Historical Perspectives of Geological Concepts from Biblical to Modern Times

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Abstract

The Earth, a part of solar planetary system behaves as a dynamic entity. The ancient Greeks' view of universe being governed by unchanging principles and their mythopoeic explanation of catastrophic earth movements were later contrasted with intelligible and discoverable natural laws. The Renaissance witnessed evolution of new concepts along with epistemological changes in geology. The serious attention to analytical approaches in the study of earth materials and importance of fossils as remains of creatures gave a concrete framework for the study of strata. With its subsequent application in mapping of geological units on regional scale, the movement took a definite shape in the following era with setting up of Geological Surveys. The modern methods of age determination of the Earth and the evolution of theories of geomorphology, in particular, provided a more rational and sound expression of the geological time i.e. long time span of earth. The geological ideas of twentieth century are based on twin waves of developments in science and technology, and the appreciation of some pattern of relationships and network or the synchronisation of major planetary events. The radiometric determination of the age of rocks and satellite imaging in geological mapping of the inaccessible areas were introduced. The new concepts in line with the systemic viewpoint, evolved into major branches of study— such as global plate tectonics and environmental geology. The paper outlines the journey of evolving paradigm of geological principles in the backdrop of the progress of time and dynamics of society. A few of the concepts are discussed as case studies to appreciate the driving forces of the history.

Key words: Age of earth, Earth science concepts, Environmental geology, Geomorphology, Global plate tectonics, Great Ice age, Observational science, Radiometric dating of rocks, Remote sensing and geological mapping, Stratigraphy, Systemic theory, Uniformitarianism.

1 Introduction

The eternal mystery of the world is its comprehensibility. It is one of the great realisation of philosophers that the postulation of real external world would be senseless without this comprehensibility.

The story of evolving comprehensibility of the planet Earth from early Biblical period to ancient, medieval and present day have been conditioned time and again by the pace of human civilisation, economic transformations and the progress of science and technology. Although new concepts are attributed to the acknowledged inventors, it is true that these concepts have come about as a result of contribution of many workers, who preceded and

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did the groundwork. The present discussion focuses on the evolving organisation of few of geological principles in the backdrop of dynamics of society, economy and individual human perception.

1.1 Biblical geology

Early references to Earth and perception of earth processes are found in Hebrew scriptures, *Genesis*, and *Exodus* and various other literatures. Hebrew and Christian scriptures are believed to have originated at the eastern end of Mediterranean area that was a region of earth movement during Biblical period. The Biblical perception of the Earth as a creation of God and natural phenomena like volcanic activities and earthquakes as His wrath on Man dominated the early literatures in which man had looked for answers in a naturalistic term.

The crossing of Jordon river, as narrated in *Joshua* (3-4) may be linked to geologically active rift system at the junction of Eurasian and African plates; a rubble dam produced by fault movement might have blocked flow of Jordon river (described in *Jeshua*) and allowed crossing over dry ground. The account of crossing of sea by people has been linked to eruption of volcano Santorini in 1470 BCE. The resultant tsunami that brought havoc in northern Crete, on Milos and in Peloponnese (peninsular part of Greece), have been recorded in these scriptures. The biblical view of geological processes and catastrophes as acts of supernatural force were abandoned and substituted with the mechanistic understanding of the planet and universe during the renaissance period (Shelley et al. 2005).

1.2 The ancient pioneers

The philosophical background for the modern concepts of science in Europe has grown out of the wisdom of ancient Greeks, Hellenists, Romans and Alchemists (from Persia). The trade was fundamental aspect of ancient Greek world. Trade with Egypt 4000 years ago was carried out largely by river and sea with Greece and other countries (Asia Minor, Syria). The collapse of earlier Greek civilisation, the Mycenaean happened towards around 11th century BCE. During Dark Age (11th to 8th BCE), Phoenicians (Great navigator and traders) dominated the trade. From 760 BCE, contacts and trade spread across Mediterranean driven by social and political factors — population movement, colonisation (of Magna Graecia–the coastal areas of Southern Italy with Greek settlers from 8th BCE), interstate alliance, coinage system, measurement standardisation and safer seas.

While the great river civilisations of other eastern areas had complex theologies that served to answer most of the larger questions about humankind's place and destiny– the Greek religion was little more than a collection of folk tales 'that were more appropriate for camp fire'. 'There was really no theology in the sense that could provide cohesive and profound explanation of both cosmos and human body'. The feature of Greek religion in contrast to that of Mesopotamia and Egypt (with splendid civilisations) was its puerility. Ancient Greece was a democracy (in contrast to Roman Empire, that were republic), and it allowed free flow of ideas and philosophical thinking abounded. The ample room for searching answers to inquiring Greek minds was left for penetrating, independent and satisfying mode of inquiry– philosophy and science were born. By 600 BCE ancient Egypt had reached a high level of civilisation; they were a very practical people who learnt to build vast structures like pyramids, temples, statues, tombs and houses. At Alexandria, Ptolemy (Greek) established an Academy with a library where people, scientists and philosophers would come to study. During 600 BCE, Egyptian ports of Nile were opened to Greek trade. Greek philosophers visited Egypt and brought new skill and knowledge.

Thales of Miletus (600 BCE) who is known as father of science was one of early Greek philosophers to seek explanation for physical world in terms of natural rather than supernatural causes, and concept of a universe governed by laws of nature, that began in Ionia (group of islands of Greece); science was based on logical thinking and mathematics (Encyclopaedia Britannica).

Two characteristics of classical Greek science were: one, universe as an ordered structure, and the other being, that parts of universe had purposes in overall scheme of things, and objects move naturally towards ends they were fated to serve (teleology). Aristotle (384–322 BCE) was the first philosopher who developed systematic study of logic; and people were taught early form of evolution and survival e.g. Anaximander and Empedocles. Mathematics brought in art of deductive reasoning to Greek people. Greeks learnt Pythagorean principle from Egyptians who used it as a thumb rule.

The appreciation of complex man-environment relationship was reflected in the selection of urban locations in ancient Greeks. In a scarce rainfall setup of Greece with intense evaporation and infertile soil, year-round water from karst springs was an important resource; the criteria for setting up of ancient Greek urban settlements included these locales due to easy availability of the essential resources (Crouch 1996).

The planning of public works, started by Hippodamus (498–408 BCE) of Miletus, was admired through Hellenistic and Roman period. Archimedes (288–212 BCE), Hero and others made extraordinary contribution to public works. The use of aqueduct is referred to Herodotus and it was rediscovered in 19th century. For example, at Samoa (in Aegean Sea) that had outgrown the capacity of wells within city limits, aqueducts through mountains were made by Greek engineer Eupalinus of Megara (6th century BC). It had a length of 3000 ft. (14 ft. deep, 8 ft. width, 8 ft. height) lined with stones and often branching off to supply water to different areas; they made bridges across valleys.

The geological understanding of ancient Greeks was matured enough to propose palaeo-geography reconstruction of the lands. Strabo, a first century Greek geographer wrote that Piraeus area of Greece (in western part of peninsula), now connected to mainland was formerly an island. Recent interdisciplinary geo-archaeological analysis demonstrated that during late to final Neolithic (4850–3450 BCE) sea level rise in Mediterranean Sea made it an island in a shallow marine bay (Goiran et al. 2011, pp. 531–534).

Pliny, the elder (author of *Natural History*, 77–79 CE) was associated with scientific texts on mining and smelting practices and inferred origin of amber as a fossilised resin from trees; he recognised octahedral habit of diamond, thus laying the basis of crystallography. Eratosthenes made accurate measurement of Earth's diameter. Theophrastus of Ephesus is considered as the author of first mineralogical treatise and, Dioscorides (40–90 CE), a Greek physician described the curative properties of minerals. The Greeks have often been considered 'independent–minded', and have made fundamental observations of geological nature much before the subject got its formal identity. Tremendous advances were made in understanding of the landscape, utilisation and application of earth materials for beneficial purposes.

1.3 Beginning of second millennium

It was a period of ascending power for loosely-knit central Asian empires. Muslim sultans cultivated science and mathematics at their courts. Greek and Roman works were translated and with exposures to ideas of Aristotle, new discoveries in astronomy and mathematics were made. Through military campaigns of the sultans, the geography and mineral resources of different regions were documented; these significant strides came about in the central Asia, 'when Europe slumped in the Dark Age'.

The observational sciences continued its journey during early second millennium through study of nature and in the writings of scholars like Al Biruni (973–1048/1050), Ibn Sina (981–1037) and others. Al-Biruni, a native of present day Uzbekistan was at the court of Sultan Mahmud/Mawdud of Gazna. His account of history and geography of India covered periods of military campaign of Mahmud in north India. He made many observations on occurrences of fossil in rocks occurring much above present day seas and described mineral deposits of the world known to him– India, China, and Fareast. In absence of translation of his works in European languages, Renaissance could experience little of Biruni's contribution to science at large and geology in particular. Ibn Sina (Avicenna) of Tajikistan, a contemporary to Al-Biruni contributed on curative aspects of minerals, mountain formation and origin of earthquakes. Shen Kuo (1031–1095) of medieval China formulated a theory of geomorphology, based on concepts of erosion and deposition of sediments; he recorded occurrences of marine fossils in a mountain far from Pacific Ocean.

Ancient mining in India: The need of the expanding empires, other kingdoms, and jewellery traders from the west ushered in a new phase of mining of metallic ores and gemstones in the sub-continent during Second millennium. The driving forces were trade interests in metal wares (particularly Bidriware) with European Countries along the Silk route and demand of metals for making guns and cannons by the kingdoms. Industrial scale production of zinc (Zawar, Rajasthan, 13–18th century,) gold (Karnataka), copper (Dariba-Singhania of Khetri belt, Rajasthan, 14–18th century), and Iron ore mining (late 2nd millennium, BCE) have been documented. The tradition of smelting of Iron and other metals evolved indigenously, were handed down to later the generations (Bagchi and Ghosh 1980, pp. 25–29).

1.4 Renaissance geology (14–17th Century)

For 1000 years, Constantinople (now Istanbul) of Byzantine Empire was the centre of a vibrant civilisation. Extensive trade existed from Egypt to Baltic with trade route passing from east through Byzantine empire onward to Genoa, Pisa, Venice of Italy. As the trade increased in early renaissance period, and Italian trade routes became conduits of culture and knowledge. After its fall in 1453, Greek settlers fled the city and people of western Europe were exposed to the wisdom of ancient Greek. The new merchant classes gained importance through financial skill and, trade formed the source of power and money over agriculture. With discovery of America and opening of sea voyages to east, new colonies grew up and under a new mercantile economic system, the governments of mother countries gave companies (such as British East India Company) monopolies to control all trades in a specific colony. They subsidised them and allowed to exploit resources of the colonies and sell back home manufactured goods. These changes came with the decline in feudalism that grew up during Middle Age and the landed nobility were poorer now.

Towards end of Middle Age, Europe witnessed major events and catastrophes that brought major changes in political and social life. Black Death (1348) and extreme weather during mid- 14th century that continued for next 300 years (corresponding to period of Little Ice Age) caused famines, crop failure resulting in death of one-third population of Europe and people moved to towns for employment. The hundred year war between England and France and with decline of power, the church and papacy that stood for unity of Europe, was becoming irrelevant. Man's spirit was being reborn and they were eager to find out all about the world.

The development of scientific and technological application in Europe during the renaissance period can be distinguished from earlier time by a distinct watershed, which represented philosophical, epistemological and theosophical particularities of the pioneers of the period. Hegel (1837) observed that:

> Through the study of antiquity, the West became acquainted with true and eternal element in the activity of man and revival of science–that occasioned with the fall of Byzantine Empire. Large number of Greeks took refuge in the West and introduced Greek literature and treasure to which that knowledge was the key; Plato became known to the West and in him, a new human world presented itself. The three events of the Europe– so-called revival of learning, the flourishing of Fine Arts and discovery of America and passage to India by the Cape ushered in a new bright day–the period (the Renaissance) is distinguished by inventive impulses in science and arts.

Thus, the intellectual basis of renaissance was a new version of humanity, derived from rediscovery of classical Greek philosophy, epitomised by pre-Socratic philosopher, Protagoras's 'Man is the measure of all things'. This new thinking manifested itself in art, architecture, politics, literature and science. Several new inventions like application of powerful innovations of printing, paper, compass and gunpowder speeded up renaissance ideas.

Francis Bacon, the English thinker set out new attitude to science. He argued that 'knowledge of the world was necessary to be certain of their truth and only way of being certain was by observation and testing'. With Renaissance, the concept of earth holding the central position in the universe as believed by Aristotle was discarded in favour of Copernican Revolution. The persons like Copernicus, Galileo, Kepler, Leonardo De Vinci and others began to experiment and observe for themselves, rather than what was written in books. Thus modern science began and observation rather than authority became central in science. Renaissance thinking brought about the changes-as empiricism and experiment began to supersede old beliefs (Gohau 1990).

The concepts of earth science grew up in the light of new outlook of the physical world. In the early phase of renaissance, Geology used to be studied alongside other fields and as such did not earn its identity as a distinct scientific discipline. However, contribution of many pioneers laid the foundation for opening up of this new branch separated from mineralogy and mining. The scholars started studying older rock formations, which was key to developing a logical picture of the planet, and more important, why things happened. The new concepts like fossils as snapshots of life at different moments of Earth's history came up. Fossils ultimately became one of the key evidences for how life evolved on Earth over billions of years and that the present day earth processes were also operative during the geological past. The Earth's crust contains chronological history of geological events that could be deciphered by careful study of strata and fossils. Geology came to influence many areas of science ranging from physics to evolutionary biology. Many pioneers of the period made significant contribution towards the birth of Geology as a distinct discipline.

Georgius Agricola (1499–1555) a German physician, broke away from the dogmatic approach of the period, and made his own ideas about medicine. He also made a classification of minerals (according to their physical properties) which was of much importance to growing industry across Europe. He was one to focus on observational sciences rather than relying on theories.

Leonardo De Vinci (1452–1519) of Florence in his notes (1508) observed that fossils found in seabed were essentially remains of creatures, a conclusion that went against Biblical deluge theory.

Ulisse Aldrovandi (1522–1605) of Italy followed De Vinci's work on fossils and made detailed study and classification of numerous fossils found in rocks, soils. He was the one to study and describe microscopic fossils, investigated with help of lens, long before microscope era began. The study of micro-fossils made Aldrovandi single out from Aristotelian trend and may be considered as forerunner of Galileo. He believed in observation as the basis of researches (Vaai & Cavazza 2006, pp. 43-63), (Shuttleworth, 2011).

Nicolaus Steno (1638–1686) provided the science of geology the next leap forward. As an anatomist in Florence, Steno (1666) who was a trained physician like Agricola, while working on dissection of shark, was struck by the fact that how much shark teeth resembled tongue stone, a triangular piece of rock that was known since ancient time. He also advocated organic origin for fossils (1669). Steno made first geological case study in the form of history of geology of Tuscany with illustration of processes of stratification. His catholic religious belief was in conflict with his scientific work and he finally abandoned to become catholic Bishop. His work was subjected to censorship by the church and neglected by contemporary workers, only to be rediscovered a century later in the Age of Enlightenment. His work became crucial part of not only geology but natural science. It was considered as the seed to many subsequent works such as Charles Darwin's theory of evolution. Leonardo da Vinci and Robert Hooke had similar views like Steno. Both Steno, (considered as founding father of stratigraphy) and Aldrovandi showed experimental attitude with priority to personal observation, intellectual methods and logical-critical check of any scientific assessment. They did certain interesting common geological observations like, processes of lithification, fossilisation of fish and wood and origin of concretion (Gohau 1990).

Renaissance Geology also overlapped with alchemy (a form of medieval chemical science aiming at achieving transmutation of base metals to gold), whereby geologists tried to know the nature and distribution of ores and smelting of iron. Eventually this led to large-scale production of metals, ushering the age of industrial revolution in England. With ready availability and easy production of iron; the focus of civilisation shifted from precious metals (gold and silver) to metals of daily use (iron).

1.5 The age of Enlightenment

With onset of industrial revolution and rapid technological changes, the role of mercantile system in economy that was continuing in Europe faced trouble during late 17th century and was considered as unsuitable. The new economic concepts of David Hume and Adam Smith of Enlightenment era influenced modern economic world by the new ideas of free trade unbounded by border, tariff and other taxes leading to the economic well-being of nation states. Most industrial nations of world adopted this new found economic vision by mid-19th century (Daily History.org).

In late 17th century, Great Britain experienced profound political changes that spread to France and German speaking kingdoms. Philosophers such as Rousseau, Voltaire, John Locke advocated political and economic freedom. Rousseau 'Social Contract' was hailed as foundation of modern western political culture of liberal thoughts, liberty and equality of men, constitutional government and separation of church from the state. The philosophical view of 18th century that dominated the Europe included a range of ideas centred on reason as the primary source of authority and legitimacy, based on natural laws and experiment and observation. Scientific methods and reductionism came to play major role in discourses and thoughts that influenced the course of science in a big way.

New centres of teaching came up, scientific publications from educated bourgeoisie proliferated; experiment and observation in which counting, measurement, or rational methods of calculation, acquired greater importance. The 18th century saw significant advances in medicine, mathematics, biological taxonomy, new understanding of electricity and magnetism. The religious, social and academic predisposition of individual thinkers of this period had significant influence in the formative stage separating geology from a broader natural science.

Comte de Buffon (1707–1788), made monumental catalogue of an account of the whole of nature, and was the first modern attempt for Encyclopaedia of natural science. He remarkably explained all of the facts with comprehensive theories and reasoning such as the concepts of reconstructing past depositional environments (paleoecology), principle of uniformitarianism, principle of sequences of sediments/rocks (stratigraphy). As one of the proponent of long history of earth, he theorised that the planet had been around long before 6000 years, as the church's claim. Buffon, although censured from the church, may be credited for building a non-Biblical explanation of Earth's history using new physics of Isaac Newton to conjure formation of the planet by matter in motion; 'to most of the Europeans of his time this was practically an eternity'.

Antoine Lavoisier (1743–1794), a French nobleman and chemist was central to the 18th century chemical revolution and biology. On a trip in France, he became interested in the study of concepts of different depths and bottom of the sea from the study of the sizes of sediments. Lavoisier (1789), based on field observation prepared an idealised profile, showing occurrences of pelagic and littoral deposits and envisaged the analogy of strata of sediments with environment of deposition. A new chapter began in geology, with attempts to reconstruct past depositional environments (paleoecology) on the basis of composition of the strata (Rosenburg 2009).

The study of evolution of geological theories in the critical period gives an extraordinary account of a conflict 'that was not so much one of religion versus science, but of religion within the science'. Though geology as a structured branch of science emerged in second half of 18th century, it had to wait until end of the century when the concepts of uniformitarianism, stratigraphy and palaeontology were established.

1.6 Uniformitarianism

The search for the root of the term 'uniformitarianism' during the Enlightenment era is an interesting study.

James Hutton (1726–1797), a Scottish physician, chemical manufacturer, experimental agriculturist, naturalist and geologist understood that, although geology was an historical science, the processes and phenomena that geologists study, operated under natural system, throughout the geologic time. He was one of the most influential participants in Scottish Enlightenment, in which 'intense discussion used to take place daily at gathering places in Edinburgh'. The thinkers of Scottish Enlightenment asserted the importance of reasoning. Many of the scientific fields, like philosophy, engineering, medicine, law and geology advanced rapidly. Hutton gratefully acknowledged the help of Guetthard, Desmarest and De Saussure of French school who more than any others paved the way for him. 'Hutton was a strong believer of Deistic theological assumption' a belief that God created universe, but permits his creation to administer itself through natural laws. This together with his exposure to available French literatures and experiences in field areas on unconformable relationship in rocks had predisposed his thinking of unconformity and rock cycles and its role in repetitive and successive rock sequences in geologic time. 'His conviction in the theory of 'uniformitarianism' (1785) predated his visit to Siccar Point in Scotland, with which, the discovery of uniformitarianism has often been correlated by many authors of geology texts' (Montgomery 2003 pp. 500–505).

Playfair and Lyell (also of Enlightenment era) were the foremost geologists to popularise Hutton's concept 'that Earth was shaped by same processes still in operation today'. Lyell's work that rested both, on uniformity of cause (also called actualism), and intensity (known as gradualism) influenced succeeding generations of geologists in their attempt to understand geological processes of the past. Thus Lyell's concept, a radical one, was counter to the Biblical Scriptures which advocated catastrophic interpretation. His contribution may be summed up as his success in freeing 19th century geology from the grip of Biblical perception and allowed it to grow as a dialectically acceptable, legitimate, scientific hypothesis. It is obvious that the principle cannot be extended back throughout the geologic time, because the processes operated in the oxygen-free environment of early years of earth history were quite different from today's processes.

William Whewell (1799–1866) in 1837 subsequently introduced the term 'uniformitarianism' to convey both Hutton's sense of order and regularity of processes in operation and, Lyell's idea of uniformity of rates of geological processes; the term became common definition of the concept. The concept of actualism is a basic and broad scientific concept of many other fields of science, as in geology; however, gradualism, as a rule of nature –is no longer considered a valid idea.

1.7 Stratigraphic succession

Nicolaus Steninis or **Steno** (1638–1686), a Danish physician was the one to realise that Earth's crust contain a chronological history of geological events, which may be deciphered by careful study of strata and fossils. It required Steno a lot of imagination to put forward the concept of 'Principle of Superposition' or the first stratigraphic diagram, although a relatively trivial one, that states that layers of rocks are arranged in time sequence with oldest layers being below and younger one above unless later processes disturb this arrangement. Stratigraphy had to go a long way to become a full-fledged subject. Giovanni Arduino (1714–1795) is credited with first chronostratigraphic division (with geological plan and section) when divided rocks of Alpine landscape into four units viz. primary, secondary, tertiary and alluvium. The pioneers who prepared county wide geological maps showing spatial distribution of lithological units that predate William Smith's, are Bauche (1746), Guettard-Lavoisier (1770), William George Maton (1797). John Strachey's (about 80 years before Smith) and John Morton (1712) made some accurate observation of sequences, cross-sectional illustration of coal beds and detailed description from quarries and pits across Northamptonshire county of Jurassic sequences, noting textures, grain sizes and cement. Maton's understanding of geological map was more clear and summarised as 'geological and mineralogical references presented in a manner of map, by which a general idea of several transitions may be obtained at one view'.

William Smith, universally acclaimed as the founder of stratigraphy, was engaged in survey for a proposed coal canal in 1790s during pre-steam locomotive days. He observed that coal bearing strata could be traced/ delineated across England and Wales (and part of Scotland). He found that each stratum contained fossils peculiar to itself and made the epochal geologic map of England and Wales in 1815. Smith, from a consistent and observed relationship among the strata, their characteristics and fossil contents, established the hypothesis of 'principle of faunal succession'. Smith was possibly aware of weaknesses of lithological approach in stratigraphic correlation and saw importance of fossil records in his early career 'that wonderful order and regularity with which nature has disposed of these singular product and assigned to each class its peculiar stratum'. Smith appreciated that the tool of stratigraphy was gainful for commercial advantage, and the concept of continuity of strata was relevant for coal exploration and agricultural activities (since type and quality of soil were dependent on strata).

Subsequently, John Phillips (major subdivisions or eras of stratigraphic column), Carl Alber Opel (zonation and correlation of Jurassic sequences across Western Europe with ammonites occurrences) and d Orbigny (concept of 'stages' as chronostratigraphic units defined by faunal zones, 1849) carried forward the concept. In subsequent years biostratigraphic zonation was further refined through micro-paleontological techniques. By middle of 19th century, the concept of stratigraphy, stratigraphic succession and correlation found its extensive practical application with the establishment of national surveys in different continents; England and Wales with British Geological Survey (1835); most American states (by 1900) and USGS (1879); Geological Survey of India (1851) in British colony of India and in many of the countries of Europe, Argentina and Japan. It remained compatible to colonial expansion and prospecting of mineral resources of the colonial world. Stratigraphy found its important application in oil exploration as well.

Initially, the task of trans-continental stratigraphic correlation and nomenclature suffered from confusions, since it was not logically possible for stratigraphic sequences from different parts of the world to correspond, if Lyell's principle of uniformitarianism is to be accepted. In 1878, the International Geological Congress (IGC) was besieged with the task of rationalisation and correlation of International Stratigraphic nomenclature; and ever since this has become a major part of IGC's objective. In late

20th century, a major revolution in stratigraphic analysis came with advent of high resolution seismic acquisition, that could resolve individual stratigraphic units into several depositional sequences bounded by sub-aerial unconformities, in response to cycles of sea-level changes, particularly in deltaic sequences; the concept of 'Sequence Stratigraphy' emerged (UKOGL, 2017).

1.8 Mass extinction of biota and palaeontology

The appreciation of the connection between stratigraphic succession and the fossils and their deeper significance as geological entity was an important milestone in the evolutionary history of earth science concepts. Perhaps, Georges Cuvier's long-lasting contribution to geology was in establishing extinction as a fact with broader ramification in geological history.

Georges Cuvier (1769–1832), Professor of Museum, Paris and who aspired to be the 'Newton of Natural History' and his friend Alexandra Brongniart (who was more of a geologist) clearly affirmed connection between fossil and geological strata, thus opening an immense field of observation and research in newly created branch of palaeontology and stratigraphy. The historical key provided by palaeontology was thus recognised and the basic principles of biostratigraphy were established. Cuvier who was a lifelong Protestant, saw organism as integrated whole in which each part's form and function were integrated into the entire body. While not accepting the concept of organic evolution, he is also credited with launching of modern vertebrate palaeontology. With increased investigation in mass extinction and their uses, catastrophism re-emerged as a hypothesis to explain some of great episodes of changes in the biota. Cuvier regarded wiping out of a number of species at geological boundaries (or revolution as he termed it) as events with natural causes which was considered to be a geological problem.

Jean-Baptiste Lamarck, Cuvier's colleague was the first to make a formal distinction between vertebrate and invertebrate, and with this distinction, invertebrate palaeontology made a proper start. The early 19th century pioneers' understanding of extinction of biota and appreciation of the concept of catastrophe were real advancement for this emerging domain of natural science. Charles Lyell, a follower of Hutton, was an uniformitarian explaining the past by using analogies with knowable circumstances and laws of constancy in nature while Cuvier and others (Buckland) were in favour of catastrophism. The 19th century thinking was divided into two opposing camps of uniformitarianism and catastrophism.

1.9 The great ice age of Pleistocene

The recognition of signatures of an ice age (Pleistocene) by Louis Agassiz (in 1835) and other pioneers was another significant landmark of 19th century geology. The hypothesis of a period of severe and sudden cooling of Earth was proposed as alternative to Cuvier's concept of mass extinction. Early workers such as James Hutton (1795), Ignaz Venetz (1788–1859), and many others explained the erratic boulders far beyond the glaciers in Europe as caused by glaciers. In 1824, Jens Esmark of Scandinavia concluded that glaciers were at one time more widespread; by 1830's de Charpentier observed many kinds of glacial features, from erratic to moraine. The works of these pioneers laid the foundation for Agassiz' postulation on ice age.

Louis Agassiz (1801–1873), Swiss naturalist and professor of Natural History started his career as Cuvier's assistant. He presented a synthesis of various evidences to show that the Earth had been subject to a past ice age i.e. larger glaciers had simultaneously encroached on plains and mountains of Europe, Asia and America (smothering entire northern hemisphere in a prolong ice age). He based his idea on the recognition of glacial erratic, that differ in size and composition from rocks in area of deposition in Rhône and Aar rivers in Swiss Alps. However, the concept of 'Ice Age' was slow in acceptance among many leading geologists of the period. Agassiz reasoned that extinct mega fauna must be tropical in nature and probably been wiped out by sudden arrival of Siberian winter or great ice age of Pleistocene (Climate change, 2002). Later it was found that, great ice age, which was strictly speaking, a figment of his imagination, had nothing to do with extinction of mega fauna including mammoth, which, on the other hand evolved all through the ice age, and became extinct at the end of last ice periods. The concept of Great Ice Age was subsequently modified, with several glacial stages of large glaciation separated by warm periods or interglacial stages (based on evidences of soil and plant remains, interlayered between glacial deposits) and finally accepted by scientists in late 1870s.

Subsequently, in 1947–1949 the circum-global voyage of Swedish deep-sea expedition vessel, Albatros brought records of deep-sea sediments and radiometric dating of coral deposits that gave precise age of last Interglacial stage. The concepts of ice ages indicate that climate on earth have changed greatly over geologic time and it set the stage for climate reconstruction in geological history and is the forerunner for global concern in climatic changes in 20th century. A brief period of 300 years (between 1450 and 1700) of lower global temperature based on tree rings in northern hemisphere has been referred to as Little Ice Age much before present spell of global warming (Andrews 2018).

2 Post-industrial revolution

Though used earlier by French writers, the term industrial revolution was first popularised by English economic historian, Arnold Toynbee (1852–83) to describe Britain's economic development during 1760–1840. Industrial revolution brought in a new form of political alignment which accelerated pace of search for earth resources.

2.1 Geomorphology

Until 17th century landforms were explained in terms of philosophy of catastrophism i.e., features on earth were either specially or suddenly created because of violent cataclysms. The concepts of geomorphology grew up in Europe and North America independent of each other essentially from Hutton's theory of uniformitarianism. The concept of wasting land or non-permanence of landscape as envisaged by some early thinkers is fundamental to modern geomorphic thoughts. The evolution of the theories of geomorphology gave a more rational and sound expression of the geological time. The view that ability of erosional processes to give shape to earth's surface needs much longer time frame of few thousand years based on accepted authority of the church during medieval period, received wider acceptance. This gave credence to the concept of a longer time span of earth, which has now been corroborated by modern methods of age determination of the Earth materials.

Industrial revolution and demand for natural resources together with the American Civil War (1861–1864), prompted the US Congress for expansion of economy, thus a triggering decisive pursuit for geomorphological studies and exploration in America. The surveys of USGS in its early days were carried out to support agriculture that was the basic occupation in early 1800's; it was entrusted with task of classification of public lands, nearly all of which were within the arid region. John Wesley Powell, a Civil War veteran and the second Director of USGS (1881–1894), known for the great 'Powell geographic expedition down the Colorado River' and exploring the west America, was primarily concerned for detail appreciation of landforms and land use. The classification of land was included as an important component of government policy of President Roosevelt's conservative programme. In the early 19th century the importance of marine erosion as a major geomorphic process was emphasised by geologists such as Charles Lyell, Sir Andrew Ramsey, and Baron Ferdinand; however, by 1860 much importance to fluvial processes began to be attributed. The studies typical of geomorphologic in scope came up in the 'later third of the nineteenth century' (Thornbury 1989).

2.2 Concept of geomorphic cycle

The pioneers of American geomorphology viz. Major J. W. Powell, G. K. Gilbert, C. E. Dutton and others, build up the foundation on which W. M. Davis propounded the concept of geomorphic cycle. They emphasised importance of geologic structures as a basis for classifying landforms, concept of limiting level of land denudation or base-level, (to which Davis suggested the name peneplane), and recognition of geomorphic differences of processes and structures. The processes of erosion operating upon the land would eventually reduce it to lowland little above sea level was termed as peneplain by Davis, a concept that was anticipated by Powell as well. He noted the geomorphic differences between scarps resulting from erosion and produced by displacement of rocks. Davis, a great analyst and systematiser, gave new life to geomorphology, by introducing genetic methods of landform study. His idea that differences in landforms are largely explained in terms of geologic structure, processes and stages of development were long rooted in thinking of geomorphologists. However, in later years many opposed the concept of stages. Hack (1960) developed theory of dynamic equilibrium (rising and fall of base level).

Gilbert, considered as first American geomorphologist attempted a quantitative approach to relate between stream load and river parameters and interpretation of

Pleistocene history of shoreline study of Lake Bonneville (or Great Salt Lake). He was the first to comprehend geomorphic evidences for fault block origin of topography of Great Basin region. Practical application of geomorphology in ground water, engineering geology, soil sciences and introduction of quantitative and experimental models using laws of hydrodynamics brought in new dimension to the science of geomorphology.

3 Twentieth century onward

The 20th century witnessed spectacular advances in science with path breaking achievement in technologies. The demands in non-metalliferous resources including fuel like petroleum and two world wars in the first half of the century redefined the course of science. It provided fresh impetus to the mineral exploration policy through involvement of instrument in geological surveys in land and ocean bed. In early 1900s, a new era in oil industry began. During and after World War II, investment and development in analytical techniques opened new vistas of quantification and applications in earth sciences. The term big sciences first appeared in an article by Alvin Weinberg in *Science* (1961) as part of new political economy in post-war regime. In contrast to the preceding period, when independent and individual researchers worked alone or with graduate students, multidisciplinary approaches with institutional involvement became the fashion of 20th century (History of science policy, 2020); (Encyclopaedia Britannica). The convergence of philosophies from different cultural origin was the hallmark of science of the era in intellectual domains. The issues like environment, climate change, and new concepts in geological principles dominated scientific arena of the period.

3.1 Remote sensing in geological mapping

The time constraints for US Geological Survey to comply with mapping assignment for the newly established Tennessee Valley Authority (1933) during the depression years of 1930's gave it an opportunity for full-scale test of use of aerial photography, with which it was experimenting since 1904. The aid of this newly developed technique and equipment, led to major revolution in map-making procedure. The period may be considered as the dawn of remote sensing in geological survey and mapping (Rabbit 1989). Subsequently, with emergence of space technology in 1960s and further improvement in satellite imaging, hitherto inaccessible areas were brought under the fold of geological mapping and analysis.

3.2 Age of the Earth

According to Biblical calculation, the Earth was considered as very young and the complex sequences of rocks, fossils etc. had been attributed to be deposited in a very short time span by Noah's flood, which was considered a global and violent event. The Vedic literatures of the East have references of geological divisions of land and of accepting the geological time scale as a long period.

In 19th century, the geologists following Lyell's ideas were willing to accept an infinitely large age for the Earth. Lord Kelvin based on rate of cooling, gave an estimation of age of earth as 10–500 million years old. It was not until work of John Joly in 1909, in which the effect of radioactive heat was considered. The realisation of the long age of the planet could finally link the genesis of earth with that of planetary system, in one hand and could make a sense of the stratigraphic divisions as a reliable history of earth's sedimentary, igneous, and paleontological records, climatic changes, geomorphologic variations, on the other.

Pierre Curie (1903) and his associates found that radium salts constantly emit heat. Lord Rayleigh and Bernard Boltwood (1905) were the first to study the radioactivity of rocks and found that ratio of Lead to Uranium did indeed increase with age. This discovery of radioactivity associated with rocks and subsequent understanding of isotopes laid strong foundation for new methods of dating of rocks and the planet that became a separate branch of geochronology with well-established field of study, in late 1950s. Arthur Holmes, also known as the father of modern geochronology, strongly argued for using radiometric dating, rather than relying on techniques of rate of sedimentation etc. In 1940s, Mass Spectrometer was improved that could separate different isotopes of same element and variation in their abundances. This was needed to help development of the atomic bomb. Several issues of radiometric age dating like U-Pb ratio, constancy of rate of breakdown of radioactive elements, Rubidium-Strontium (1950s, 1960s), K-Argon, K-Calcium (1920s, 1940s) have been seriously discussed among the geologists. By using lead isotope data from Canyon Diablo meteorite, Clair Patterson (1956) calculated an age of earth at 4.55 billion years, which was a figure far more accurate than those existing at the time. This figure has been refined but largely remained unchanged since then. Darwin finally got the luxury of time for evolutionary process of life to allow. H. C. Urey and G. J. Wasserburg applied Mass Spectrometry to study geochronology. The introduction of SHRIMP and ICP-MS has enabled geologists to expand the database of geochronology. The recent SHRIMP studies on U-Pb isotope ratio of zircons from 'Paleoarchean Older Metamorphic Tonalite-gneiss' of Champua areas of Kendujhar, Orissa have pegged the earliest dating of rocks on Earth at 4.24 Ga (Chaudhuri et al. 2018, p. 7069); a previous study of zircon from this area yielded an age of 3.6 Ga. Detrital zircon grains in meta-sedimentary rocks of Jack Hills of Australia have given ages up to 4.4 Ga (Burnham et al. 2017, pp. 451–461).

The radiometric clock has put astonishing finishing to evolutionary history. For more recent periods of 20,000 yrs, radiocarbon (^{14}C isotope) developed by Walter Libby (1952) proved to be an effective tool. The emerging new methods, have helped to pin down evolution of hominid ancestors, 'which is at a time-distance of geological eyeblink'.

3.3 The Systemic theory

The 20th century science saw a shift in epistemological details, from parts to whole as the central aspect of the conceptual revolution. Gradually scientists began to realize that nature does not appear as a mechanical universe composed of fundamental blocks, but rather as a network of relations in the interconnected web; precisely there are no parts at all. This shift was similar in experiences of quantum physicist in atomic phenomena, biologists in wholeness in organism, and ecologists in their studies of animal and plant communities. Biological sciences took the lead in introducing ecological concepts and multidisciplinary approaches (Capra 1997). The geological ideas of twentieth century, not only accepted reduction of earth science to principles of physics and chemistry, but also some pattern of relationships need to be asserted to physical laws. The additional factors were the network or synchronisation of major planetary events, like climatic changes, mountain building, marine transgression etc., with geological time or at stratigraphic cross over, of which two concepts viz. theory of Plate Tectonics and concept of Environmental Geology, are discussed here.

Theory of Plate Tectonics

The theory of Global Plate Tectonics, which is considered as significant as Darwinian Evolution and important to humankind is an attempt at integrating and interpreting endogenetic and exogenetic processes. It has revolutionised thinking about the earth and earth processes. The concept of wandering continents, that evolved through last several centuries, as against a fixed one, is an important pillar of modern geological science. The ancient theory of flat earth was abandoned long back. As early as in 1596, Abraham Ortelius, a Dutch mapmaker suggested that continents have not always been at their present positions. Sir Francis Bacon (1620) and others have recognised similarity of shorelines of east coast of South America and west coast of Africa. Antonio Snider Pellegrini's gave earliest specific reference to the idea of continental drift in 1858.

The first significant evidence from geological records of 'once-united continents' was provided by an Austrian geologist, Edward Suess (late 19th century) who noted strong similarities among Late Palaeozoic plant fossils from India, Australia, South Africa and South America, as well as evidences of glaciation in the rock sequences of these continents. It was Alfred Wegener who proposed in 1915 the idea of drifting continents based on the evidences of palaeo-climate, geology including fossil evidences and matching of coastal geometry of continents. Alexander du Toit who was the main baton carrier of Wegenerian theory of continental drift published '*Our Wandering Continents*' in 1937.

Since early 20th century several leading scientists, including Einstein were convinced that, the universe and nature in general were different from what we had thought. It was realised that man's observations were restricted to the surface of the earth. It led us to think that what we observed with our intuition was all that really happened as if in a small playpen. Yet stretching further the domain of study encompassing all the geological time and deep into oceans and the Earth's interior, pure thoughts allowed us to see what happened there and of the planet's configuration since remote past (Bodanis 2000).

In late 1940's with help of new scientific tools, new lines of investigation like aeromagnetic survey for submarine geomorphology, seabed drilling etc. started. The new set of data on sea floor and sub-sea were made accessible to the scientists that paved the way for the concept of continental drifting. Maurice Ewing in 1947 confirmed existence of rise in level of sea floor in Central Atlantic Ocean, now known as mid oceanic ridge systems. Sam Carrey in 1958 made scale model of Earth and concluded that a fit of ancient continents could be made more precisely provided the diameter of earth was taken to be smaller at the time of Pangaea. 'However these basic observations were ignored while formulating the theory of Plate Tectonics'.

Similar assumptions were arrived at by other workers like, Lindemann (1927), C. Otto Hingelberg (1930's), Jan Kozier (1980's), Klaus Vegel (1980–90) and Carrey (1950–1990) that led to a concept of 'terrestrial expansion brought about splitting and gradual dispersal of continents as they moved radially outward during geological time (about 50-60% of its present size). In its present form, the theory of plate tectonics assumes that radius of Earth remained constant throughout its life span of 4500 million. In 1961, Harry Hammond Hess, an American geologist began theorising new sets of observations into a theory of sea floor spreading; new findings of 1960s included data on ocean floor topography, marine magnetic anomalies, palaeo-magnetism and geomagnetic reversals and sea floor spreading. The theory of plate tectonics (1968) is preceded by the hypothesis of Sea Floor Spreading (proposed in 1960–61). The hypothesis of sea floor spreading, holds that the ocean floors, which remained mostly unmapped until after World War II are now considered to be youthful with thin veneer of sediments that hardly go beyond Cretaceous period.

Concept of Environmental Geology

The renewed concern of integrating fate of human society with the larger framework of the well-being of the planet came in the world of scientific thinking during fifties and continued in the subsequent decades of last century. The emerging social and political crises in the post-war era that blew up in spiralling civil disturbances across continents can be traced in its origin in environmental ethics. While in Europe "resources had long been used with utmost care under government control and conservation was part of its political economy", the scenario was different in rest of the world including colonies (Rabbitt 1989).

The immediate sources of this crisis are many viz. overpopulation, urbanisation, problems of resource management and generation of wastes and little regards for environmental ethics. The application of geological concepts to environmental problems is based on understanding of exogenetic and endogenic processes that create, maintain and destroy earth materials, collectively referred to as Geologic Cycle (including more important tectonic, hydrologic and geochemical cycles) and vulnerability to damages by natural geological processes.

4 Conclusion

The development of concepts of geology during its journey from early period to present time is driven by the dynamic forces of human society including religion, trade, colonial expansion, capital and industrial activities, and finally by crisis of sustainability of civilisation itself. The evolutionary process is continuous; new domains (and understanding) of interest as well as concern for the society have come up during recent decades that include concept of sequence stratigraphy, geological processes operative in Quaternary period and sea level fluctuation, climate change, global warming and planetary science.

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