Shifting paradigms: why history matters in geological sciences

C. P. Rajendran

Geology as a scientific enterprise emerged in the 18th century, both at intellectual and commercial levels, as an exploitive tool in the hands of imperial powers to locate and assess natural resources, and it eventually evolved into a post-modernistic manifestation of an all-embracing science of sustainability, called Earth-system science. Following the timeline of geology, which began as a classical scientific discipline, we see a prime example of a socially embedded science that goes through various cycles of growth pangs and transitions during its evolution concomitant with epochal changes in social perspectives. This article explores how geology as a scientific discipline evolved to its present status.

Keywords: Geological sciences, history, shifting paradigms.

THE logical empiricism dictates that production of scientific knowledge is a process that is independent of all cultural and social contexts. According to this view, the social milieu with which the researcher interacts will have no bearing on her rational scientific work – some sort of a virtual-bubble world where pure objectivity rules the roost, an ideal world where social influences are to be resisted because of their inherent tendency to introduce bias that would affect the integrity of scientific results. How true is this depiction of nature of knowledge in a real world? A prime example of European renaissance demonstrates that the state of society had a big role in preparing the ground for germination of new ideas, most importantly, the emergence of modern science. Thomas Kuhn (1922–1996) is probably the foremost theorist who saw how science is socially embedded and how social context could drive radical changes in the production of knowledge in natural sciences and control its evolutionary trajectories[1]. Kuhn posits that during the collection of scientific knowledge, the process itself undergoes phases of rapid changes or transformations, which he qualified as paradigm shifts. The paradigms are defined as the period of regular science activity – a prevailing framework that alternates with periods of turmoil, bringing about a fundamental change in the basic concepts and experimental practices of a specific scientific discipline.

Admittedly, the degrees to which the social or historical context would impact might also differ between diverse branches of science. The case in point is the differences between basic sciences that include physics, chemistry and biology, and historical and derivative sciences like geology, cosmology and anthropology. Knowledge generation in the latter set may be regarded as 'plural, partial and provisional'[2]. Science such as geology or even cosmology may be considered as imprecise as it deals with incompleteness, poor resolution of data and lack of experimental control. Geology started in the 18th century, both at intellectual and commercial levels, as an exploitive tool in the hands of imperial powers to locate and assess natural resources, and it eventually evolved into a post-modernistic manifestation of an all-embracing science of sustainability, known as Earth-system science. Following the timeline of geology, which began as a classical scientific discipline, we see a prime example of a socially embedded science that goes through various cycles of growth pangs and transitions during its evolution concomitant with epochal changes in social perspectives.

Classical geology: the philosophical underpinnings

Perhaps it was started with René Descartes – the belief that scientific knowledge is obtained by breaking it down into simplest parts, elevated to the status of a creed in the later years by Karl Popper[3]. Converse of this view is that branches of science such as geology or even cosmology are imprecise as they deal with incomplete data with poor resolution, and lack of experimental control. Frodeman[4] defines research pathways followed in classical geology as hermeneutic (theory of interpretation). Hermeneutics is an interpretative method evolved in the 19th century to evaluate the biblical readings consisting of both literal and metaphorical parts from which apparent truths must be deciphered. Here objectivity is at a premium because the reader also brings in her 'presuppositions and expectations'.

C. P. Rajendran is in the Jawaharlal Nehru Centre for Advanced Scientific Research, Bengaluru 560 064, India.
e-mail: rajendran@jncasr.ac.in

Traditionally a geologist is trying to read the history of the Earth as a visual text from various rock exposures, appropriately weighing the clues, based on their quality and relative significance. The geological reasoning in the 18th and 19th centuries was more hermeneutic than any of the sciences that our perceptions to a certain degree are determined by our expectations or conceptions. This brings in the paradox of involvement versus non-attachment. The Tao informs us that, 'Truth waits for eyes unclouded by longing'. Preston Cloud, when wrestling with paleobiogeography unaided by 'plate tectonics', mentioned a similar concern. He commented wryly both in words and in a graph that, 'the more interpretative the subject, the more prevalent the effects of the involvement'[5].

The bottom line of the arguments is that the discipline of geology fortified by its unique narrative power and reasoning prowess which are the hallmarks of all historical sciences, cannot be seen from the perspectives of physics nor should it be treated as a derivative science[6]. Geology is a 'preeminent example of a synthetic science', wherein the geologist employs a suite of logical techniques and tools to understand nature and its components. And, such reasoning powers that depend on the classical hermeneutical methods or interpretative logical procedures offer far superior methodology to find answers in a world of complexities and uncertainties that we now inhabit, be it safe disposal of nuclear waste, climate change or receding groundwater levels.

Old geology and early concepts

I would like to consider Leonardo Da Vinci (1452–1519) as the first renaissance geological thinker (although in some respects the 10th century polymath from central Asia, Al-Bīrūnī could be considered as Da Vinci's forerunner). Da Vinci's deep interest in geology is not only evident in his discussion on rivers, rocks and fossils in one of his notebooks called *Codex Leicester*, but also in the details of landscape that acts as background in all his famous paintings, most importantly 'Virgin of the Rocks' and the 'Mona Lisa'. By the 18th century, geology had evolved into a fiercely argumentative exercise. As a hermeneutic (interpretive) science, classical geology in the beginning offered a forum for clash of different schools of thought, which interpreted the visible nature differently. This was also a period defined by a society that was obsessively curious about the world. Puzzled by the same questions, it was James Hutton (1726–1797), a polymath in Edinburgh in 1760s, who showed some extraordinary insights[6]. Hutton, prominent among the early renaissance scholars, was destined to make a lasting impact with his masterpiece, *A Theory of the Earth and Proofs and Illustrations*. This can be considered as the true beginning of the science of geology. He introduced the concept of 'deep time' and speculated that incremental changes that transform the landscape take place at the cost of immense amount of time. Hutton also introduced another concept called 'uniformitarianism' – the fundamental principle of geology, which mentions that the natural processes which are operating today are the ones that have always operated. The implied gradualism that underpins all the processes in nature is conveyed by the phrase 'the present is the key to the past'.

The next major unravelling of geology starts with Charles Lyell, who was professor of geology for some time at King's College in London. His contribution was his magnum opus, *The Principles of Geology* published in three volumes (1830–1833), in which he elaborated on the thoughts of Hutton. Two schools of thought dominated during Lyell's time – catastrophism and uniformitarianism. Catastrophism, as the name implies, is representative of a world that is shaped by cataclysmic events. An idea that resonated with the biblical story of a great flood that marooned Noah and his ark, the church and clerics were supportive of this new thinking, as contrasted with that of uniformitarianism that expounded 'deep time' and gradual changes over an enormously long period of time.

It was also the time when major discoveries were made in palaeontology, globally. The second voyage of *HMS Beagle* (1831–1836), which had contributed immensely to the understanding of natural history and geology, finally ended up in some epochal discoveries on the origin of mankind[7]. Darwin probably got the idea of 'incremental change' from his reading of geology, which he applied profitably to develop his theory on natural selection. Darwin may have also been influenced by the philosopher and mathematician William Whewell, whose ideas on consilience – the coming together or convergence of many different strands of evidence in support of the same theory, even in the absence of a single conclusive piece of experimental or observational data. Largely ignored by the historians of science, the American geologist Thomas C. Chamberlin had by then developed a 'method of multiple working hypotheses'[8], which is a practical expression of how to make best use of consilience. Incidentally, in later years, Karl Popper started to reformulate his falsification method in terms of simultaneous, relative testing of alternative hypotheses. However, Chamberlin was there first. His idea is that when working in the field, for example, you should be constantly comparing how well different working hypotheses fit ('consile with') the accumulating evidence, rather than constantly thinking in terms of only seeking critical evidence to test a single hypothesis.

Stephen Jay Gould eloquently discusses consilience in the section of *Wonderful Life*[9] entitled 'The Burgess Shale and the Nature of History'. This is an important book even if Gould did perhaps overinterpret the philosophical significance of the Burgess Shale work of Whittington *et al*. (among them, Derek Briggs and Simon

Conway-Morris, both disagree with Gould on this). In that section, Gould argues that historical science is critically dependent on consilience as a method of testing its theories[10].

Changing paradigms: old geology to a born-again science (1920–1968)

Courting the controversies and dating

The French mathematician and naturalist Georges-Louis (later known as Comte de Buffon), who was the first to estimate the age of the Earth, obtained a maximum age of 168,000 years, clearly a gross under-estimation. Perhaps the raging controversies on the age of the Earth motivated Lord Kelvin (William Thomson) to estimate the same. He based his calculation on the first law of thermodynamics (law of conservation of energy), although he did not foresee the Earth's radioactivity as a continuous source of heat. His first assumption was that the Sun would have exhausted its fuel, had it been very old, and therefore the planets cannot be that old. Kelvin based his estimates on heat loss within the Earth and from the Sun to the Earth. However, geologists had already identified the Cambrian strata (deposited 500 million years ago) with fossils. Kelvin refused to appreciate the geological insights into deep time, till his death. The concept of 'deep time' probably represents the greatest intellectual contribution evolved from geological studies that has probably resonated even with a few modern theoretical physicists[11]. Finding the age of the Earth was a work in progress being executed by stratigraphers, palaeontologists, geochemists and geochronologists, to which details are constantly being added and finer calibrations being made[12].

A major turning point in this exercise came when the geologists led by Arthur Holmes (1890–1965) from Imperial College, London found that using the long half-life period of certain elements, the age of the Earth could be determined accurately. Although initially resisted, applications of radiometric dating gained momentum by the end of 1920, and the geological community by and large accepted the methodology, leading to yet another transformation in geology. The techniques based on dating the radioactive mineral finally proved that the Earth was about 4.5 billion years old – an experimental result that matched with the geological observations.

As exemplified by Holmes, who introduced physics and chemistry to help constrain geological problems, the uneasy relationship between experiment and observation was also recognized by the first great experimental petrologist, Norman L. Bowen (1887–1956). He wrote in 1928 – decades before Popper – that 'it is but poor recommendation for a hypothesis that it can be checked against observation to such a limited extent that it is difficult to prove wrong'[13].

Drifting theories

Determining the age of the Earth by radiometric dating may have brought geology to the mainstream of the scientific world, and in a sense, that may be its first renaissance. However, a discovery of far greater impact was waiting to happen. This grand theory unified continental and seafloor mobility that explained a host of phenomena like earthquakes, volcanoes, origin of mountain belts and biodiversity. This theory also swept away some dated classical concepts and explained how it makes the Earth inhabitable. The discovery of radioactive heat generation and a convective mantle within the Earth in the 1920s could have been the natural stepping stone to reach this new theory that envisages fragments of top-cooled crustal parts moving on a mobile inner part warmed up by radiogenic heat.

To reach the Holy Grail of complete understanding of this phenomenon called plate tectonics, the world had to wait for another 30 years, although two mavericks, one in USA and another in Germany, had hit upon the spark of an idea called continental drift by the end of the first decade of the 20th century. The credit of originally proposing the theory of continents moving on the Earth's surface should naturally go to Frank Bursely Taylor in 1908, an amateur geologist and a Harvard dropout. Three years later, in Germany, Alfred Wegner, a meteorologist, proposed a similar theory. It is not clear if Wegner independently developed the theory of continental drift, or he 'picked up' Taylor's idea and 'appropriated it'[14].

What is remarkable is that Wegner was not even remotely connected with geology. On 6 January 1912, he literally startled a meeting of the Geological Association in Frankfurt with his radical vision of continental drift to explain the evolution of Earth's geography – of widening seas and rising mountains. His theory was stiffly opposed in the US on the pretext of lack of causal mechanism, although more favourable voices emerged from Europe. Holmes' publication in 1929 presenting a model of continental drift appeared in *Transactions of the Geological Society of Glasgow* and a book devoted to drift theory satisfied few, and the controversies continued to rage.

Geologists were equally curious about the structure of the crust under the sea and how it is different from the continental crust. Fortunately, in the 1920, the US Navy started funding seafloor exploration; its major interest was in the measurement of gravity[14]. By then a Dutch geophysicist, Felix Vening Meinesz (1887–1966) invented a gravimeter capable of withstanding sea-rolling. The seaborne gravity surveys attracted many scientists, and the combined efforts and results from various parts of the world oceans proved the veracity of gravity anomalies (areas showing negative gravity values; lower than normal) along some trenches where the ocean is excessively deep. Along with field data, laboratory models suggested rising convection currents at the centre of the ocean, and words like 'plate motion' and 'convection' were slowly entering the lexicon of geology. The world was also about to see a greatest transformation in geology.

If we look for a single factor that made a huge difference to funding for research in the US during the Second World War, we will have to conclude that it was the German U-boat[14]. Part of the deadly arsenals of Germany, U-boats were causing huge material losses to the Allied and the US Navy during the Second World War. The US Navy was interested to know if marine geophysics could provide means of avoidance and detection of German submarines[14]. Naomi Oreskes, who tracked the timeline of research in plate tectonics is spot on, in qualifying the period from 1945 to 1970 as the most exciting time in the history of American Earth sciences[14].

In 1962, the Princeton geologist Harry Hess, who had closely been watching these developments published a paper, detailing mantle convection as the driving force that moves fragments of the outer layer of the Earth consisting of the crust and part of the upper mantle, together known as the lithosphere. Locus of the rising temperature, the mid-oceanic ridge on the ocean floor is where the new seafloor is produced, pushing the previously formed older part of the floor. Robert Dietz, a geologist from Scripps, USA, called this process as seafloor spreading, where new oceanic crust is formed. Tuzo Wilson, a Canadian geologist, soon pitched in with his exposition on transform fault that allows the plates to slide move past each other horizontally, without forming a new crust. Standing tall among the research pioneers was Dan McKenzie from the Cambridge University, UK. His paper along with R. L. Parker on 'Tectonics on a sphere' marked a watershed moment in Earth sciences research.

Another turning point in Earth sciences research was the establishment of World-Wide-Standard Seismograph Network (WWSSN), which began in 1960. This seismograph network enabled determining the locations of global earthquakes and their slip directions. The earthquakes were found to follow certain patterns in their spread that essentially cluster along the margins of tectonic plates. By 1968 an integrated global picture of plate tectonics emerged, thanks to the efforts of many geoscientists. Thus, in a real sense, the discovery of plate tectonics is also a by-product of the Cold War, when the need to detect nuclear tests became fundamental, as indeed has been the importance of seismology in building the confidence for detente and in nuclear test limitation treaties.

Mostly under-appreciated, what may be called as an act of symbolism took place at the end of the 1960s (contemporaneous with the plate tectonic theory), which brought home the fragility and vulnerability of a life-sustaining planet in the background of unnerving cosmic barrenness, more effectively than any other human tool that can be used for the public understanding of geological sciences. This was when Neil Armstrong stood on the surface of the Moon, and looked and probably gasped at that pale blue planet on the horizon – the most wonderful sight in all known cosmos. The relayed picture of the Earth as a blue dot seen from the Moon probably got etched in the public psyche for generations to come. Simon Winchester in his book *A Crack in the Edge of the World* records this event as a 'profound paradigm shifting moment of unforgettable symbolism' that changed the science of geology forever, and it became a born-again science[15].

By the end of 1968, plate tectonics unravelled its complete beauty, and another momentous event of epochal proportions also occurred contemporaneously – space travel and lunar exploration became a reality. It was also the year that changed the world, which saw wars, riots, fallen leaders, failed revolutions and lunar dreams. The 40th anniversary special published by *Time* magazine was devoted to the year 1968. 'Like a knife blade, the year severed past from future', says Lance Morrow, the American essayist in his opening comments.

Birth of a new science: the 21st century

Geology blossomed during the Industrial Revolution and emerged in the 19th century as a tool for exploiting the seemingly infinite Earth resources. Geological tools helped colonial powers to locate and exploit rich Earth resources from Asia, Africa and South America. The actual knowledge on Earth processes generated during that period thus was merely incidental, like the discoveries of fossils of flora and fauna during the exploration of coal and oil. Through most of the 20th century, geology primarily served as a tool for the exploration and exploitation of natural resources.

A tectonic shift from exploitation to sustainability began to manifest in the 1980s. At that time, the United Nations had set up the Brundtland Commission to assess the interrelationships of environment and development. The report of the commission, *Our Common Future*, introduced for the first time the concept of 'sustainable development'. The change in ethos is reflected such that the Earth sciences are increasingly harnessed to promote sustainability in an era that may be qualified as a nascent post-industrial society[16].

We are now witnessing a paradigmatic shift – one that has swept our feet and thrown us into the uncharted waters of a new unusual stage in Earth's history. For one thing, this has no parallel in the geological past, and the famous geological dictums may seem meaningless. The observer himself has now become the player, or vice versa[17]. We are entering a new geological epoch in which humans compete with the natural forces in shaping the landscape. Paul J. Crutzen (who shared the Nobel Prize in Chemistry for the discovery of chlorofluorocarbons (CFCs) that cause the ozone hole) writes, 'it seems appropriate to assign the 'Anthropocene' to the present, in many ways human-dominated, geological epoch, supplementing the Holocene – the warm period of the past 10–12 millennia'[18].

As technology became sophisticated to cater to mass consumption, the Earth's atmosphere is being filled up with CFCs and greenhouse gases like carbon dioxide and methane. The burning of fossil fuels has been adding more CFCs since the Industrial Revolution, that may initiate a runaway global warming phase and rise in sea level, which would impact the availability of shelter, food and water[19,20]. The temperature is predicted to rise to 1.1°–6.4°C by the end of this century, according to the United Nations Intergovernmental Panel on Climate Change reports – an all-time predicted high (the last thermal maximum was at the Paleocene–Eocene boundary; about 50 million years ago).

Increased use of nitrogenous fertilizers led to dramatic increase in food production, but it also resulted in acidification of oceans and rivers, and enhanced nitrogen fixation. Accelerated urbanization and transplanting of people from villages to cities will see perennial water depletion and shortage. Landscape changes owing to construction activities create new pathways and diversion of the groundwater. Further, human activities are causing accelerated extinction of various species, including those living in shallow seas. Some geologists consider this to be similar in magnitude to the major extinction event that took place in the Cretaceous–Tertiary boundary (60 million years ago).

New tools and approaches, including partnership with other sciences will help in understanding the consequences of anthropogenic interactions with other entities in nature, oceans and the atmosphere, and the future will see Earth sciences increasingly getting involved in finding solutions to environmental problems. The increased ability to probe active natural systems facilitated by improvements in the field of instrumentation, observational and real-time data delivery systems has heralded a major transformation in earth sciences[21,22]. The human mind will, however, continue to be the most important tool for generating the required explanatory narratives, celebrating geology's unique model of reasoning, which resonates in a line from T. S. Elliot[10], 'I only ask you to return to a place well known and see it for the first time'.

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