

GEOCHRONOLOGY

On 14th March 2018 Alan Gray gave a most interesting, comprehensive and entertaining talk on Geochronology – the science of dating and determining the time sequence of events in the history of the Earth. The sequence is defined by the International Commission on Stratigraphy and presented in summary form in the International Chronostratigraphic Chart and updated periodically. The latest version (available online) is presented below as Figure 1.

It can be accessed online at www.stratigraphy.org/index.php/ics-chart-timescale

Alan emphasised that the Chart was worth further study and a brief description is given below with an explanation of some of the terms used.

Stratigraphic classification encompasses all rocks of the crust of the Earth divided into a series of chronostratigraphic units based on the time of formation of the rocks. It is sub-divided into Eons, Eras, Systems, etc.

| Division | Descriptions/Examples |
|---------------------|--|
| Eonothem or Eon | The formal stratigraphic unit of the highest rank, e.g. The Phanerozoic – rocks in which the evidence of life is abundant – is divided into erathems. |
| Erathem Or Era | The Phanerozoic Eonothem is divided into the Palaeozoic, Mesozoic and Cenozoic Erathems. An Era is the temporal (or time-related) equivalent of an Erathem. |
| System or Period | A system represents a time span and an episode of Earth history sufficiently great to serve as a worldwide reference and is the fundamental unit of the chronostratigraphic classification of Phanerozoic rocks. Examples are the Cambrian, Ordovician, Silurian, etc. A Period is the temporal (or time-related) equivalent of a System. |
| Series Or Epoch | A stratigraphic that ranks below a system and is always a sub-division of a System. Examples are the sub-division of the Jurassic into Upper, Middle and Lower or the sub-division of the Silurian into Pridoli, Ludlow, Wenlock and Llandovery. An Epoch is the temporal (or time-related) equivalent of a Series. |
| Stage Or Age | A subdivision of a Series, e.g. the Danian or Maastrichtian which lie above and below the globally significant K/T boundary. |

Boundaries and names of Stages are established by the International Commission on Stratigraphy (ICS) of the International Union of Geological Sciences. As of 2008, the ICS is nearly finished a task begun in 1974, subdividing the Phanerozoic eonothem into internationally accepted stages using two types of benchmark. For younger stages, a Global Boundary Stratotype Section and Point (GSSP), a physical outcrop clearly demonstrates the boundary.

The positions of established GSSPs are indicated in Figures 1 and 2 below with the symbol of a “Golden Spike”.

The GSSP definition effort started in 1977. As of 2012, 64 of the 101 stages that need a GSSP have been formally defined.

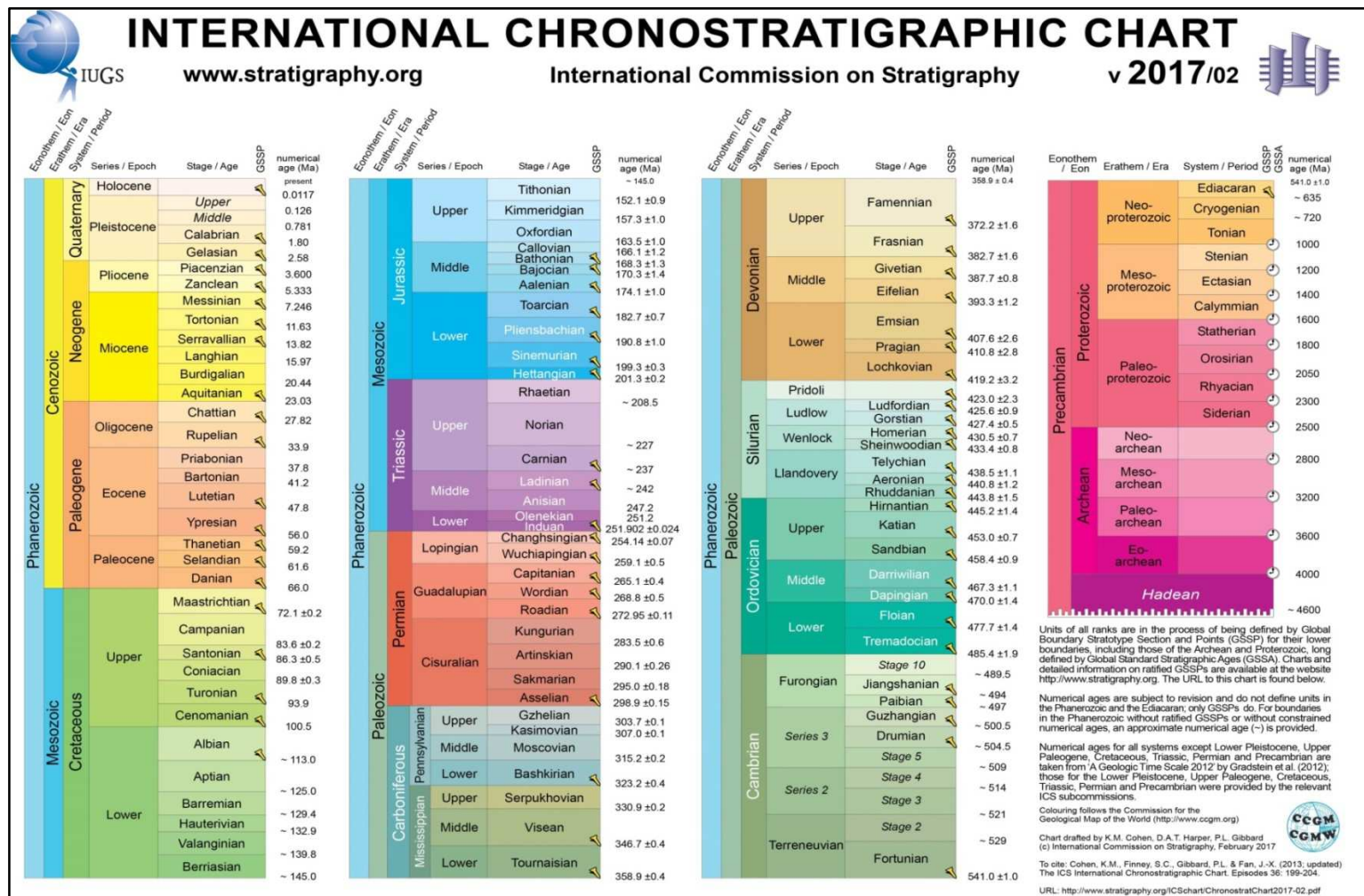


Fig. 1 International Chronostratigraphic Chart (2017)

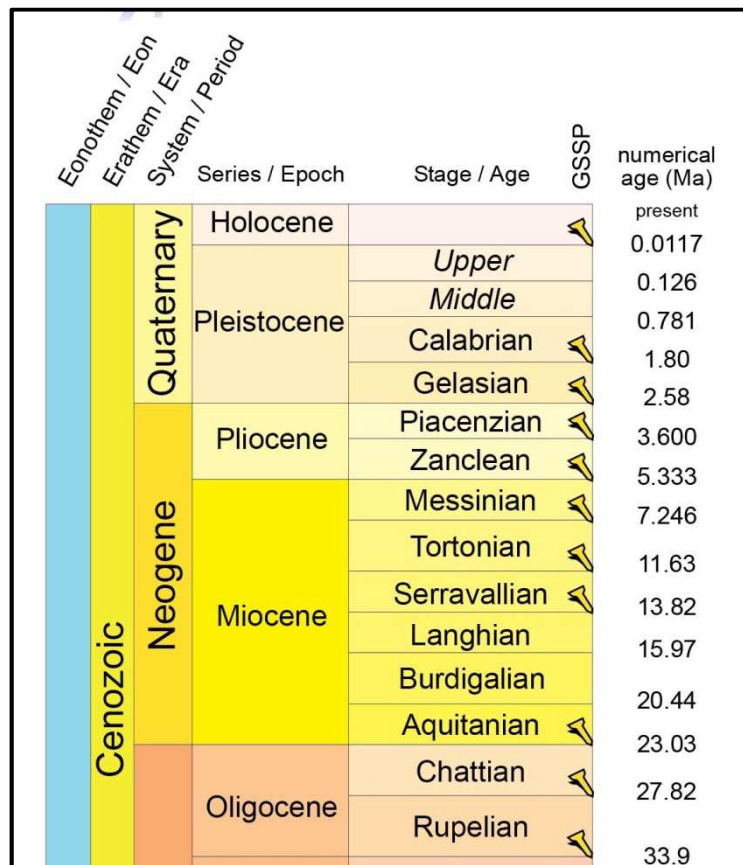


Fig. 2 Section of the International Chronostratigraphic Chart (2017) showing established “Golden Spikes”

A Global Boundary Stratotype Section and Point (abbreviated to GSSP) is an internationally agreed upon reference point on a stratigraphic section which defines the lower boundary of a stage on the geologic time scale. The effort to define GSSPs is conducted by the International Commission on Stratigraphy, a part of the International Union of Geological Sciences. Most, but not all, GSSPs are based on paleontological changes. Hence GSSPs are usually described in terms of transitions between different faunal stages, though far more faunal stages have been described than GSSPs.

RELATIVE AND ABSOLUTE DATING

Rocks can be dated by two distinctly different methods:

- **Relative or Comparative Dating** – where time-order is based on superposition derived from the comparison of different sites or sequences which have been mapped in detail, or on fossil content.
- **Absolute Dating** – where an age is measured in years before the Present by radiometric dating techniques.

RELATIVE DATING

Accurate Relative Dating is dependent on being able to demonstrate the age relationships between different horizons using either lithostratigraphic or biostratigraphic methods, or both.

A. Lithostratigraphy

What appears to be a full succession may be disrupted by processes such as disconformities, unconformities, etc. and obtaining the full sequence may involve integrating sequence mapping from different localities of the same age. The rules and procedures involved in defining these were originally outlined by Steno in the 17th Century. These include:

1. **The Principle of Superposition** – whereby when rocks are accumulated in beds one above the other the highest bed is the youngest. However, the Grand Canyon is an excellent example of how an exposed rock succession may not be the full succession – see Figure 2 below and note the unconformities and disconformities which indicate interruptions in the sedimentary sequence.

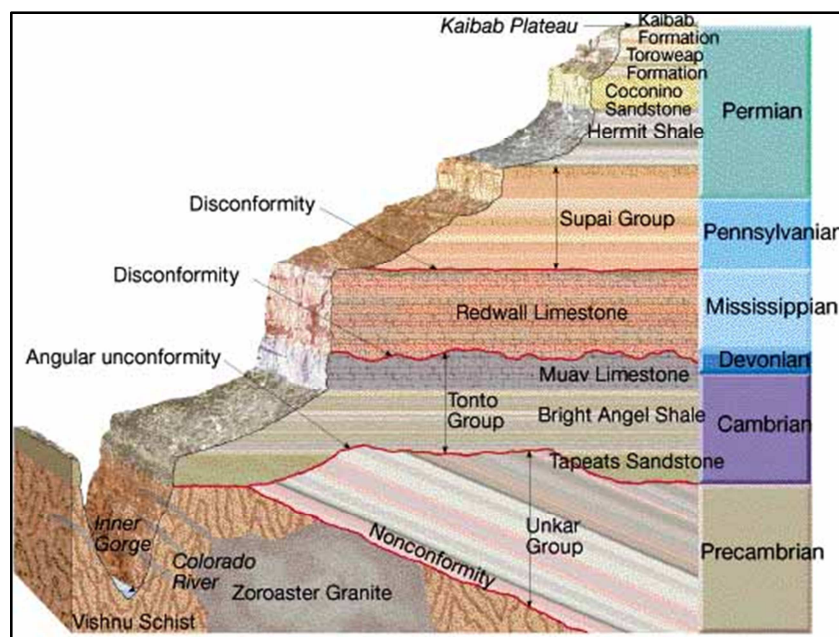


Fig. 3 A Schematic section through the Grand Canyon

2. **The Principle of Original Horizontality** - whereby it is assumed that at the time of deposition sedimentary layers are horizontal. If they are no longer horizontal they must have undergone some form of deformation e.g. folding and faulting - after deposition.

Special care must be taken to ensure that no sections of the area mapped have areas where folding has resulted in overturned strata. The correct “way up” can be determined using sedimentary features such as cross-stratification, graded bedding, scour structures, load structures, flute casts, etc. – see below.

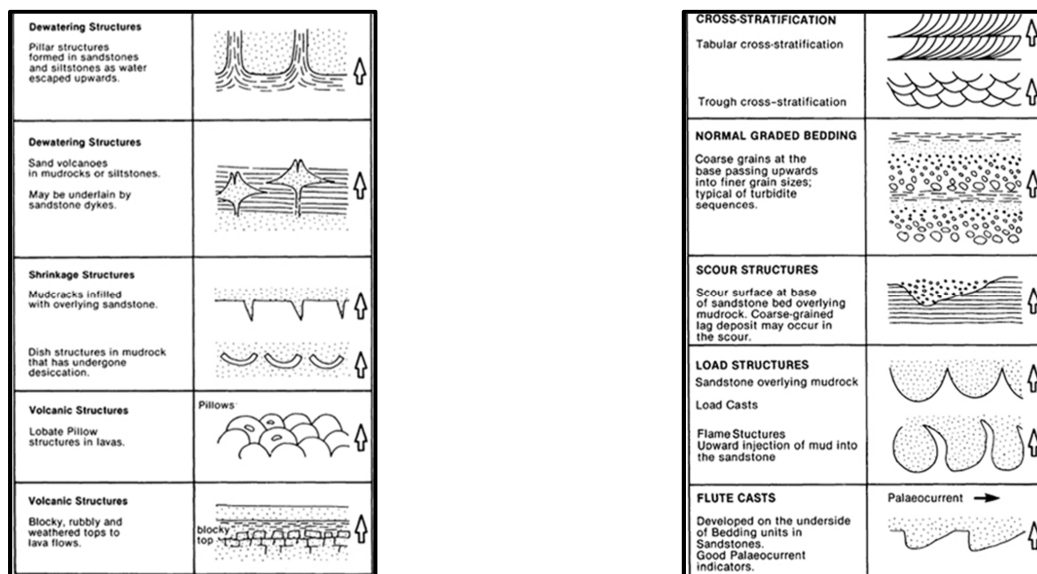


Fig. 4 Features used to determine “the way up” in sedimentary rocks

3. **The Principle of Lateral Continuity** - at the time of deposition sedimentary layers are contiguous for long distances. If they terminate abruptly, they have either undergone deformation or they have been eroded. The two most common causes of abrupt bed termination are faulting and unconformities. An unconformity is a surface that represents an episode of geological time missing in the sedimentary sequence either because it has not been deposited (a disconformity) or subsequently removed by erosion (an unconformity). Sedimentary layers can also taper laterally into other sedimentary units.

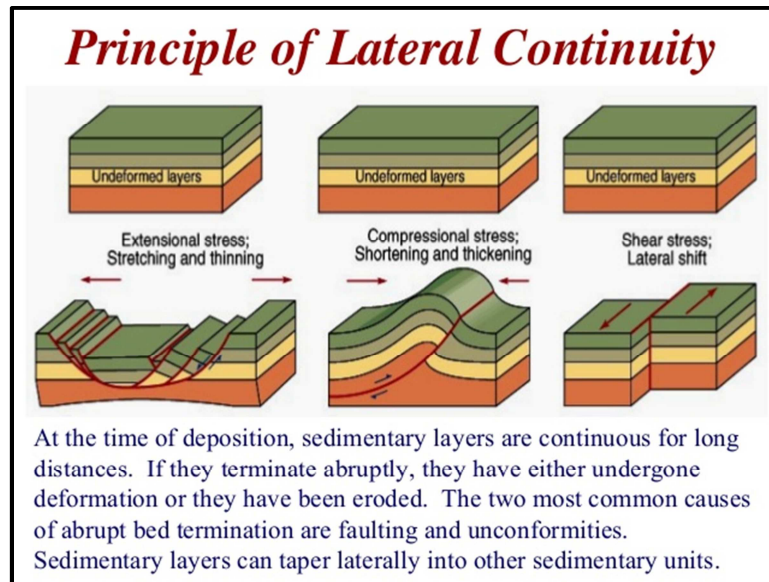


Fig. 5 The Principle of Lateral Continuity

4. **The Principle of Cross-cutting Relationships** – whereby a rock body that is cut (or crossed) by another rock body, structure or unconformity is older than that which is cutting it.

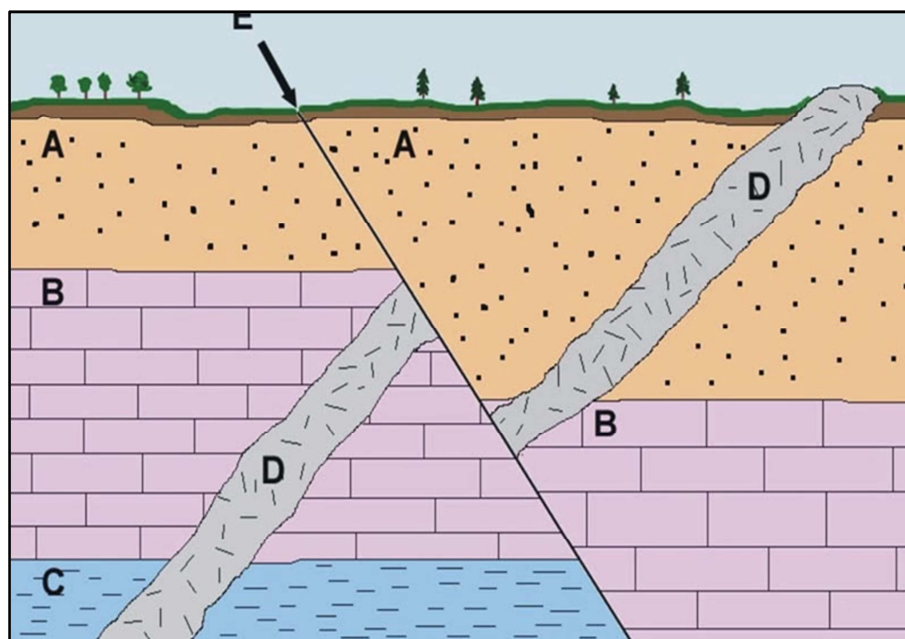


Fig. 6 The Principle of Cross-cutting Relationships

5. The Principle of Inclusion

Figure 7 below shows inclusions of differing types.

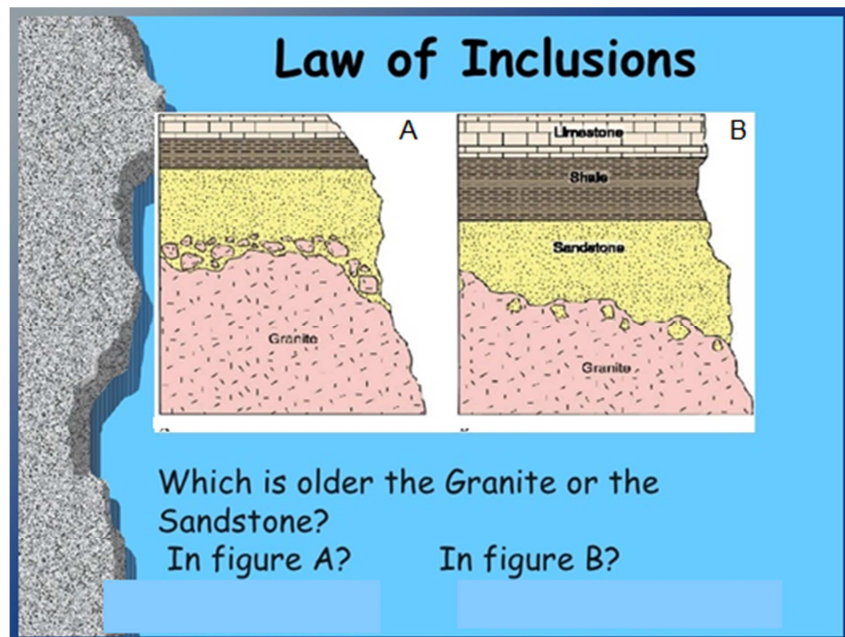


Fig. 7 The Principle of Inclusion

In A (LHS) fragments or clasts ("inclusions") of granite are held within the overlying sandstone. The granite has been eroded before the majority of the sandstone has been deposited and is obviously younger than the granite.

In B (RHS) fragments, or xenoliths, of sandstone are held within the granite. The granite has intruded the sandstone and is obviously younger.

B. Biostratigraphy

The Principle of Faunal Succession was set out by William Smith – the first person to recognise that:

"Each stratum contained organised fossils peculiar to itself, and might, in cases otherwise doubtful, be recognised and discriminated from others like it, but in a different part of the series, by examination of them".

This has given rise to the concepts of "Zones", "First Appearance Datum" and "First Occurrence" which are principally used with Indicator Fossils.

Index Fossils

An Index Fossil is a fossil that identifies and dates the strata or succession of strata in which it is found. The best and most useful Indicator Fossils have the following characteristics. They should be:

| | |
|-----------------------------------|--|
| Widespread | Existing in both Pelagic and Oceanic Environments |
| Abundant | Usually small and existing in large numbers |
| Easily Fossilised found | Complete and are easy to extract from the rock in which they are found |
| Short-lived | Displaying the greatest time resolution produced by rapid evolution |

Easily Recognised
identified

With clear anatomy and require no specialised equipment to be

A good group of indicator fossils that satisfy most of the above criteria are conodonts – the very small, fossilised mouth-parts of a series of animals which existed from the Cambrian to the Upper Triassic. Note the pin head in Fig 8 below.

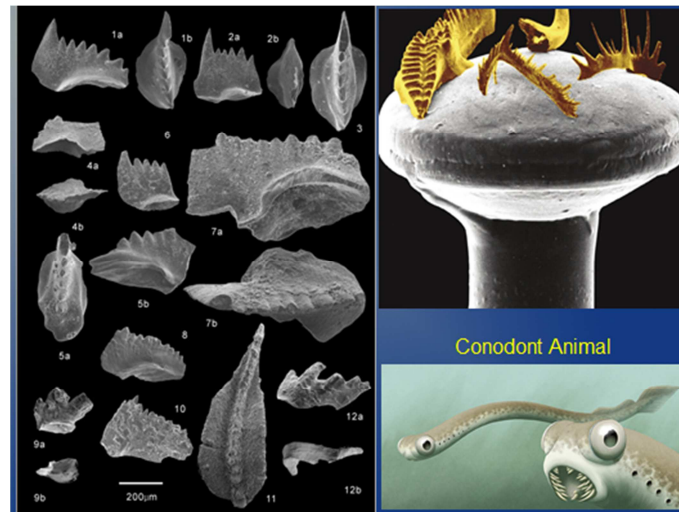


Fig. 8 Conodonts

One particular conodont *Hindeodus Parvus* marks the top of the Permian and the base of the Triassic at 251.17 ± 0.06 my – the P-T major mass extinction event with up to 96% of all marine species and 70% of terrestrial vertebrate species becoming extinct.

Figure 9 below shows the GSSP at Meishan in China where there is a “Golden Spike” to mark the transition.



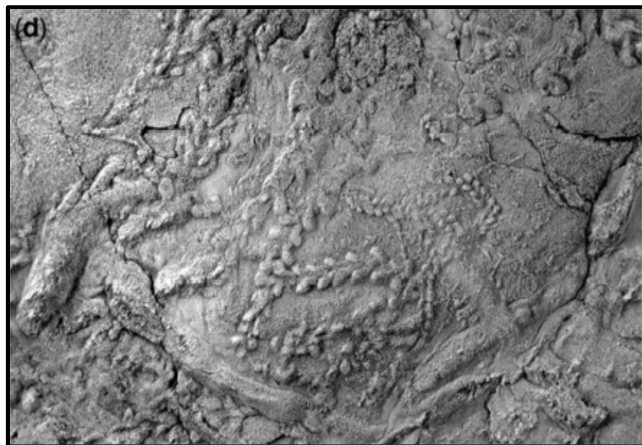
Fig. 9 Meishan GSSP site, China



Fig. 10 Photograph of an actual GSSP, marking the base of the Toarcian Stage (lower Jurassic) 182.7 at Ponta de Trovão, Peniche, Portugal

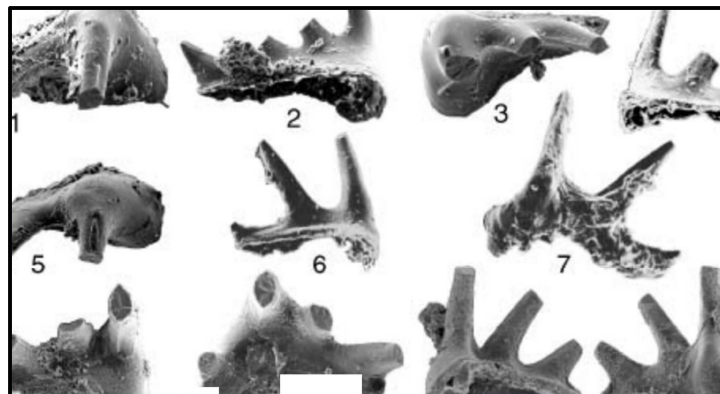
Other important indicator fossils include:

- **Trace fossils** such as *Treptichnus pedom* -

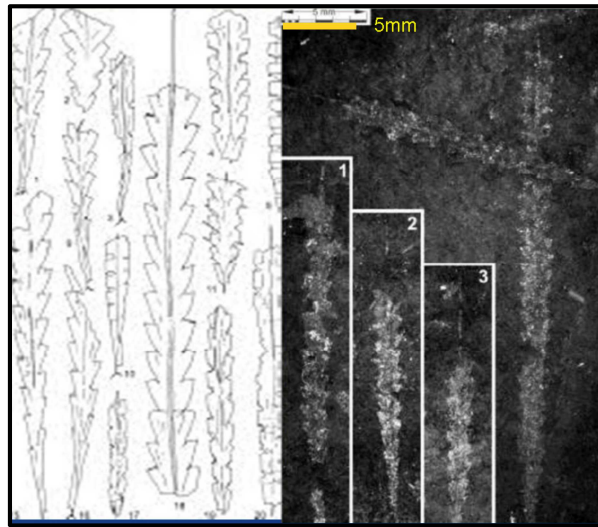


the preserved burrow of an animal rather than a fossil of that animal. It is regarded as the earliest widespread complex trace fossil with an earliest appearance, around 542 my - the base of the Cambrian.

- **Conodonts** such as *Iapetognathus fluctivagus*, which marks the base of the Tremadocian stage of the Ordovician at 485.4 my



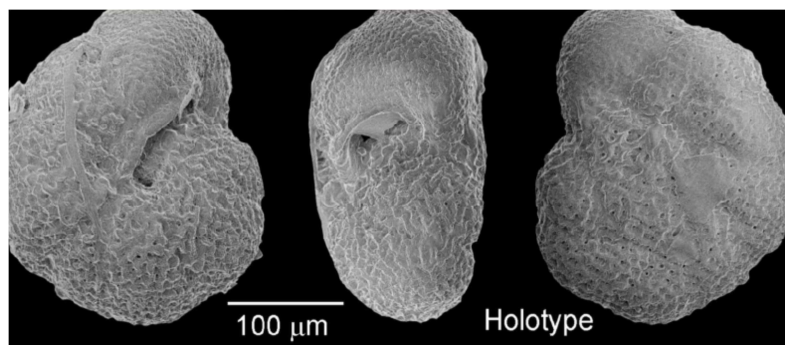
- **Graptolites** e.g. the FO of *Akidograptus ascensus* marks the base of the Silurian (the Rhuddanian Stage of Llandovery epoch (443.8 my) – the first of 7 divisions based on graptolite fauna



- **Ammonites** e.g. *Dactylioceras* (*Eodactylites*) *simplex*, the first occurrence (FO) of which marks the base of the Toarcian Stage (lower Jurassic) at Ponta do Trovão, Peniche, Portugal, and is marked by a “Golden Spike” or GSSP.



- **Foraminifera**, such as *Paragloborotalia kugleri* the first appearance of which marks the base of the Aquitanian (the lowermost stage of the Miocene series and also the Neogene System at 23.03 ± 0.05 Ma.



Another very important datum (which is entirely independent of fossils) is the “**Iridium Geochemical Anomaly**” It is not a fossil but a horizon at the Cretaceous – Palaeogene boundary with elevated and anomalous levels of iridium, osmium, and other various members of platinum group elements. It is found worldwide at the base of the Paleogene - the Danian stage of the Paleocene Series – and associated with a major extinction horizon (dinosaurs, ammonites, foraminifera, etc.).

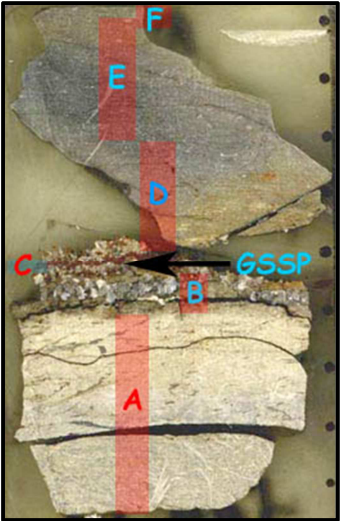


Fig 11 Base of the Palaeogene

In Fig 11 above:

- A. is the uppermost Maastrichtian. Frequent burrows are visible as dark stains, filled with dark clay from the Danian.
- B. Is the leached, topmost Maastrichtian, containing only casts of Maastrichtian foraminifers.
- C. Is a reddish ejecta layer, rich in iridium, altered microkrystites (sanidine, smectite and goethite) and Ni-rich spinels.

The global distribution of the K/T boundary clay and its associated iridium geochemical anomaly is generally attributed to the Chicxulub impactor - an asteroid, estimated at 10 to 15 kilometres in diameter, which struck the Earth in the northern Yucatan peninsula in Mexico, at the end of the Cretaceous Period, approximately 66 million years ago.

C Biostratigraphic Classification

This is based on the fossil content of the rocks and is not determined by the lithological composition of the strata. This makes the fossil assemblages of any one age unique.

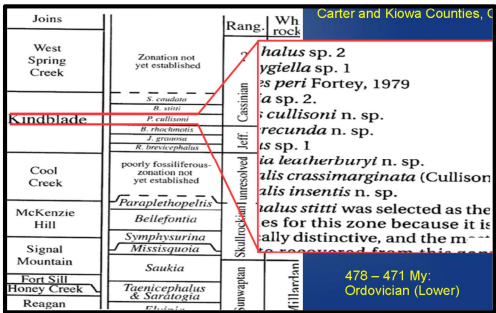


Fig 12 An example of the trilobite species typical of the Ordovician Kinblade Formation in Oklahoma, USA

ABSOLUTE DATING

Absolute dating, sometimes called numerical dating, gives rocks an actual date, or date range, in number of years. It is thus very different to relative dating, which only puts geological events in time order.

It is dependent on the rates of radioactive decay of certain isotopes which fulfil other criteria, as explored below.

Firstly, a few definitions are useful;

Atomic Number: Every element has an Atomic Number – the number of protons in the nucleus of an atom of that element. The Atomic Number controls the chemical characteristics of the element and its position in the Periodic Table.

The image shows a standard periodic table of elements. The title 'The Periodic Table of the Elements' is at the top. The table is organized into groups (columns) and periods (rows). Each element cell contains its symbol, atomic number, and name. A legend on the right side categorizes elements into groups: alkali metals, alkaline earth metals, other metals, transition metals, metalloids, nonmetals, halogens, noble gases, and unknown elements. A color-coded legend is also present. The table includes elements from Hydrogen (1) to Oganesson (118). A small diagram of an atom with a nucleus and electrons is shown in the bottom left corner.

Fig 13 Mendeleev's Periodic table of the Elements

Atomic Mass: Most of the mass of an atom is in the nucleus which is made of a number of protons and neutrons. As each of these has an atomic weight near one, the atomic weight of an element is very nearly equal to the number of protons and neutrons in the nucleus.

Hydrogen has one proton and no neutrons in its nucleus and thus an atomic mass of one; helium with one proton and one neutron has an atomic weight of two.

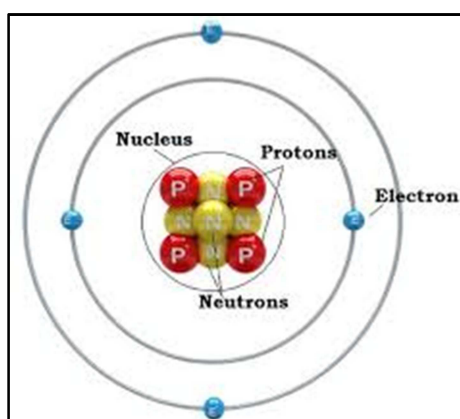


Fig 14 Compositions of Atoms of Elements

In Figure 14 the Atomic Number (z) is the number of protons in the nucleus and the Atomic Mass (A) is the number of protons plus the number of neutrons in the nucleus.

Isotopes: Some elements can incorporate additional neutrons in the nucleus. All isotopes have the same number of protons and thus similar chemistry. The introduction of additional neutrons can destabilise the nucleus which then breaks down by radioactive decay. Some isotopes of an element are stable; others are not.

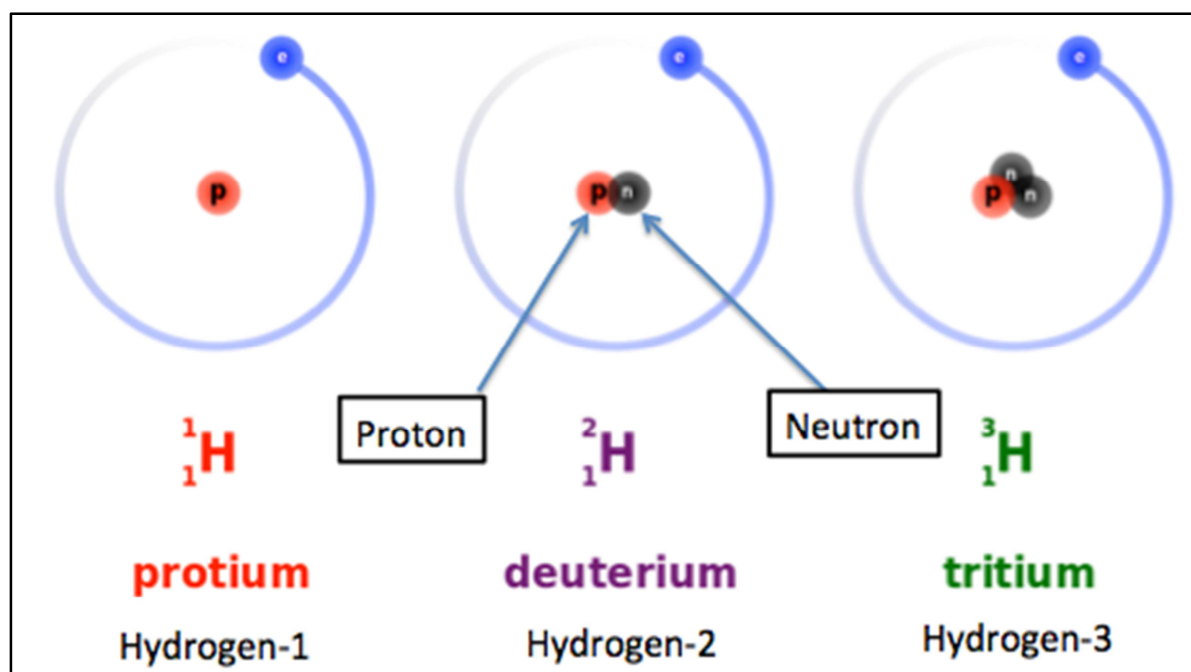


Fig 15 The different isotopes of Hydrogen

Radioactive Decay: The spontaneous transformation of an unstable atomic nucleus into a lighter one (or daughter products), in which radiation is released in the form of alpha particles, beta particles, gamma rays, and other particles.

Half-Life: It is not possible to predict when an individual atom might decay. But it is possible to measure how long it takes for half the nuclei of a piece of radioactive material to decay. This is called the half-life of the radioactive isotope and it is unique to that isotope and does not change.

There are two definitions of half-life, but they mean essentially the same thing. Half-life is the time taken for:

- The number of nuclei of the radioactive isotope in a sample to halve
- The count rate from a sample containing the radioactive isotope to fall to half its starting level.

Different radioactive isotopes have different half-lives. For example, the half-life of carbon-14 is 5,715 years, but the half-life of francium-223 is just 20 minutes.

Also, the same element may have several radioactive isotopes which decay in different ways:

Uranium has two particular isotopes – one with an atomic weight of 238, the other with an atomic weight of 235.

- ${}^{238}\text{U}$ decays to ${}^{206}\text{Pb}$ by the Uranium Series (a half-life of 4.47 billion years),
- ${}^{235}\text{U}$ decays to ${}^{207}\text{Pb}$ following the Actinium Series (a half-life of 710 million years).

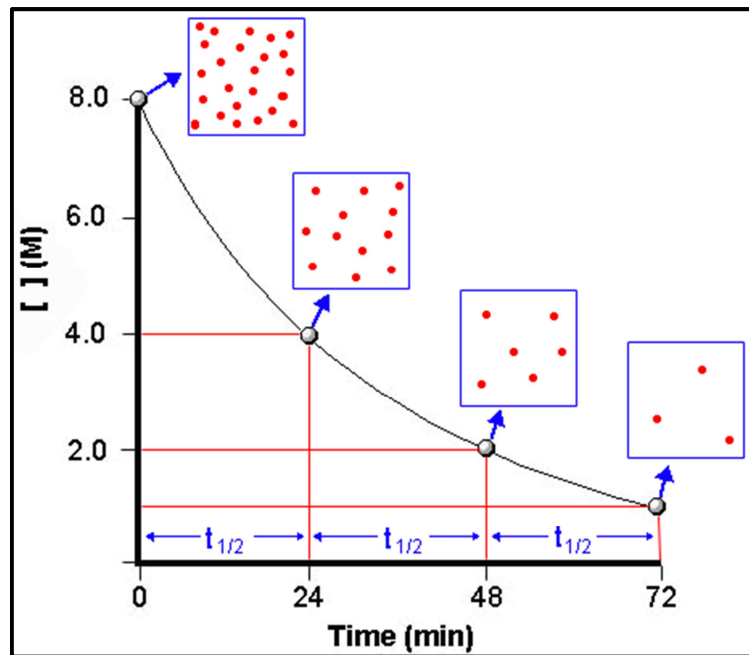


Fig 16 The Radioactive Decay Curve of the Actinium Series

The unstable ^{235}U isotope of Uranium decays to the stable ^{207}Pb isotope of Lead - Half-Life approximately 710 million years.

Radiometric (or Absolute) dating: This is a technique used to date materials or minerals in which trace radioactive impurities were selectively incorporated when they were formed. The method measures how much of a naturally occurring radioactive isotope occurs within the material/minerals and compares this to how much there is of its decay products. As the formation of the daughter products takes place at a known constant rate of decay the ratio of parent and daughter allows calculation of how long the process has been active – the age of the mineral or rock in which it is contained.

Due to the variation in half-Lives different isotopes are appropriate to determining the ages of different rocks from ages – a variation ranging from uranium's Actinium Series being used for Pre-Cambrian rocks to Carbon¹⁴ being used for archaeological dating purposes.

| Isotope | | Half-life of parent (years) | Useful range (years) |
|--------------|--------------|-----------------------------|--------------------------|
| Parent | Daughter | | |
| Carbon 14 | Nitrogen 14 | 5,730 | 100 - 30,000 |
| Potassium 40 | Argon 40 | 1.3 billion | 100,000 - 4.5 billion |
| Rubidium 87 | Strontium 87 | 47 billion | 10 million - 4.5 billion |
| Uranium 238 | Lead 206 | 4.5 billion | 10 million - |
| Uranium 235 | Lead 207 | 710 million | 4.6 billion |

Fig 17 Different Decay Series which determine different ages ranges through Geological Time

| ISOTOPES | | HALF-LIFE OF PARENT (YEARS) | EFFECTIVE DATING RANGE (YEARS) | MINERALS AND OTHER MATERIALS THAT CAN BE DATED |
|--------------|--------------|-----------------------------|--------------------------------|--|
| PARENT | DAUGHTER | | | |
| Uranium-238 | Lead-206 | 4.5 billion | 10 million-4.6 billion | Zircon Uraninite |
| Potassium-40 | Argon-40 | 1.3 billion | 50,000 - 4.6 billion | Muscovite Biotite Hornblende Whole volcanic rock |
| Rubidium-87 | Strontium-87 | 47 billion | 10 million - 4.6 billion | Muscovite Biotite Potassium feldspar Whole metamorphic or igneous rock |
| Carbon-14 | Nitrogen-14 | 5730 | 100 - 70,000 | Wood, charcoal, peat Bone and tissue Shell and other calcium carbonate Groundwater, ocean water, and glacier ice containing dissolved carbon dioxide |

Fig 18 Different Decay Series are used to date different minerals

For radiometric (or Absolute) dating of rocks to be successful a number of criteria must be satisfied.

Firstly, there must be a means of determining accurately the relative amounts of parent and daughter products.

The equipment used is a Mass Spectrometer in which a sample to be dated is introduced, is vaporised by an electron beam and its constituent isotopes are given a net electric charge due to the loss or gain of one or more electrons.

The ions are then accelerated through a powerful electromagnet which deflects the ion beam by pre-determined amount. The amount each individual ion is deflected depends on its atomic weight (lighter ions are deflected most; heavier isotopes the least) thus causing the isotopes to be separated from each other. A number of detectors designed to receive specific isotopes then allow the relative amounts the parent and daughter isotopes to be counted and thus the age of the specimen determined.

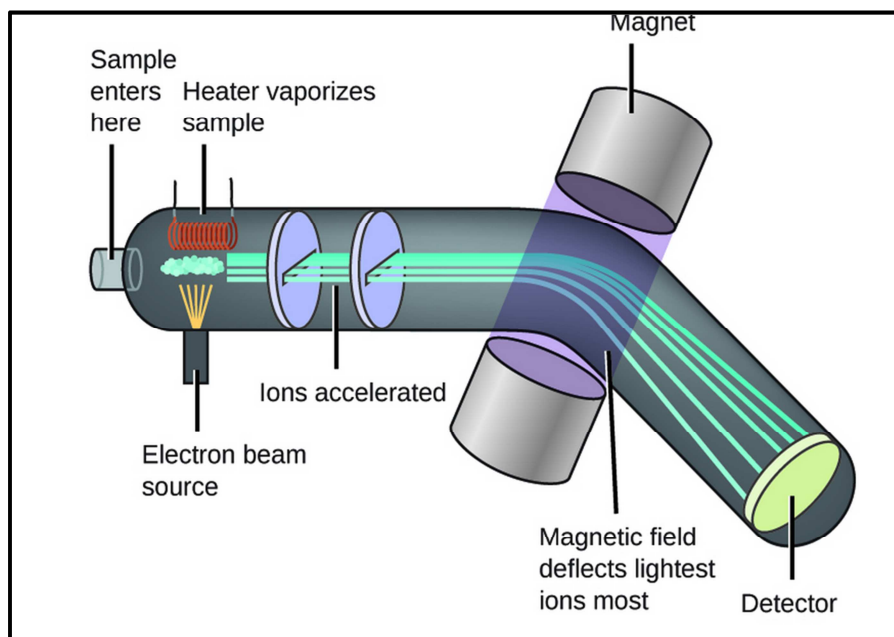


Fig. 19 A mass spectrometer

Secondly, the unstable isotopes (elements) which will undergo decay must be held within a mineral, the internal structure of which will not allow the release or loss of either the original unstable element or the daughter products produced by its radioactive decay since its formation.



Fig. 20 A zircon crystal

Zircon (ZrSiO_4) is a ubiquitous trace mineral in many igneous, metamorphic, and clastic sedimentary rocks. Its ability when forming, to concentrate uranium and exclude lead is the basis of U-Pb geochronology and its refractory nature and concentric growth patterns create robust records of crystallization age.

It is extremely durable. Zircon grains that crystallised 4.4 billion years ago are the oldest surviving pieces of the Earth's crust (the oldest rocks visible on the planet today did not form for another 400 million years).

Zircon has a unique crystal structure that allows small amounts of uranium (U) to substitute into the crystal when it forms. Over time this uranium radioactively decays into lead (Pb).

No other geological events which have affected the rock/mineral since its formation alter the $^{238}\text{U}/^{236}\text{Pb}$ or $^{235}\text{U}/^{237}\text{Pb}$ ratios thus preserving the record of its age.

Other minerals which can be dated include:

| ISOTOPES | | HALF-LIFE OF PARENT (YEARS) | EFFECTIVE DATING RANGE (YEARS) | MINERALS AND OTHER MATERIALS THAT CAN BE DATED |
|--------------|--------------|-----------------------------|--------------------------------|---|
| PARENT | DAUGHTER | | | |
| Uranium-238 | Lead-206 | 4.5 billion | 10 million-4.6 billion | Zircon Uraninite |
| Potassium-40 | Argon-40 | 1.3 billion | 50,000 - 4.6 billion | Muscovite Biotite Hornblende Whole volcanic rock |
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| Carbon-14 | Nitrogen-14 | 5730 | 100 - 70,000 | Wood, charcoal, peat Bone and tissue Shell and other calcium carbonate Groundwater, ocean water, and glacier ice containing dissolved carbon dioxide |

Fig. 21 Other minerals used in dating

Other Nuclear Radiation Dating techniques include:

Fission track Analysis - a radiometric dating technique based on analyses of the damage trails, or tracks, left by fission fragments in certain uranium-bearing minerals and glasses.. Fission tracks are sensitive to heat, and therefore the technique is useful at unravelling the thermal evolution of rocks and minerals.

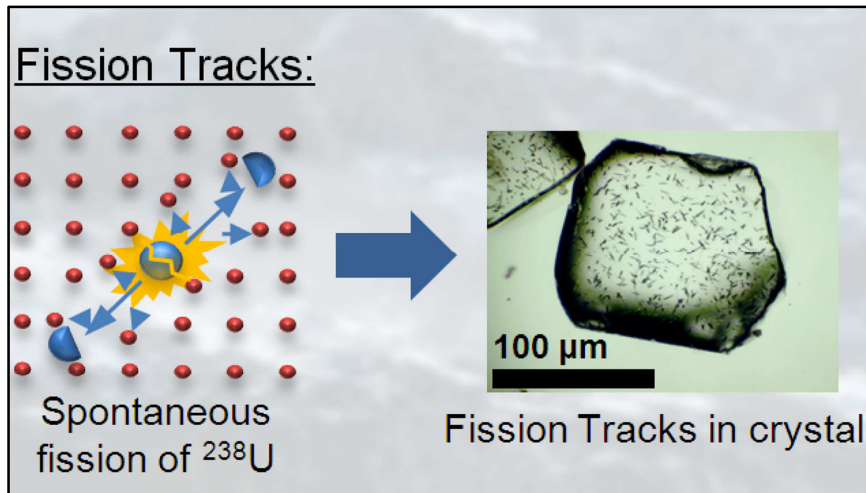


Fig. 22 Fission tracks

Unlike other isotopic dating methods, the feature measured in fission track dating is an effect in the crystal rather than a daughter isotope. The fragments emitted by Uranium-238 fission process leave damage trails in the crystal structure of the mineral containing the uranium. Chemical etching of polished internal surfaces of these minerals reveals spontaneous fission tracks, and the track density can be determined. The density of fossil tracks correlates with the cooling age of the sample and with uranium content, which needs to be determined independently – usually by irradiation in a nuclear reactor with an external detector, such as mica, fixed to the grain surface.

The resulting induced fission of the uranium-235 in the sample creates induced tracks in the overlying external detector, which are again later revealed by chemical etching. The ratio of spontaneous to induced tracks is proportional to the age.

Luminescence dating refers to a group of methods of determining how long ago mineral grains were last exposed to sunlight or significant heating. It is used to provide a date when such an event last occurred by using various methods to stimulate and measure luminescence. It includes techniques such as optically stimulated luminescence (OSL), infrared stimulated luminescence (IRSL), and thermoluminescence dating (TL).

All sediments and soils contain trace amounts of radioactive isotopes of elements such as potassium, uranium, thorium, and rubidium. These slowly decay over time and the ionizing radiation they produce is absorbed by mineral grains such as quartz and potassium feldspar in the sediments.

The absorbed radiation causes an electrical charge to remain within the grains in structurally unstable "electron traps". The trapped charge accumulates over time at a rate determined by the amount of background radiation at the location where the sample was buried.

Stimulating these mineral grains by using either light (blue or green for OSL, infrared for IRSL) or heat (for TL) causes a luminescence signal to be emitted as the stored unstable electron energy is released, the intensity of which varies depending on the amount of radiation absorbed during burial (i.e. the length of time the sediment has been buried) and specific properties of the mineral.

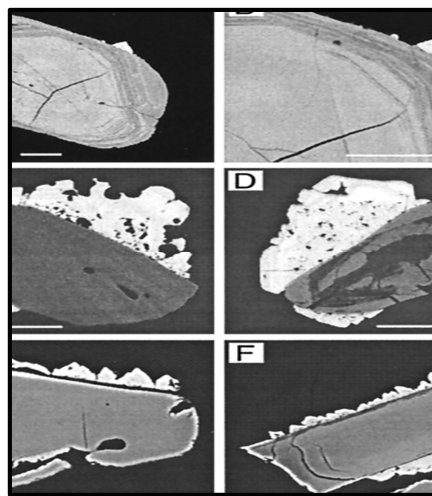
Radioactive Xenotime – Used for Dating Sediments

Diagenesis is the sum of all of the processes, chiefly chemical, by which changes in sediment (an unconsolidated mass of rock fragments, minerals, precipitates, fossils and other detritus) are brought about after its deposition and continue until it is finally converted to rock.

Xenotime is a rare-earth phosphate mineral, the major component of which is yttrium orthophosphate (YPO_4). Xenotime:

- a. Grows in sediments during diagenesis, shortly after deposition
- b. Can incorporate U and/or Th which can be dated - the capture of U and Th occurs once the sediments has formed and stops when the sediment is converted to rock
- c. Is common in siliciclastic sedimentary rocks.

Xenotime is an ideal U–Pb chronometer. It contains elevated levels of U (generally >1000 ppm) and very low concentrations of initial common Pb. In addition, it has an exceptional ability to remain closed to element mobility during later thermal events.



Scale Bars: 20µm

Fig. 23 SEM images of detrital zircon grains with Xenotime overgrowths

A and B: Rounded detrital zircon grain with pyramidal xenotime outgrowth.

C and D: Rounded zircon with large xenotime outgrowths showing zonation, later growth and partial dissolution

E and F: Detrital zircon lined with xenotime crystals

The Geomagnetic Timescale – the correlation of rocks of different ages with the Earth's magnetic field

The study of palaeomagnetism is possible because iron-bearing minerals such as magnetite may record past directions of the Earth's magnetic field.

Magnetostratigraphy is a geophysical correlation technique which works by collecting oriented samples at measured intervals throughout a section or traverse. These are analysed to determine their *characteristic remnant magnetization* (ChRM) which reflects the polarity of the Earth's magnetic field at the time the rocks were formed. Near mid-ocean ridges, dating the basalts defines the timing of reversals.

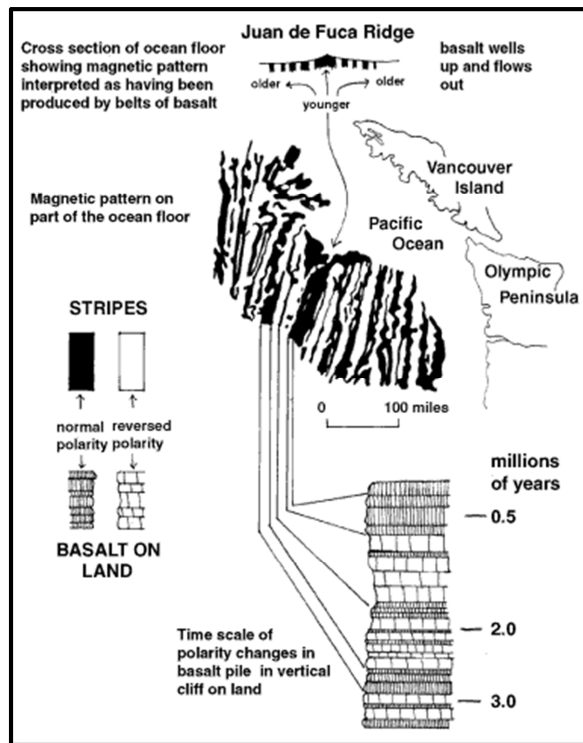


Fig. 24 Palaeomagnetic correlation between land and ocean

Figure 21 above shows the familiar striped appearance of oceanic magnetic reflecting changes in remnant magnetism due to reversals in the Earth's magnetic field as intruded basalts move away from spreading centres over time.

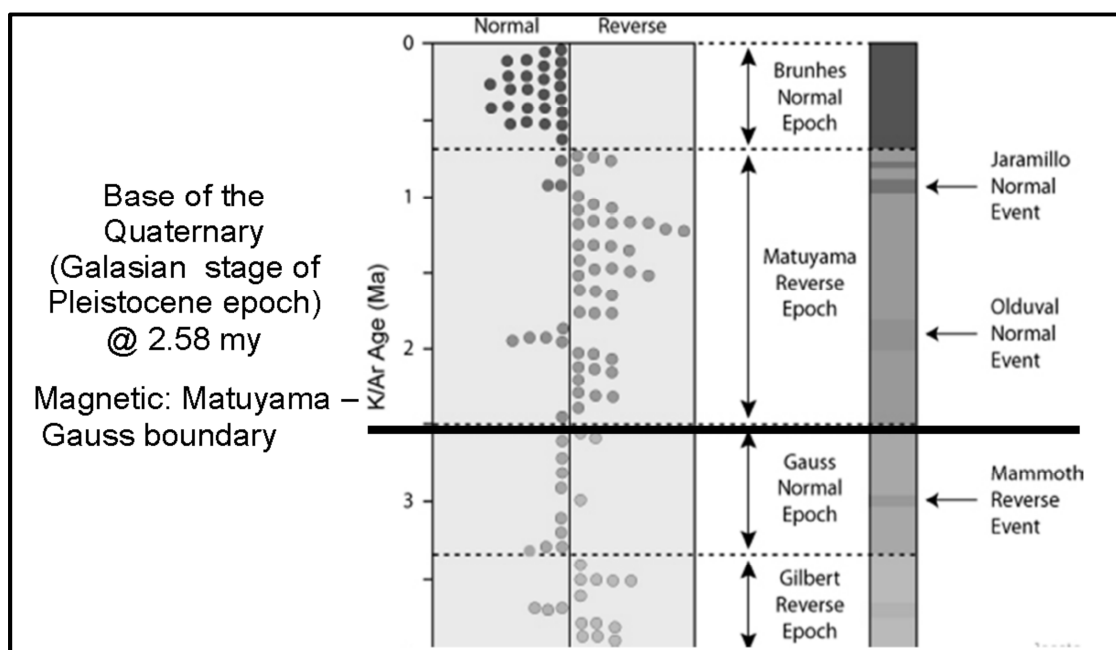


Fig. 25 A Geomagnetic GSSP

Figure 22 shows that the base of Quaternary (fixed at 2.58 my) is also the boundary between the Gauss Normal Epoch and the overlying Matuyama Reverse Epoch – a Geomagnetic GSSP.