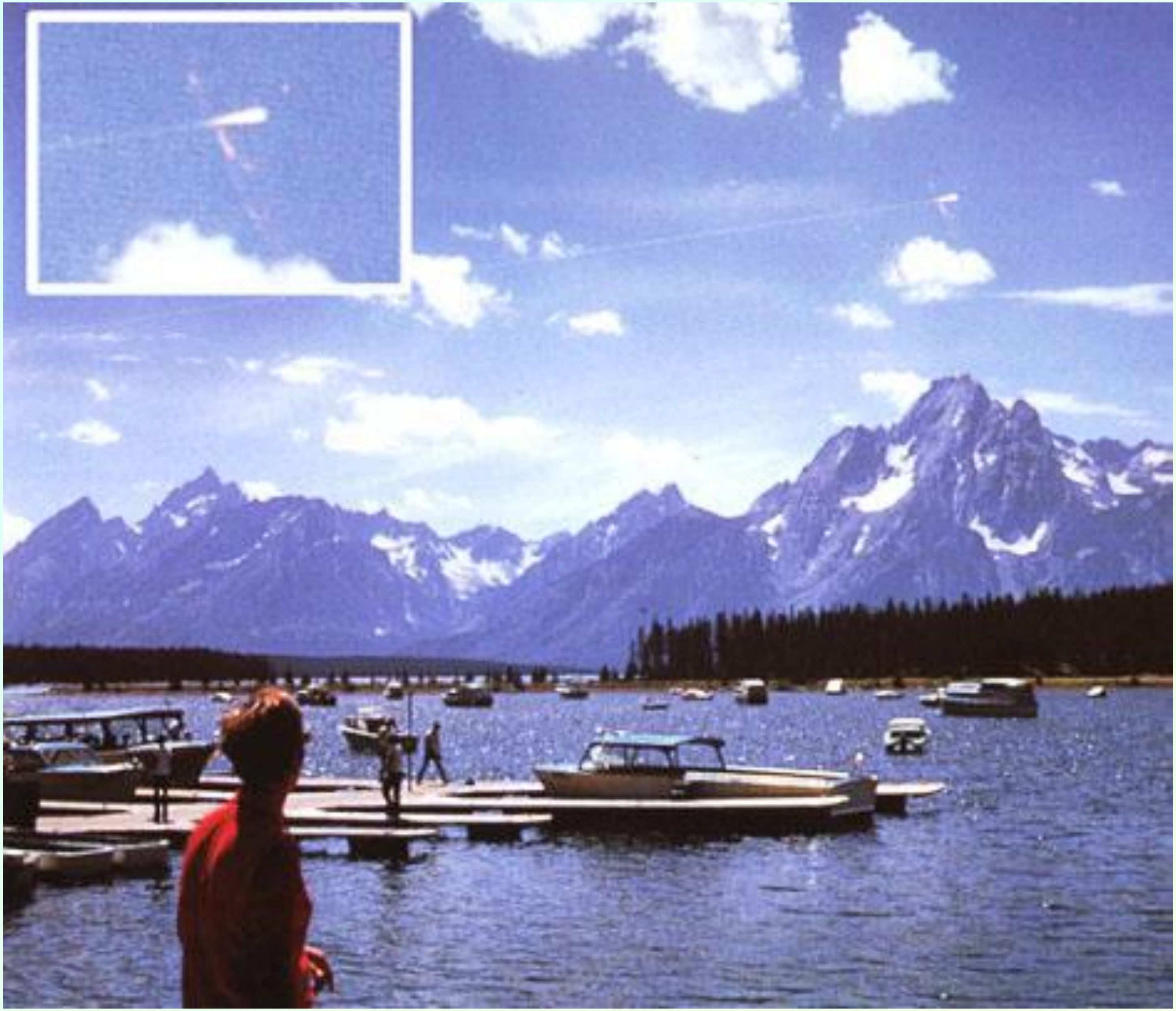
- Meteorites → pieces of extraterrestrial rocks that fall on Earth
- originate mainly from the asteroid belt (pieces of asteroid)
- some from the Moon and probably Mars (SNC meteorites)
- when meteoroids enter atmosphere at high speeds (up to 40km/sec)

  → produce bright trails across the sky (called meteors)
- very small meteorioids are slowed down by the atmospheric friction

  → tremendous frictional heating → may burn up
- large meteorites impact without slowing down
- frictional heating melts a thin surface layer of meteorites to form

  a glassy fusion crust

Meteoroid over Teton Mtns. Wyoming, USA



Impact processes on Earth

- Larger meteorites (>10 tonnes) are not slowed and impact on the surface at 10-30km/sec → most vaporise on impact → produce large craters
- meteorites Kgs - 0.5tonne → sample material we can collect
- more than 200 large craters are known on Earth
- many are known in Australia e.g.

  - Wolfe Creek in Western Australia

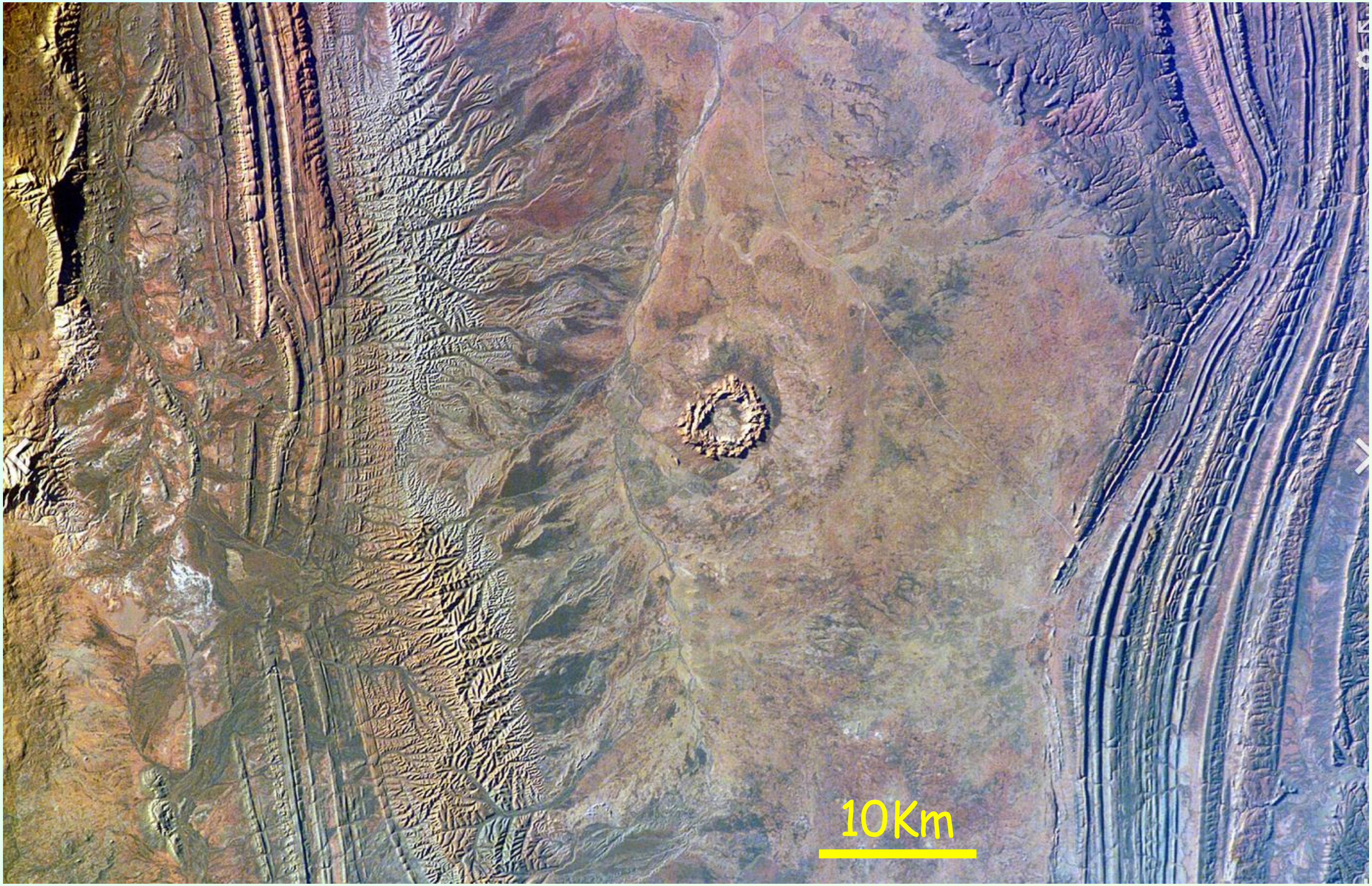
  - Gosses Bluff in Central Australia

  - Acraman in South Australia

Meteorite crater - global localities

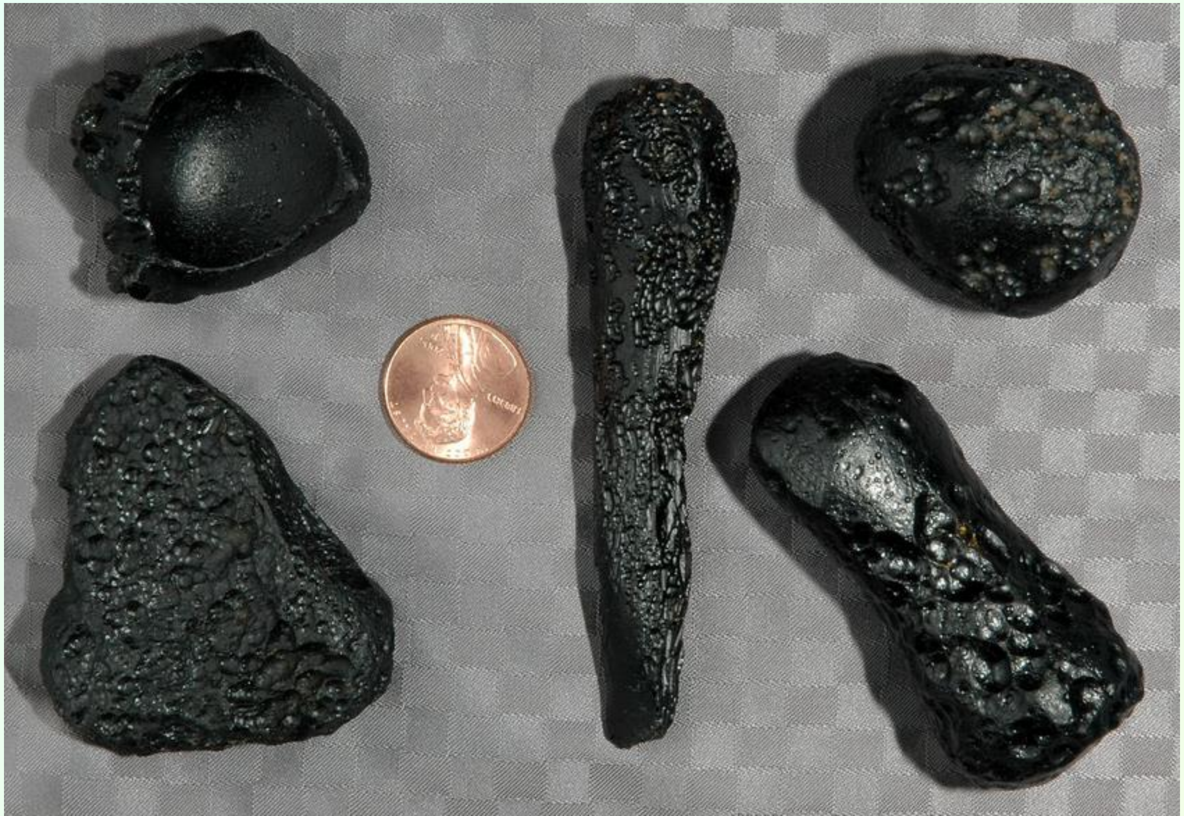
Meteorite crater - Wolfe Creek, WA

Ancient impact - Gosses Bluff



Tektites

- Natural glass formed by spray of droplets of molten terrestrial rocks resulting from meteorite impact
- superficially similar to volcanic glass (obsidian)
- lack phenocrysts, are anhydrous, contain lechatelierite

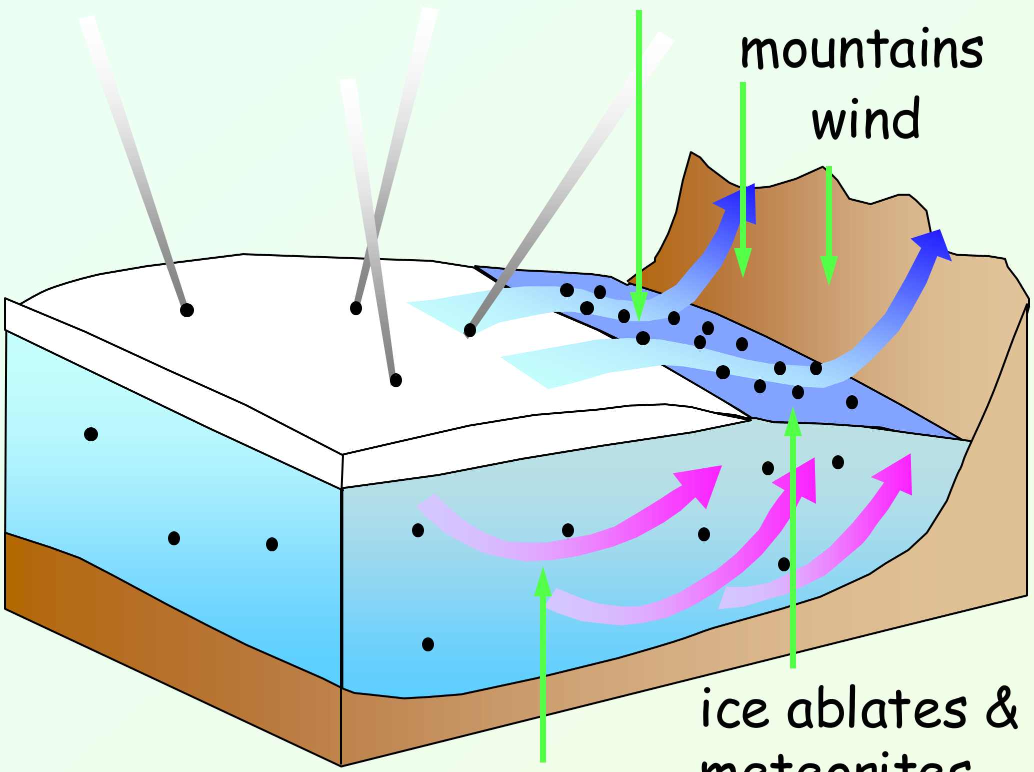


Meteorites on the Earth

- 100-1000tonnes of meteorite material enters atmosphere per day → most is fine dust → burns up in atmosphere
- about 1,000 tonnes of meteorite material falls on the Earth each year
- meteorites are rare, but distinctive rocks found all over the world
- over last 50 years large numbers have been collected in Antarctica (up to 40,000)
- the only rocks found on the surface of an icecap are meteorites

Antarctic meteorites

- The Antarctic ice cap acts as a giant meteorite collector
- Antarctic meteorites have vastly increased the number of meteorites in world collections
- meteorites concentrated on surface where ice ablation occurs



Three-fold meteorite classification

- Iron meteorites 5.7% of all meteorites
- Stony meteorites 92.8% of all meteorites
- Stony-iron meteorites 1.5% of all meteorites

- Stony meteorites are further divided into:

  - chondrites → most abundant group of all

  - achondrites → ~8% of known meteorites

Iron meteorites

- Composed entirely of Iron-nickel alloys
- two Fe-Ni alloys are found:
  - Kamacite with 5.5% Ni
  - Taenite with 27-65% Ni
- have a characteristic intergrowth texture called Widmanstatten structure formed by elongate Fe-Ni minerals
- characteristic structure of alloys cooled very slowly from high temperature molten state
- formed deep in once-molten asteroid bodies
- same physical properties as the Earth's core
- examples: Henbury (NT) and Cranbourne (Vic)

Fe-Ni meteorite (Henbury meteorite)

Fragment of Henbury meteorite

Slice through the Henbury meteorite showing the prominent Widmanstatten texture

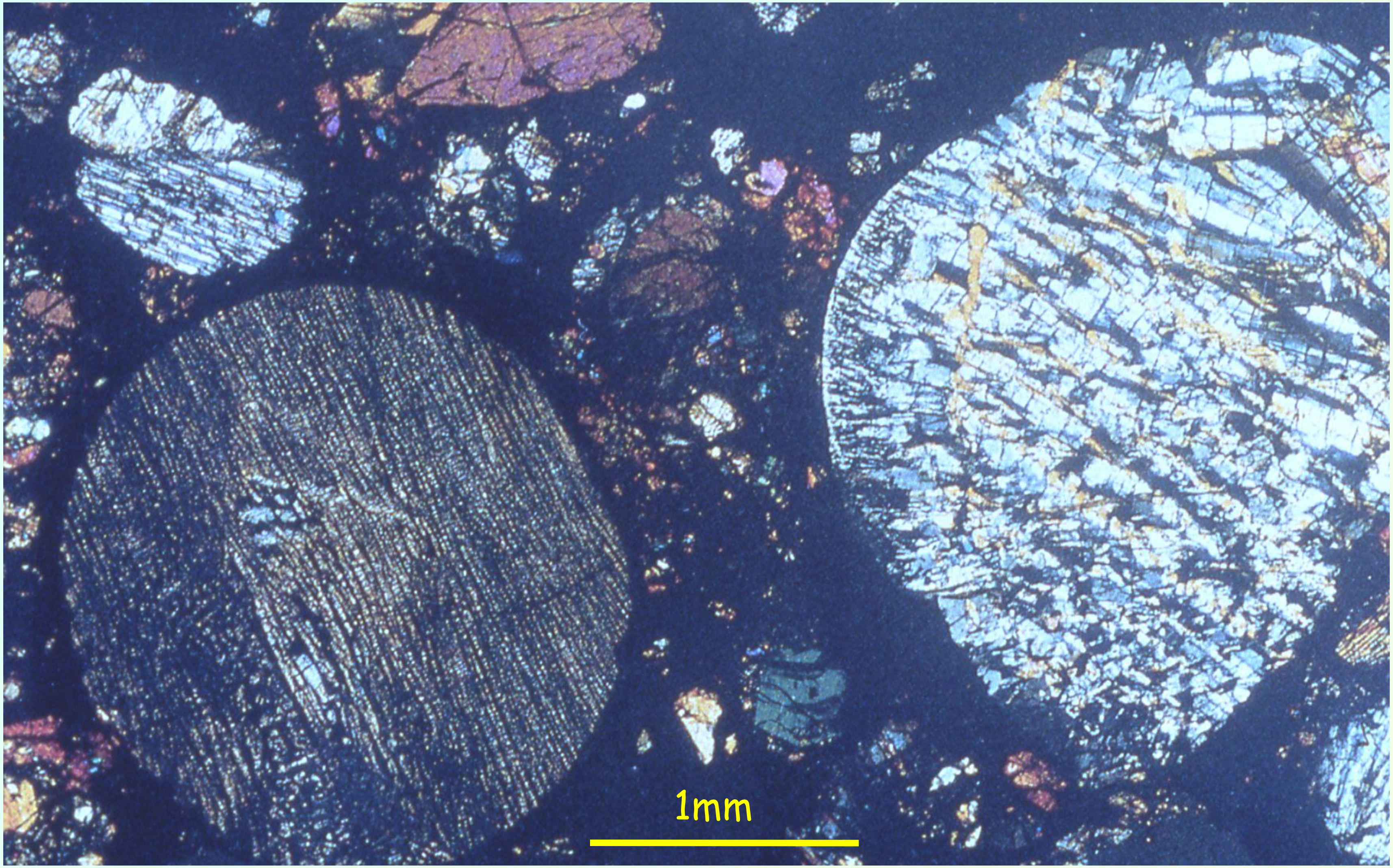
Stony meteorites - chondrites

- Vast majority (~86%) of stony meteorites → chondrites of which there are a number of types (E-type, Ordinary, Carbonaceous)
- stony meteorite that has not been modified by either melting or differentiation of a parent body
- contain chondrules
- mainly composed of magnesium-rich silicate minerals:
  - Olivine $(Mg,Fe)_2SiO_4$
  - Orthopyroxene $(Mg,Fe)SiO_3$

Chondrite textures

- Chondrite meteorites contain small spheroidal particles called chondrules
- chondrules → couple of mm in diameter and contain within them a feathery texture
- texture indicates rapid cooling of once molten droplets
- they were like a fine spray of molten silicate liquid thought to have condensed from a hot gas → very common
- chondrules set in a very fine-grained matrix
- matrix appears to be a cold aggregate of particles stuck together

Chondrite textures



Carbonaceous chondrite - Prairie dog meteorite

Ordinary chondrite

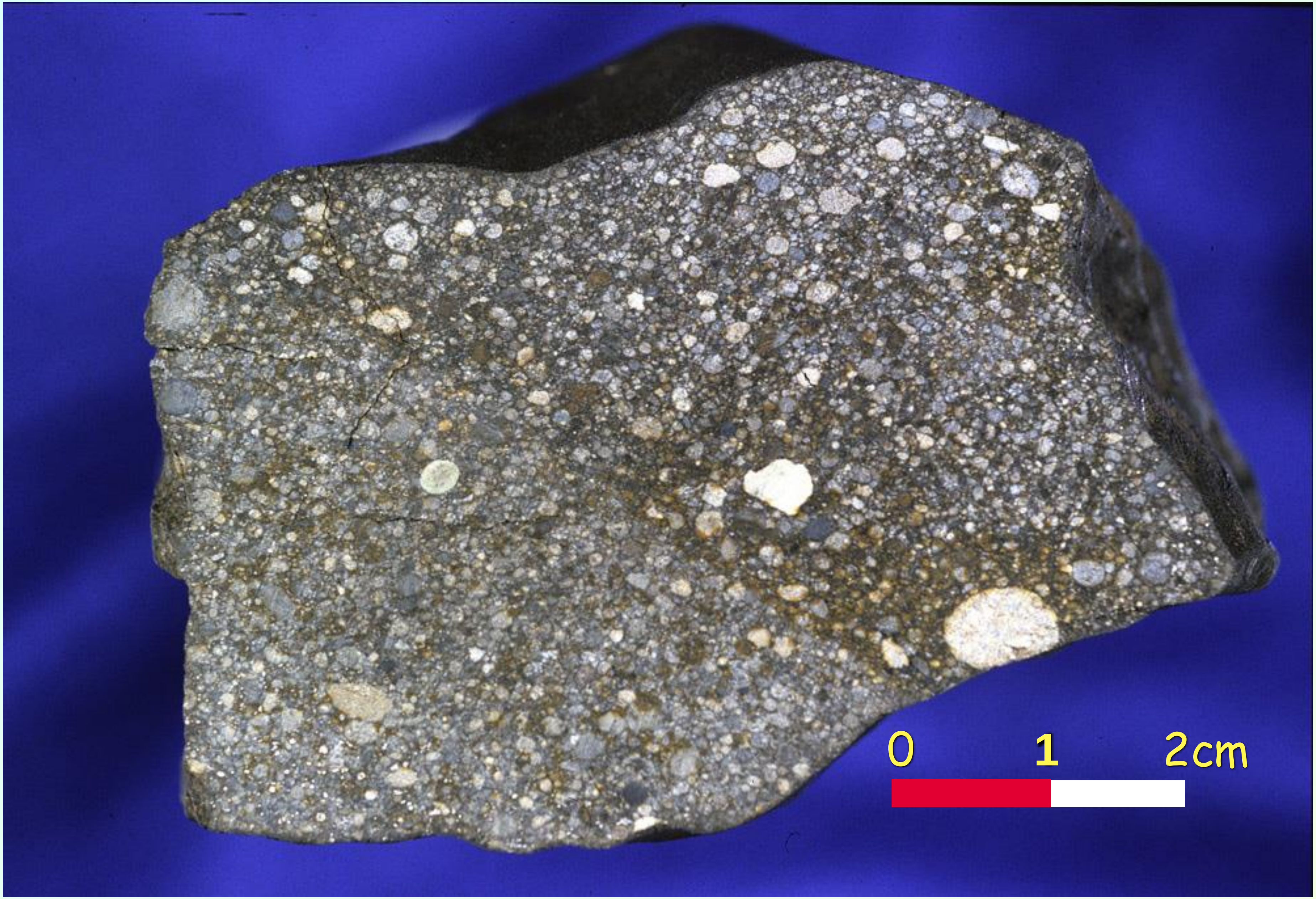
- Most common type of meteorite to fall on Earth
- about 80% of all meteorites and >90% of chondrites are ordinary chondrites
- they contain abundant chondrules, sparse matrix and variable amounts of Fe-Ni and troilite (FeS)
- chondrules are generally in the range 0.5 – 1mm
- depleted in Ca, Al, Ti and rare earths

Slab from ordinary chondrite

Carbonaceous chondrite meteorites

- Carbonaceous chondrites comprise <5% of chondrites that impact on Earth
- carbonaceous chondrites are very rich in carbon and organic compounds (up to 14%)
- organic compounds not biological → complex carbon compounds
- carbonaceous chondrites were never completely melted
- examples are Murchison and Allende both fell in 1969 in Victoria and Mexico and were collected while still warm
- thought to have formed the farthest from the Sun of any chondrites → high proportion of volatile compounds

Mezö-Madaras carbonaceous chondrite



Achondrites

- Rarer stony meteorites (comprise ~8% of known meteorites)
- contain no chondrules
- igneous rocks, similar to basalt and gabbros
- mostly originate from crust of asteroids
- few thought to come from the Moon, others probably from Mars (SNC meteorites)
- Example types → eucrites, diogenites, Howardites

Achondrites - eucrites

- Eucrite most common achondrite type
- basaltic composition (plagioclase, pyroxene)
- glassy fusion crust and flow lines from frictional heating
- originate from the surface of asteroids

Moama eucrite

Achondrite meteorites – Diogenites, Howardites

Diogenite (Oman)

- Fusion crust absent
- igneous rock
- composition hypersthene, plagioclase and olivine
- originate from deep asteroid crust
- rare

Howardite (Sahara Desert)

- Breccia from crust
- consists mainly of eucrite and diogenite fragments
- large black melt clasts
- formed from impact ejecta → buried (later impacts) → lithified

Stony iron meteorites

- Quite rare
- mixtures of Fe-Ni alloy and silicate minerals, mainly olivine

  e.g. pallasites, mesosiderites
- Pallasites

  Consist of silicate crystals (mainly olivine) in a meteoric iron matrix
- Mesosiderites

  Breccias (fragmental rocks) → show evidence of metamorphism.

  Meteoric iron occurs as clasts

Stony iron meteorite

Brenham Pallasite, stony-iron Meteorite (Ni-Fe alloy and olivine)

Mesosiderite, stony-iron meteorite (Ni-Fe alloy, olivine, pyroxene and anorthite)

Martian meteorites

- Rocks ejected from the Martian surface by large impacts

- of ~61,000 meteorite samples collected on Earth → 277 believed to originate from Mars (all but 3 SNC meteorites)

- Evidence ?

  (1) Younger formation ages (1300-575Ma)

  (2) unique isotopic composition

  (3) aqueous weathering products

  (4) similar composition to Martian surface rocks

  (5) gas inclusion content similar to Martian rocks

Martian meteorites

- Almost all Martian meteorites are SNC meteorites (Shergottites, Nakhlites, Chassignites)

  Shergottites – basalts or lherzolites (575-180 million years old)

  Nakhlites – augite rich basalts or clinopyroxenites (~1300 million years old)

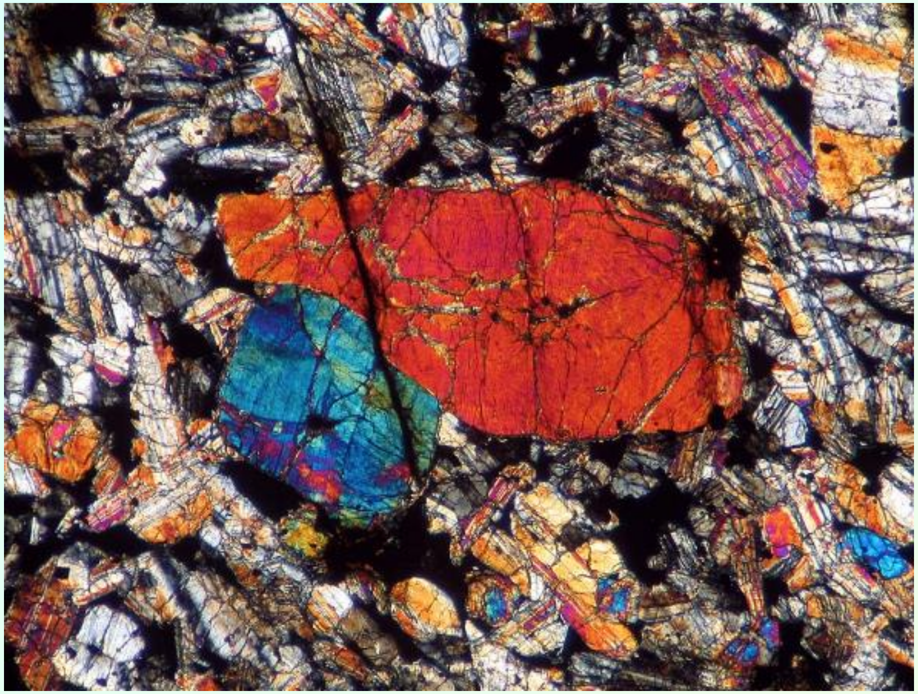
  Chassignites – orthopyroxenites (~620 million years old)

Martian SNC meteorites

Shergottite NWA6963

Shergottites ~75% of SNC meteorites

- medium grained
- composed of olivine, orthopyroxene, maskelynite and minor spinel



Martian shergottite (FOV =3mm)

Shergottite meteorite

Martian SNC meteorites

Nakhlite NWA998

- Medium-grained
- composed of brown orthopyroxene, green olivine and black titanomagnetite (inclusion of ankerite)

Chassignite NWA2737

- Medium-grained cumulate rock
- composed mainly of olivine with lesser clinopyroxene, plagioclase and chromite

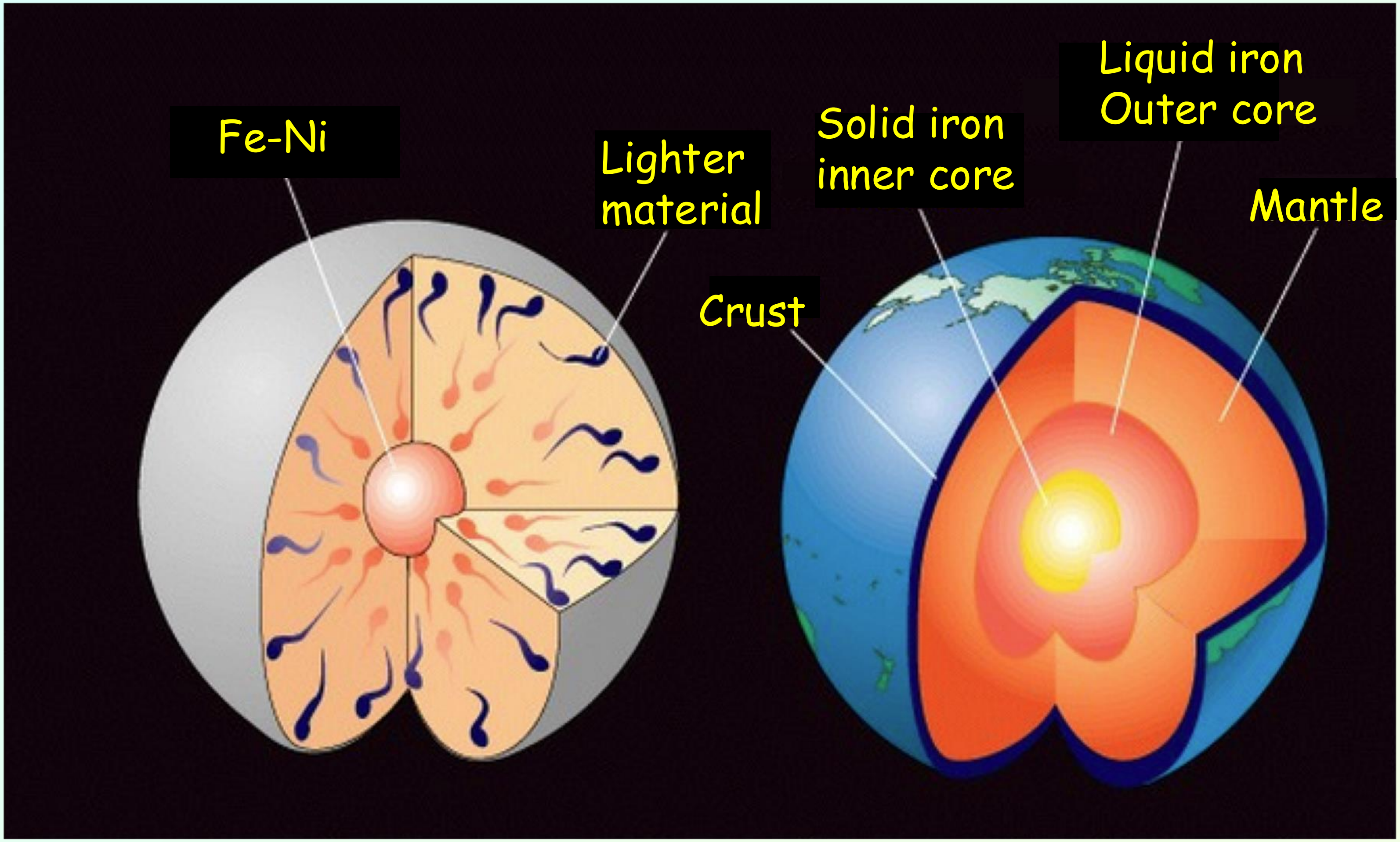
Meteorite parent bodies

- Iron and achondrite meteorites were once completely molten
- chondrites → hot droplets of molten silicate minerals aggregated in cold state
- iron meteorites came from the core of small planetary bodies
- achondrites came from crust and mantle of small planetary bodies
- the stony iron meteorites are a mixture of the two types and come from the core-mantle boundary
- the minor meteorite groups originated from early small planetary bodies differentiated and were broken up by later impacts
- chondrites → original bodies → formed differentiated bodies

Differentiation model

- A differentiation model is proposed for the structural formation of terrestrial bodies and asteroids in early history of solar system
- there started off with a body that was accreting space debris
- accretion through impacting → generates heating → melting
- rapid decay of intense radioactive elements e.g. plutonium
- combination of these processes caused early formed asteroid-sized bodies to melt, some became completely molten
- dense material sank to the centre, lighter material as scum to the surface → 4 layered structure

Differentiation model

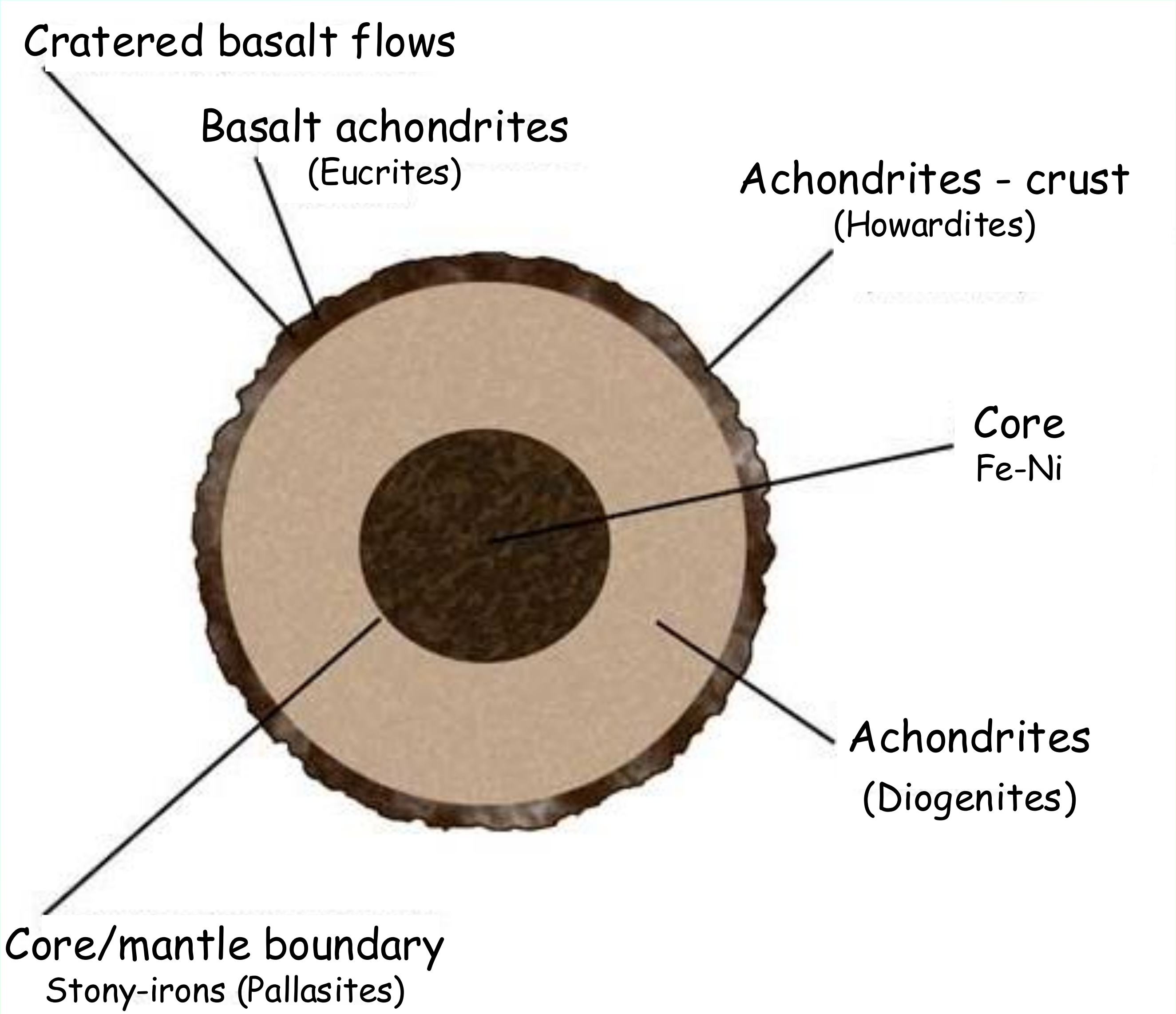


Formation of asteroids

- Many of the small asteroid-sized bodies were subsequently smashed by continuing impacts with other asteroids
- iron meteorites come from the core of these bodies; stony iron from base of mantle; achondrites from mantle and crust
- chondrites seem to represent original bodies from which minor bodies formed without segregation into different components

Origin of meteorites

Different types of meteorites originate from different layers



Significance of meteorites

- Oldest known objects in Solar system - 4,600 million years
- carbonaceous chondrites have a primitive chemical composition
  - original material of the Solar system, never completely molten
- similar composition to the heavy elements in the Sun
- they are typical of the material from which the terrestrial planets formed
- provide important clues to the origin of the Solar system and the interiors of planets