WORKINGS OF THE EARTH

A Geological Supplement to
'Ugborough Parish Heritage Appraisal 2016'

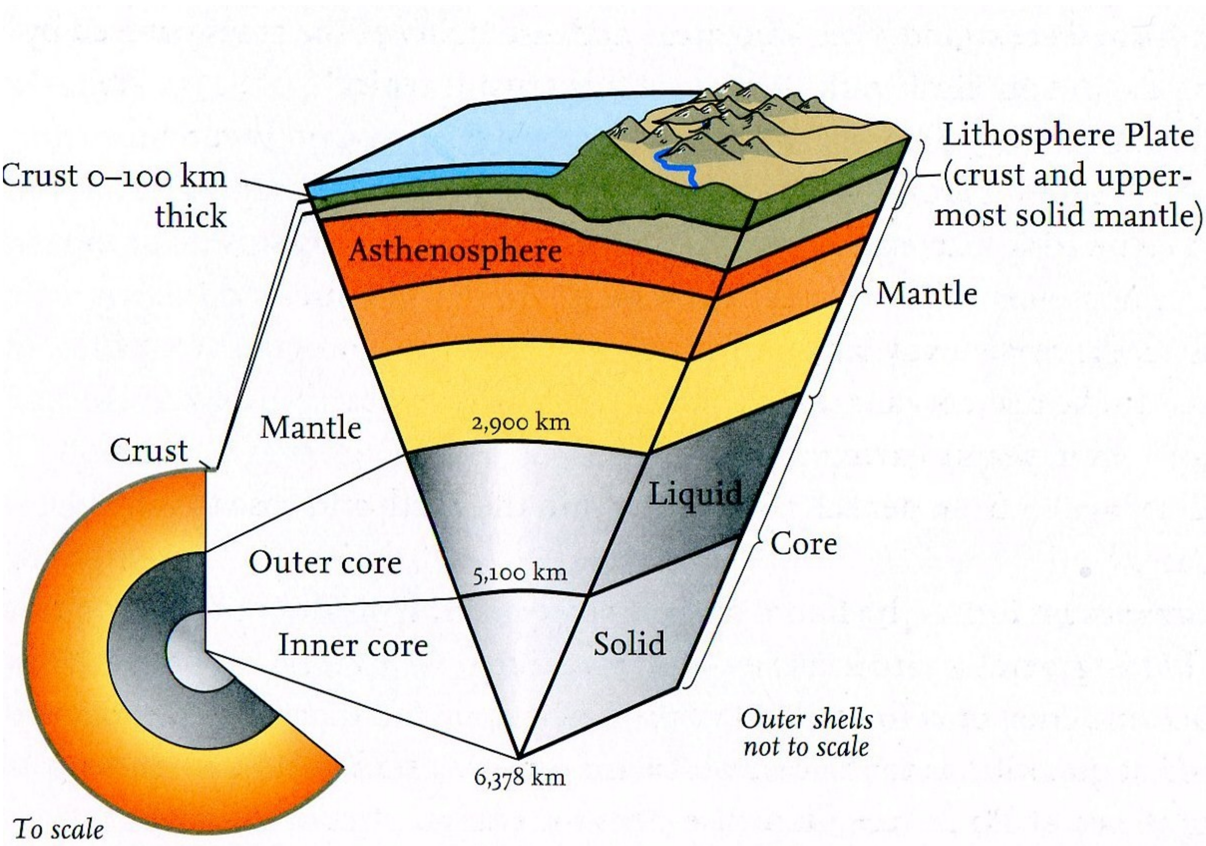

Fig. 1

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PREFACE

In 2003 the two organisations Area of Outstanding Natural Beauty South Devon and South Hams District Council, initiated and published as a component of 'Life into Landscape', a series of studies whereby professionals from Exeter Archaeology collaborated with local history societies to prepare Heritage Appraisals of twelve parishes in the South Hams. The very large amount of data, old and new, which resulted from these collaborations had never before been systematically collated and was a major contribution to the history of the District. But rather surprisingly although the study was part of 'Life into Landscape' no attempt was made to consider the origins of that landscape and its significance to human occupation and activities.

History as we usually use the term is the chronicle of human collaboration and competition in exploiting the natural resources of an area, namely **Soils** (and associated vegetation); **Water Supplies;** and **Mineral Resources** (for building, road-making and as economic commodities). All of these together with the **Climate,** present and past, and the **Topography** are absolutely determined by the **Geological History** of the area. The influence of geology was seen to be particularly obvious in the case of Ugborough Parish which straddles the boundary between granite and slates, and hence between Moorland and Lowland with their different but complementary potentials. In the 2nd Edition of the Ugborough Heritage Appraisal, therefore, an attempt was made to show how the Parish's natural resources had evolved over half a billion years, and at the same time to show how our own minute fragment of the Earth's surface related to global events through time.

To appreciate this account fully, a little basic knowledge of the principles of geology was necessary. As some readers would not already have this, it was decided not to unduly lengthen the text with explanations but to publish a short explanatory supplement which readers could use or not as they saw fit. It is hoped that the following text will prove intelligible, interesting and useful for this purpose; and perhaps also for others who may just wish to know in concise terms how modern geologists see our World.

The author wishes to thank Mr Adrian Wardle for designing the cover and for help in improving the text.

Robert Perrin
November 2016

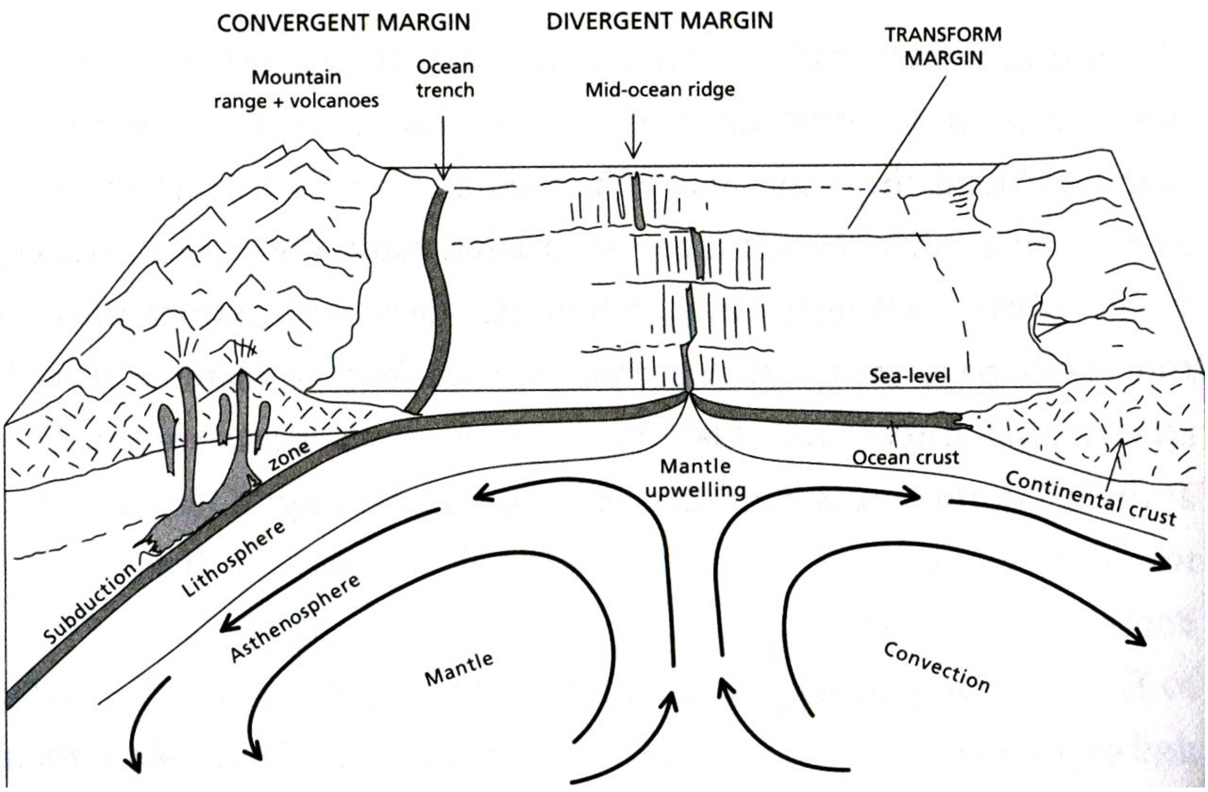
CONVERGENT MARGIN
DIVERGENT MARGIN
TRANSFORM MARGIN
Mountain range + volcanoes
Ocean trench
Mid-ocean ridge
Sea-level
Ocean crust
Continental crust
Mantle upwelling
Subduction zone
Lithosphere
Asthenosphere
Mantle
Convection

Fig. 2

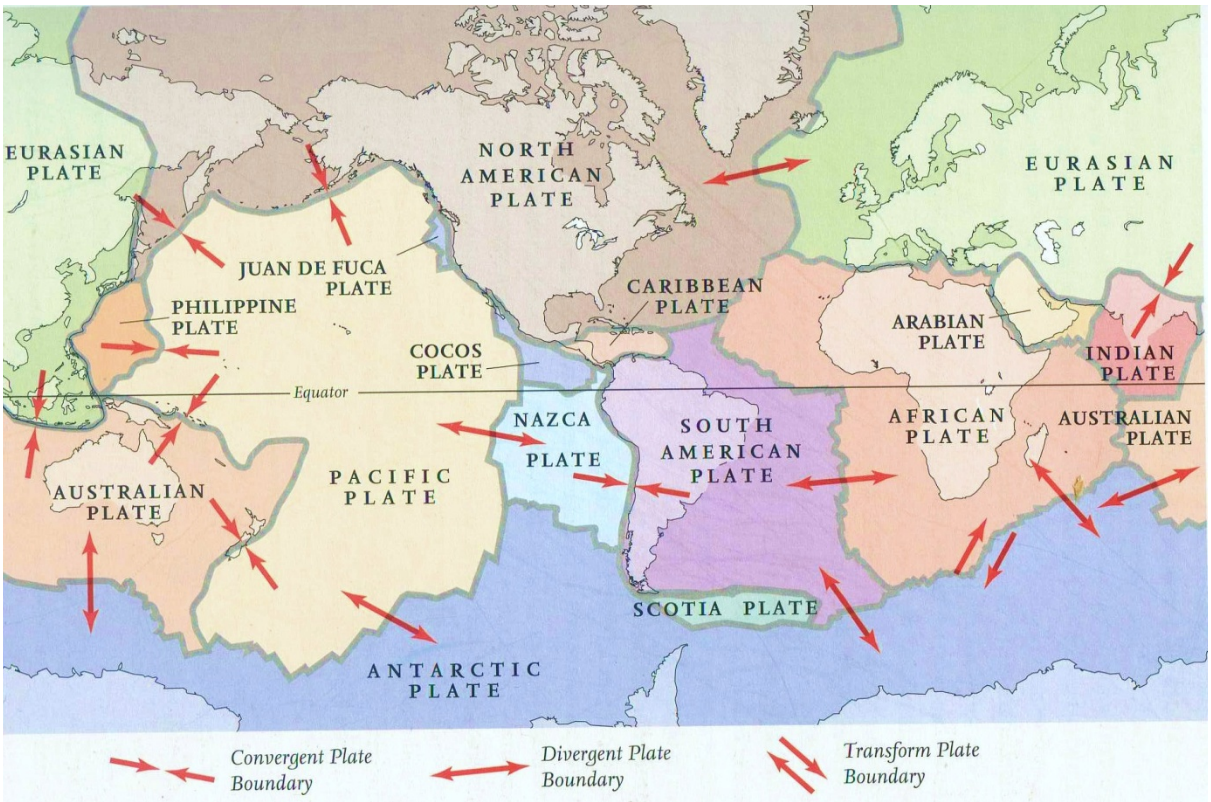
EURASIAN PLATE
NORTH AMERICAN PLATE
EURASIAN PLATE
JUAN DE FUCA PLATE
PHILIPPINE PLATE
CARIBBEAN PLATE
ARABIAN PLATE
COCOS PLATE
INDIAN PLATE
Equator
NAZCA PLATE
SOUTH AMERICAN PLATE
AFRICAN PLATE
AUSTRALIAN PLATE
PACIFIC PLATE
AUSTRALIAN PLATE
SCOTIA PLATE
ANTARCTIC PLATE
Convergent Plate Boundary
Divergent Plate Boundary
Transform Plate Boundary

Fig.3

WORKINGS OF THE EARTH

In the last 50 years there has been a revolution in our perception of how the Earth has developed since its beginning some 4.6 billion years ago, and it is now generally accepted that most of geology is explicable in terms of the over-arching concept of *plate tectonics* (*Gr. tekton*, a builder). For very readable accounts of the theory, see Fortey (2004) *'The Earth'* for a World view, or Friend (2008) *'Southern England'* for our region.

Plate Tectonics

The Earth originally separated into the metallic *core* and the *mantle* which occupies the outer 2900 km of its radius (Fig.1). The core and the deepest and middle parts of the mantle can be ignored for our purposes but the uppermost part is of crucial significance. It is divisible into (i) an inner spherical shell called the *asthenosphere* (Gr. *asthenos*, no strength) which is hotter and stiffly plastic; and (ii) an outer shell some125km in thickness called the *lithosphere* (Gr. *lithos,* stone) which is cooler and more rigid. Both are composed of relatively dense *basic*+ rock with a high proportion of *ferromagnesian minerals** +.

The **asthenosphere** contains areas of very slow convection currents whereby semi-molten rock, bringing up heat from the deep interior, rises to the base of the lithosphere, spreads out horizontally and then descends back into the depths (Fig. 2).

The **lithosphere** is divided into a mosaic of adjoining *plates* rather like the panels of the skin of a football. These are of widely varying shape and extent, ranging from areas greater than the present continents, to ones only hundreds of kilometres across (*micro-plates*).
At the moment there are six major plates named after the continents they carry (North and South America, Eurasia, Africa, Australia and Antarctica) and a seventh, the Pacific, which has no continental crust (Fig. 3). There are several medium sized plates e.g. India and Arabia, and a number of minor ones. A plate of whatever size that moves independently is termed a *terrane*. Unlike the panels on a football, plates are in constant relative motion, rather like ice-floes, being dragged by the horizontal flows at the tops of the convection currents. Rates of movement are very slow, of the order of a few centimetres a year, but over millions of years a plate can move thousands of kilometres.

Where two convection currents diverge under a plate they may induce a fracture from which the two sides will be dragged apart while *magma*+ from below will move up into the gap. Most of this will solidify below the surface and be added to the lithosphere on both sides of the fracture as the plates grow away from each other, while further magma will force its way to the surface and emerge as volcanic lava flows of the basic rock *basalt*+. Where, as is most often the case, the fracture occurs under an ocean the sub-marine basalt flows build up into a *mid-ocean ridge* from which *oceanic crust* about 5 to 10km thick is carried off on

+ *Items marked thus are defined in the Glossary*

* *The most abundant elements in the Earth's mantle are oxygen, silicon, aluminium and iron, with lesser amounts of calcium, sodium, potassium and magnesium, so that the great majority of rocks are silicates or alumino-silicates of the other metals. Ferromagnesians are silicate minerals rich in iron and magnesium and are relatively dense. Feldspars+ are complex alumino- silicates with potassium, calcium or sodium; and micas+ with potassium. Quartz+ is silicon dioxide or silica. These latter minerals are relatively light.*

the surface of each plate as they diverge. This is known as *sea floor spreading.* Not all the top of a convecting cell will be moving at the same rate so that *transform faults*[+] will develop parallel to the direction of flow. Transform margins can also develop between whole plates where they are being dragged past each other horizontally, as is the present case with the African and Antarctican plates (Fig. 3) and the San Andreas Fault in California.

Clearly the total area of plates cannot exceed the surface area of the Earth, so they must also be being destroyed. This can occur where two plates are being dragged strongly towards each other under the influence of opposing convection cells. At some point, one plate, with its oceanic crust, starts to be forced under the other, forming a trench on the ocean floor, in a process known as *subduction*, and descends back into the mantle. There it ultimately melts and in effect returns to its origins. The consequences of this cycle will be considered below. All these processes are shown in simplified form in Fig. 2.

Continents and Oceans

As the Earth first cooled sufficiently for the first *igneous*[+] rocks to form, differentiation occurred whereby the lighter minerals such as *quartz* and *feldspars* were relatively concentrated at the surface of the lithosphere as *continental crust.* Such rocks are termed *siliceous* or *acidic* and are of similar composition to *granite*[+]. There was not enough material to provide a continuous crust over the whole surface of the Earth but it coalesced in 'sheets'*, some 35km thick, in effect floating on the denser basic lithosphere. The latter was too rigid for these sheets to move horizontally although, by analogy with a boat, a local increase in weight could depress the base of a sheet at that point, up to as much as 85km below major mountain chains.

The primordial sheets, formed about 3-4 billion years ago, were the original *continents,* and all subsequent continents have had cores of these ancient rocks termed *cratons*[+]. The spaces between them (about 2/3 of the surface) became filled by the first *oceans* of waters exhaled and condensed from the cooling Earth and/or from impacts of comet debris. It is not known whether the terranes were initially all joined in one supercontinent but this has occurred more than once in the past. Throughout geological time they, and smaller fragments of continental crust, have been carried in kaleidoscopic fashion, at times widely separated, at others dragged into contact and *sutured* to each other. From time to time a plate would split across a continent with the production of two or more terranes with new oceans opening between them. The modern African Rift Valley and its extensions up the Red Sea, Gulf of Aqaba and Dead Sea are an early stage in this process. The Red Sea is already visibly a widening ocean.

Coasts as shown on maps are not necessarily the edges of continents but are fringed by variably wide gently sloping *shelves* with comparatively shallow water (average depth about 175m). Beyond these, steeper *continental slopes* lead down to the oceanic crust (3 –5km deep), the true edge of a continent thus being the edge of the continental shelf, perhaps many kilometres from actual coasts.

** 'Sheet' is a better term than 'slab' as it refers to an object that is only tens of kilometres in thickness but often thousands of kilometres across.*

Weathering and Sedimentation

The first siliceous rocks to form at the top of the continental crust were subjected to violent *chemical weathering* by hot rainfall and a primitive acid atmosphere, which in those early times besides carbon dioxide included sulphur oxides and hydrochloric acid (the latter ultimately forming the majority of salts in the sea). Chemical weathering has continued to the present day whenever rocks are exposed to air and water containing carbon dioxide although, since the explosion of life in the late-Proterozoic and the accompanying photosynthesis, oxygen has replaced the earlier acid gases. In simplistic terms, feldspars are *hydrolysed*+ to *clay minerals*+ (e.g. *kaolinite*+*);* and ferromagnesians to a mixture of clay minerals and *iron oxides* (the yellow hydrated mineral *limonite*+ in moist conditions but in hot dry environments this is mostly replaced by anhydrous red *haematite*+). In all cases, the soluble products of hydrolysis (sodium, potassium, calcium or magnesium, which are termed *bases*, and silica) tend to be leached away and lost in the drainage water and thus ultimately returned to the ocean.

Limestones+, dominantly made up of calcium carbonate (*calcite*+), which is slightly soluble in water containing carbon dioxide, are weathered in moist conditions at rates depending on their hardness and porosity.

As a very rough general rule the rate of a chemical reaction doubles with each 10^0C rise in temperature, so that the rate and degree of weathering are strongly dependent on climate.

Physical weathering is brought about by thermal spalling of rock surfaces in hot dry climates or by frost shattering in very cold ones, by local root pressures under some vegetation and by abrasion in rivers or glaciers, on beaches or by wind-blowing. *Quartz* is highly resistant to chemical weathering but it is gradually reduced to sand or silt grade particles by physical abrasion.

All these processes lead to variably weathered loose accumulations of mixed minerals, which may become the *parent materials* of soils. *Soil-formation* starts when micro-organisms such as algae colonise surfaces which are sufficiently moist. Their dead remains provide an organic-rich substratum in which pioneer species of plants can establish root systems, and from then on a soil and its associated vegetation and soil fauna develop together in a direction that depends on the local environmental factors. Primitive soil-formation must have started in the Silurian when plants first colonised land surfaces. The processes are described in detail in the monograph *'Ugborough Parish Heritage Appraisal. 2nd Edition. 2016'.*

Long-continued erosion of weathered surfaces and soils, and transport of the products by rivers (or sometimes by glaciers or wind), inevitably reduces the landscape to low plains very gently sloping down to the sea level of the time (*planation* or *erosion surfaces*), the detritus being deposited in shelf seas as marine sediments. In general terms these sediments are *muds*+ (mainly clay minerals and very finely divided quartz) in deeper, and *sands* (almost all quartz) in more agitated shallow, waters; with further deposition and compaction these are transformed respectively into *mudstones*+ or *shales*+, and *sandstones*+. In clearer waters, calcium carbonate may be segregated biologically as coral reefs, shell beds or deposits of calcareous algae, and occasionally chemically, to form limestones. Marine deposits of ash from volcanoes in the sea or on adjacent land masses consolidate to *tuffs*+ (which are often intercalated with lavas from the associated vulcanism).

At times in geological history, notably after episodes of mountain building, huge areas of continental crust have been subjected to hot arid climates. With no permanent rivers to transport weathered debris to shelf seas these are largely re-deposited inland by flash floods and winds to form *breccias* (angular gravels), sands and silty beds low in clay mostly coloured red with haematite (and hence known as '*Red Beds'*). To distinguish them from marine sediments these formations are termed *continental.*

Sea levels

As noted above, all landscapes ultimately tend to be reduced by weathering to planation surfaces. But sea level *relative to the land surface at any point* is not constant: globally, it can rise or fall according to the amounts of water locked up as ice around the Poles, the mean temperature of the oceans or their changing geometry; locally, the level of continental crust itself can be altered by transfer of weight, e.g. by erosion of land surfaces with the accumulation of the resulting sediments in shelf seas; or by warping, rising or subsiding of the crust under the influence of underlying plate movements. The local interplay of all these processes can be complex and difficult to interpret.

Changes in sea level can have profound local effects. Consider an area that has been reduced to a low planation surface at a particular sea level. If the latter falls, rivers will readjust to it, cutting down and dissecting the surfaces on which they had been flowing and initially leaving residual terraces or plateaux (which, given time, will also be reduced to a new erosion surface). If sea level rises, shelf seas will advance and cut back into any remaining higher land, forming cliffs and producing new planation surfaces in the form of *wave-cut platforms.* These themselves may later be exposed to sub-aerial erosion by tectonic uplift or further falls in the level of the sea; or, if the latter rises, covered with later sediments.

Mountain Building

As noted earlier, when two plates collide one is subducted under the other. This causes huge frictional and distortion effects with associated earthquakes, and rises in temperature which cause local melting. Much magma is forced towards the surface and some emerges as lines of volcanoes of basic rocks (Fig.2).

Where both plates carry continental crust, the leading edges of both plates and associated shelves will buckle to accommodate the shortening of the crust and develop a series of basins and ridges roughly at right angles to the main thrust, the former rapidly filling with sediments. Meanwhile the light continental crust will be scraped off the subducted plate and pushed up onto the over-riding one, coming into conflict with the sediments of the shelf seas and their hinterlands. The rocks of both continental crusts will be squeezed together with intense and complex folding and fracturing (*faulting*$^{+}$) at right angles to the dominant pressures. In extreme cases slabs of rock can be detached and *overthrust* over each other, sometimes by many kilometres, or displaced horizontally along vertical *wrench-faults*$^{+}$ aligned with the maximum pressure differences at the time.

The rocks subjected to such conditions are in varying degrees *metamorphosed*$^{+}$. As an example, shales and mudstones are converted to *slates*$^{+}$ with well developed *slatey cleavage* as clay minerals are converted to minute flakes of mica, which are squeezed into parallel alignment. Lavas, tuffs and limestones are also altered to harder forms, sometimes slatey.

The thickened crust bulges downwards into the lithosphere and then, because of its lower density, it is gradually (over millions of years) lifted back to produce mountain ranges along the line of contact, while increased heating at depth causes local melting and the development of magma chambers with associated volcanoes. An episode of mountain building is termed an *orogeny*$^{+}$*,* named after its present or past location e.g. 'Variscan', 'Alpine' or 'Himalayan'.

As the new mountains are raised into the atmosphere they come increasingly under attack from the usual agents of weathering (i.e. rain and/or ice, chemical weathering etc., always with the assistance of gravity) and a new cycle of erosion is initiated as described above.

Stratigraphy and Palaeogeograhy

Stratigraphy is the study of rock successions (*strata*) and the interpretation of these as sequences of geological events. In the early days of geology the only way to compare the *relative* ages of formations not directly in contact was the intensive study of fossils and their evolution (*palaeontology*); this was highly successful and by the middle of C19 a world-wide classification primarily into *Eras,* and *Periods (*or *Systems*)* was largely complete. Eras define four fundamental divisions of life on Earth as *Protero-, Palaeo-, Meso-* and *Ceno-zoic,* i.e. 'First', 'Ancient', 'Middle' and 'Recent' Life. Within Eras, Periods or Systems, e.g. 'Cambrian' or 'Devonian', represent major biological divisions ranging from about 30 to 80 Ma, and are sometimes dramatically separated by worldwide extinctions of life.

With the techniques available in C19, clear stratigraphic distinctions were not possible much further back than Cambrian times for lack of hard-bodied organisms to provide fossils. At that time also there was no way to assign *actual* ages in years but in C20 increasingly sophisticated radiometric measurements on rocks have made this possible to remarkably fine limits. At the same time modern methods of studying microfossils and traces of soft-bodied biota have extended our knowledge further back into pre-Cambrian (Proterozoic) times. *World Stratigraphy* (or *Geological History*) with presently accepted dates in millions of years (Ma)** is shown below.

Palaeogeography is the study of the distribution of ancient continents and oceans through geological time. It commenced with theorising on the causes of the apparent 'fit' between the west coast of modern Africa and the opposite coast of South America*** and has progressed slowly and with much controversy over more than a hundred years. Recently, with the general acceptance of plate tectonics, great progress in reconstructing ancient geographies has been made with the aid of many techniques. These include the geographical matching of continental shelves, and of geological formations and faunal distributions across oceans; and by tracing out the roots of ancient mountain chains, assisted by radiometric dating and measurements of the magnetic properties of rocks as evidence of past orientations with respect to the Poles.

** A 'Period' is a measure of geological time; a 'System' is the assemblage of rocks corresponding to that Period.*

** * Based on a table in 'Vanished Ocean' by Dorrik Stow. For simplification ages are rounded off to the nearest 5Ma. For the Quaternary only 'ka' means thousands of years.*

*** * It is now known that this is due to sea floor spreading from the Mid-Atlantic Ridge which commenced in the Cretaceous and is still proceeding at a rate of 3-5cm per annum.*

WORLD GEOLOGICAL HISTORY

CENOZOIC	**QUATERNARY**		
	Holocene	0-10 ka	Modern oceans and continents. Soil-formation on Post-Glacial surfaces. Modern humans, rodents and insects dominate
	Pleistocene	10ka-2.6 Ma	Ice Ages (recurrent glacials and warm inter-glacials). Great changes in sea levels due to ice-sheets waxing and waning
	TERTIARY		
	Neogene	2.6-25 Ma	*India* collides with *Asia*: Himalayan mountain building starts *Antarctica* drifts towards South Pole. Progressive climate cooling Modern life evolves. First hominids c. 5 Ma
	Paleogene	25 -65	*Africa* (having separated from *Gondwana*) closes on *Europe*, Alpine mountains develop. *India* drifts N towards *Asia*. Rapid radiation of life, notably of mammals and birds
MESOZOIC	**CRETACEOUS**	65 -145	N. Atlantic opens. Highest-ever sea levels/global temperatures Excess calcareous oceanic plankton (Chalk). Cretaceous Mass Extinction (65 Ma): end of dinosaurs and ammonites
	JURASSIC	145 -205	S. Atlantic opens, sea levels rising, extensive shelf seas. Modern fishes and reptiles, ammonites and plankton gardens develop
	TRIASSIC	205 - 250	*Pangaea* commences fracturing. Very low sea level. Hot desert climates and Red Beds. Corals, ammonites, early reptiles, first dinosaurs. At end, Triassic Mass Extinction (205 Ma)
PALAEOZOIC	**PERMIAN**	250 - 300	*Pangaean* supercontinent completed (260 Ma). Vast hot deserts and mountain chains with formation of Red Beds. End-Permian Mass Extinction (250 Ma), the greatest known, ends Palaeozoic life
	CARBONIFEROUS	300 - 360	*Gondwana* and *Laurussia* fusing in Variscan mountain building Huge areas of swamp forests (coal). Winged insects evolve.
	DEVONIAN	360 - 415	*Laurentia* and *Baltica* finally fuse to form 'Old Red Sandstone Continent' (*Laurussia*). Hot arid climates and Red Beds. Ancient fishes, amphibians, large land plants
	SILURIAN	415 - 445	*Baltica, Avalonia* and *Laurentia* colliding about 20^{o}S. Caledonian mountain building. Jawed fishes, vascular plants, early land animals
	ORDOVICIAN	445 - 490	*Avalonia* moving N to 35^{o} S. Trilobites, jawless fishes, corals
	CAMBRIAN	490 - 545	Scattered continents: *Gondwana, Laurentia, Baltica* etc. *Avalonia* identifiable at 60^{0} S on N side of *Gondwana* 'Cambrian Explosion' of life. Hard body parts yield more fossils
PROTEROZOIC		545 - 2500	Soft-bodied fauna proliferate (640 Ma), fossils hard to identify
ARCHAEAN		2500- 4600	Life originates (3500 Ma). Oceans form (4000 Ma) Earth's origin (4600 Ma) and core-mantle-crust forms

GLOSSARY

Acid rock	Rock high in silicon as quartz and feldspars, and low in ferromagnesians, hence of pale colours and low density
Basalt	Dark fine-grained basic lava of feldspars and ferromagnesian minerals making up oceanic crust
Bases	Most important metallic ions occurring in soils and drainage waters, i.e. calcium, magnesium, sodium and potassium.
Basic rock	Rock containing high proportion of ferromagnesian minerals, with feldspars but no quartz.
Calcite	Mineral form of calcium carbonate
Clay	Fine-grained mineral material with particles less than 0.002 mm in diameter*; hence also, the name of a geological deposit or a soil-type where clay is a dominant component
Clay minerals	Fine-grained platey alumino-silicate minerals resembling mica flakes but of clay size. They have active surfaces conferring water absorption, plasticity, cohesion and the ability to absorb and release bases. Examples are kaolinite, illite and chlorite
Fault	A fracture face formed by shearing in a rock body under opposing forces
Feldspars	Complex alumino-silicate minerals with varying amounts of sodium, calcium and potassium, having white or pale colours (often pink) and low densities
Ferromagnesians	Silicate minerals with high amounts of iron and magnesium, with dark and/or greenish colours and high densities
Granite	Coarse-grained acid igneous rock of quartz, feldspars and micas
Haematite	Anhydrous iron oxide with red or purplish colours
Hydrolysis	Alteration of minerals by water in chemical weathering at the surface, or at very high temperatures in hydrothermal activity during magma emplacement
Igneous rock	Rock formed by solidification of molten material
Kaolinite	A clay mineral formed by weathering or hydrothermal alteration of feldspars
Limestone	Rocks composed mainly of calcium carbonate usually from biological, but occasionally chemical, processes
Limonite	Hydrated iron oxide (‘rust’) with yellowish, orange or brown colours
Magma	Melt usually with suspended crystals and dissolved gases, derived from mantle or crustal rocks
Metamorphism	Processes by which rocks are re-crystallised by heat, pressure or active fluids
Micas	Complex alumino-silicate minerals containing potassium, with very perfect platey cleavage. Black mica is additionally a ferromagnesian mineral
Mud	Loose deposit of clay minerals and finely divided quartz, sometimes with iron oxides and/or organic matter or calcite
Mudstone	Structureless accumulation of hardened mud
Orogeny	The process of mountain building (Gk. *Oros,* mountain)
Quartz	Hard, very stable crystals of silicon dioxide, with white or pale colours and low density
Sand	Mineral or rock grains, most often of quartz, conventionally defined as of 2.0 to 0.06 mm diameter*, with no surface activity
Sandstone	Sedimentary rock containing more than 25% sand
Shale	A mudstone, but visibly stratified and more or less fissile
Silica	Silicon dioxide. Mainly present as the mineral form quartz but it is slightly soluble and occurs in small amounts in natural waters
Silt	Mineral or rock grains of 0.06 to 0.002 mm diameter*, with no surface activity, most often largely composed of quartz

Slate	Fine-grained metamorphosed mudstone or shale in which sub-microscopic mica flakes have been strongly orientated by pressure producing typical ‘slatey cleavage’
Thrusting	The driving of one body of rock against, and over, another during crustal shortening
Transform fault	See ‘Wrench fault’
Tuff	Consolidated sediment of volcanic ash
Wrench fault	Roughly vertical fracture face in a rock body along which separating segments have slid horizontally

** Geologists, pedologists (soil scientists) and civil engineers use varying scales of particle sizes; the ones quoted here are those most commonly used by pedologists.*

REFERENCES

Fortey, R.A. 2004 *The Earth* Harper Collins

Friend, P.F. 2008 *Southern England* Collins (New Naturalist Series)
(Source of Figs.1 (cover illustration) and 3)

Stow, D. 2010 *Vanished Ocean* OUP
(Source of Fig. 2 and the table ‘World Geological History’)