Challenges in Earth sciences: the 21st century

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The 21st century poses many challenges for global sustainability. Among them, most importantly, the human race will encounter scarcity of raw materials and conventional energy resources. And, India may have to take the brunt of these problems as it is going to be the most populated region of the world with concomitant increase in energy demand and requirement of other resources. India will be the testing ground for introducing newer ways of green technology and innovative principles of resource management and utilization. With the vagaries of potential climate change gathering clouds in the background, Earth sciences will have a special and predominant role in guiding the society in prioritizing our resource discovery, utilization and their consumption and the upkeep of environment. On the fundamental level, Earth sciences are going through a most exciting phase of development as a born-again science. Technological breakthroughs including the satellite-based observations augur well for gaining new insights into Earth processes. A set of exciting fundamental problems that are globally identified will set the stage for an exhilarating period of new discoveries. Improvements in numerical and computer-based techniques will assist in modelling of Earth processes to unprecedented levels. India will have to take special effort in improving the existing experimentation facilities in the Earth science departments of the country, and also the general level of Earth science education to meet the global standards. This article presents an Earth science vision for the 21st century in an Indian context.

Keywords: Climate change, Earth sciences, environment, fundamental research.

Introduction

THE 21st century is bringing a renaissance in the Earth sciences, the scientific disciplines that include dynamics and evolution of Earth crust, interactions with the life it supports, interactions with the oceans and the atmosphere, and the Earth's deep interior and near-space environment[1]. Issues that require the attention of the earth scientists have an immediacy that has attracted the attention of world leaders as they and their citizens confront global warming, the end of petroleum, shortages of fresh water, depletion of soil and the vulnerability of urban areas to natural hazards. Earth sciences are also at the centre of philosophical and religious debates about humankind's place in the cosmos, such as the young-earth creationism of fundamentalist American Christians and the old-earth creationism common in Muslim circles. The outcome of all of the above issues may influence the future and sustainability of human life on Earth.

Geology emerged in the 19th century as a tool for exploiting the seemingly infinite earth resources. It helped colonial powers locate and plunder rich resources from Asia, Africa and South America. The actual knowledge generated on the various Earth processes during that period thus was merely incidental. Remember that the primary mission of *HMS Beagle* was to map the coast of South America to meet the imperial requirements, and Charles Darwin joined the expedition because Captain FitzRoy wanted an amiable and a well-mannered mate to share his cabin, one who could put up with his temper tantrums. The search for petroleum and coal led to the incidental discoveries of fossils of flora and fauna – the missing links in the evolving story of human evolution.

Through most of the 20th century, Earth sciences primarily served as a tool for the exploitation of natural resources. During this time industrial output increased 13-fold whereas energy use expanded 16 times with concomitant increase in water consumption by a factor of 7 (ref. 2). The same industrial juggernaut also created conditions for about 25% of human population to live in reasonable comfort. This is a victory at the cost of Earth's environment, and the big question is whether such an improvement in human conditions can be made sustainable and whether the remaining Earthlings can be raised to the same standards without further degrading the Earth's environment. Science in general and Earth sciences in particular will have a major role in reaching this difficult goal along a bumpy road.

A tectonic shift

A tectonic shift from exploitation to sustainability began to manifest itself in the 1980s. At that time the United Nations set up the Brundtland Commission to assess the interrelationships of environment and development[3]. The commission's momentous report[3], 'Our Common Future', introduced the concept of 'sustainable development'. The change in ethos is reflected such that the Earth sciences are increasingly harnessed to promote sustainability in an

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era that may be qualified as a nascent post-industrial society. This transformation has come from the realization of the delicateness of an intricately weaved web of earth processes, its interrelatedness and the life it supports. Anthropogenic forcing is now recognized to be a major feedback force in the earth processes and the Earth sciences offer methodologies to develop a sustainable human society that would take care of the potentially collapsible ecology that is currently under serious global threat.

Not that this is geology's first renaissance. Some of us still in the field today can recall being schooled in paradigms that were swept away in the 1960s and 1970s by plate tectonics, the bold and grand unifying theory that continues to explain earthquakes, volcanoes and the origin of mountain belts. But equally important is a forgotten act of symbolism – to be seen more as a powerful metaphor for the cosmic interrelatedness – 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 of known cosmos. The picture of Earth seen from the Moon probably got etched in the public psyche for generations to come, and 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 put to use for the public understanding of science.

The quest for sustainability: the role of Earth sciences

Environmental hazards are on the increase, directly correlated with the increased usage of environmentally vulnerable and fragile regions of the Earth as habitats and also as zones of resource exploitation by the exploding human population. The loss of life from the 2010 Haiti earthquake resulted far more from human errors, compounded by abject poverty, than from the earthquake itself. The horrific impacts of hurricane *Katrina* off the coast of the state of Louisiana and the cyclone *Nargis* in Myanmar more or less tell the same story of a collision of huge vulnerable populations at risk and few if any precautions or mitigations. The fact that we should take into account in all our discussions is that the world population has grown by a factor of four to about 6000 million and the urban population has increased 16-fold since the industrial revolution. According to UN sources, in 2008, for the first time, more people lived in cities than in rural areas. Consequently, millions of people concentrate into megacities, many of which are prone to various natural hazards. The growing anthropogenic influences that result in destruction of wetlands and sand dunes expose coastal communities to ocean-related hazards (http://www.agu.org/sci_pol/positions/naturalhaz.shtm). The exponential growth of urban areas has brought urgency to mitigation of hazards associated with earthquakes, floods, drought, volcanic eruptions and landslides[4]. Another leading factor during this period of rapid expansion of urbanism is that not only are more poor people building homes in vulnerable areas (often on the margins of cities, areas previously considered unbuildable), they are building them themselves, without the proper engineering and materials for the hazards they face (http://www.earthmagazine.org/earth/article/2c9-7d9-c-b). These hazards, moreover, can make a mockery of international boundaries, as illustrated by the 2004 Indian Ocean tsunami and the eruption of the volcano Eyjafjallajökull in Iceland. Like the Red Cross (or Crescent) activities, we may have to think of a global action plan to mitigate hazard impacts irrespective of where the event takes place. This will help to provide scientific expertise, advice and equipment to those who need them.

Global hazards

The list of global hazards is ever expanding: the maintenance of purity of air, water and soil, among them are fundamentally related to the very existence of man. The key to this problem is the realization that a major spoiler of the natural environment is Man himself. The role of Man in shaping the landscape is now acknowledged as equivalent to a geomorphic agent with the same order of magnitude as that generated by the entire Earth dynamics[5]. Surface processes play a major role in changing the landscape and consequently these geological processes that play out in varied temporal and spatial scales are of paramount importance to the stability of biological systems. Now, anthropogenic force competes with natural agents in driving landscape changes.

Geomorphic modelling will become a common tool of environmental managers in understanding the surface processes, which will include river, watershed and hazard management[6]. The depletion of forest and agricultural/construction activities can impact the rate of sediment transport, water flow and nutrient availability. The need to have sustainable landscape will force us to rely on models of watershed processes. Such models will have to be based on inputs from high resolution topographic data sediment tracers, dating methods and wireless sensors[7].

It is proven that the Earth's carbon, nitrogen and sulphur cycles can be perturbed by agricultural and industrial activities. It is suggested within a narrow range of uncertainties that human activities can alter the chemistry of the atmosphere that can result in global warming and possibly in climate change, resulting in the changes in sea level and the hydrological cycle. Such a change can damage the physical and biological systems, as detailed in the UN Intergovermental Panel on Climate Change (IPCC) reports[8].

In this background, a few broad areas that should receive utmost attention in the new century are listed below[9]:

1. Monitoring of the Earth system processes.
2. Exploration, management and supply of energy resources
3. Conservation and management of water resources
4. Conservation and management of agricultural soils
5. Natural disasters reduction.

Rapid strides in technology will certainly help efforts in forecasting and mitigating natural hazards. For example, we can probably expect major breakthroughs in earthquake forecasting, related to some of the world's major subduction zones. We will have generated a large database on the complete deformation cycle related to the major subduction zone earthquakes (e.g. the 2004 Andaman–Sumatra earthquake), augmenting our efforts in earthquake forecast. Real-time Earth observation is now possible by satellite-based remote sensing techniques, and computing powers have increased multifold to conduct simulations and build predictive models of various Earth processes. However, we need to be cautiously optimistic here because earthquakes have occurred without any precursory signals. For example, the February 2010 Chile M_w 8.6 subduction event was precisely captured by real time GPS stations, but it was not preceded by any typical precursory phenomena. Nonetheless, the message here is that we must keep working hard on this problem.

To help solve these problems, we also require approaches and solutions novel enough to represent a complete break with the past. This shift in paradigm will result from the realization that the Earth is a complex system and her problems cannot be addressed through a reductionistic approach as followed in classical physics[1]. Interestingly, the interconnectedness of the Earth processes has emerged from an unexpected quarter. Recent studies have singled out water as an agent for stabilizing the temperature and thus generating large lithospheric buoyant stresses that trigger the plastic/brittle failure, which initiated plate tectonics[10,11], thus bringing out the intricate linkages of various, though apparently independent, processes. All these observations bring home the inescapable conclusion: the Earth is inherently a complex system, it is more than the sum of its parts, and an Earth scientist should have the wherewithal to approach the problems holistically. The newer set of problems will also demand out-of-the-box solutions. To paraphrase Salman Rushdie, 'the only people who [will] see the picture are the ones who step out of the frame'.

Brewing environmental crisis: an Indian context

As in many parts of the world, major environmental crises are brewing in India, and Earth scientists will be naturally the first ones to be called upon to address these issues. India is already facing severe water shortages, especially in the north and northwestern regions of the country. Cassandras predicted that wars in the future will be fought over water. Globally water usage is expected to increase by more than two trillion cubic metres by 2030, forty per cent more than what could be tapped from the available water resources. The recent Chinese attempts in the high land of Tibet (in a zone that sourced major earthquakes in the past) to construct dams across all the rivers including the Brahmaputra (Tsangpo) should be seen as part of their vision in view of the predicted shortages of water globally, although it is going to create a water scarcity for the downstream riparian countries including India. Water shortage can be considered the biggest environmental threat to the prosperity of India. It is prudent to remember that many of the ancient urban civilizations, most prominently the ancient Harappan settlements along the Indus River, became extinct predominantly due to the climate change and environmental degradation[12]. To quote the Brundtland Commission report[3]: 'Societies have faced such pressures in the past and, as many desolate ruins remind us, sometimes succumbed to them. But generally these pressures were local. Today the scale of our interventions in nature is increasing and the physical effects of our decisions spill across national frontiers'.

Water crisis

Some parts of India, in spite of our GDP growth are probably slipping into a state of irreversible damage to the human environment, including our oceans. The proportion of the urban population in India increased from 11% in 1901 to 29% in 2001 leading to the growth of urban slums. What is astounding is that 20% of the population still has no access to safe drinking water and 58% does not have safe sanitary facilities. We still do not have a strategy to use human waste, and the garbage generated is left uncollected. Another area of concern is the unchecked exploitation of building materials like river sand, which has affected the natural channel flows and lowered the groundwater levels.

Most critically to human existence, water trouble is also brewing all over the country, most astoundingly even in the river basin of Ganga. This river considered to be holy is turning into a 'toxic sewer', thanks to the rapid industrialization and consequent environmental degradation. It is ironic that the dam at Tehri that is being constructed at the upstream region in the Himalaya is making that region water deficient by disrupting the area's natural springs, the main perennial source of water for the local residents. The Indo-Gangetic plains is also notorious for over utilization of groundwater, threatening the hydrological balance and it is estimated that groundwater utilization in India has increased from 10–20 km^3 to 240–260 km^3 in the last 50 years[13]. Agriculture is proven to be the biggest user of fresh water and for this reason, alone the aquifer level in the Indo-Gangetic plains is lowered by 4 cm per year between 2002 and 2008 (ref. 14). The arsenic toxicity of the aquifers of the Bengal basin is another serious problem that cries for remedies. The rivers in the peninsular India are also threatened with extinction. For example, the overcrowding of pilgrims on the upstream part has made River Pamba in the apparently water-rich state of Kerala into a sewer.

A quadruple leap in India's water usage by 2050 is projected, to which we may also have to factor in reduced supply because of glacier retreat due to global warming. Models of grandiose technological fixes, as panacea to all the water-related problems, will gather momentum. For example, the concept of interlinking all the major rivers (inter-basin water transfers) in India could gather momentum as an geo-engineering solution to the continued water depletion in the country. Geologists and hydrologists will be called on to assist communities in evolving newer methods in groundwater (as well as flood water) management, as it is realized that India's water crisis is essentially man-made. It is a creation due to the unholy alliance between poor management, inadequate or unclear laws, government corruption and due to the huge production of industrial and human waste. The dichotomy between perspectives, engineering solutions versus natural sustainability, will continue to persist in the society and the geologist will be required to take a well-reasoned stand in such issues. The need of the hour is to evolve a national water policy, which will involve a holistic watershed (a geographical unit determined by local physiographical and geological conditions) management with a participatory role for local citizens for monitoring the hydrological cycle with the help of scientists, engineers and biologists (see open edit article by T. N. Narasimhan in *The Hindu* dated 4 November 2010).

Energy security

As important as the issues related to water are, we in India need to worry also about energy security. According to the International Energy Agency, the global demand for energy will go up by 60% by 2030. The challenge for India probably is to achieve self-sufficiency in energy by 2050. The question is whether we have a road map to reach this goal, and what would be the role of a geologist in these national efforts? In the short term, there will be increased effort in locating newer reserves of oil, gas and coal. In the longer term, emphasis should be to develop alternate forms of energy such as based on geothermal, nuclear, wind, tidal, solar and biomass. The lack of sufficient uranium reserves will have a strong bearing on the development of nuclear energy and we will be heavily dependent on external sources.

David Mackay in his recent book (www.withouthotair.com) suggests a number of alternate energy options. He suggests an equivalent of 1000 km by 1000 km squares in the desert would be enough to supply energy for every person in the world, if technological and logistical issues can be overcome. This means a day will come when the Rajasthan desert will become a source for perennial energy for India and the neighbouring countries!

An ultimate energy security worldwide could be the harnessing of fusion (fusing light nuclei like what happens in the Sun) – a realistic goal to some, a pipedream to others. In all these endeavours, the geologists will work more with the material scientists who will be demanding alternate raw materials in the forms of major and trace elements to develop fast breeder reactors or new energy saving photovoltaic batteries or iPhones. Geologists would be compelled to come up with plans to increase the production of rare earths (in fact, they are not rare, but difficult to extract) from the existing mines, which itself will lead to a catch-22 situation of environmental toxicity. We have seen how China, a Saudi Arabia of rare earths, is punishing Japan, a major investor in electronic goods, with its import restrictions on rare earths. Another major area that will demand attention from the Earth scientists is going to be the exploration of underground reservoirs and aquifers for carbon dioxide storage to offset the increase in green house gases in the atmosphere. I think this is going to be a major challenge, similar to the need for disposal of nuclear waste. It will be important not only to identify suitable sedimentary basins but also to monitor the leakage either by diffusion or through fissures and fractures. All these geo-engineering options require much research to understand their side-effects.

Cross-disciplinary approaches

Earth scientists need to apply cross-disciplinary, system science approaches to find simpler natural ways of sustainable solutions. The required disciplines are not only geologists, but also geographers, ecologists, oceanographers, engineers and social scientists. The next generation earth scientists would also be required to perform observational and numerical studies of the responses of natural systems to anthropogenic manipulations and see how the systems retain the essential degrees of natural freedom. Earth systems are complex by nature, which means they are intrinsically nonlinear, fractal and chaotic and exhibits self-organized criticality and non-Gaussian distributions of outputs[15]. Further, they are highly sensitive to feedback loops: negative feedbacks make the system stable whereas positive feedbacks lead to environmental instability[15]. The primary objective of such a system science approach would be to generate higher-end quantitative models on the interactive processes among atmosphere, hydrosphere, lithosphere and biosphere, and can be done only with pooling of resources from various disciplines and by collecting high quality observational data.

Geoscience practitioners have to take upon themselves the task of sensitizing the community about the key concept of feedback loops and their implications for the environmental stability. Society, in turn, will be able to make intelligent choices and devise newer ways of using geology in everyday planning and decision making, especially in the areas of toxic waste management, hazard mitigation, shrinking groundwater, increased water degradation and the risk due to the disposal of high-level radioactive waste. Consider the floundering plan to dispose of high-level radioactive waste under the Yucca Mountain, in the Nevada desert (USA). The scientific case for Yucca Mountain as a waste repository located in a sparsely populated desert state of Nevada was seemingly sound; a prognosis arrived at after more than 30 years of geological study. But project had to be shelved, pending the final decision from the Nuclear Regulatory Commission. A decision, critics allege, that is more to do with politics rather than science. More of such issues will raise their heads in our societies where the attention and the advice of the geologists will be constantly required on the basis of which communities will be forced to legislate more stringent environmental regulations[4].

Democratization of science and data accessibility

As every citizen is a potential stakeholder, the question of the role of lay public in science policy is being debated, especially when developments in the new generation sciences (e.g. nanoscience, bioscience and Earth science) have wide ramifications in human life. If the blog discussions on scientific issues like climate change are any indication, we are seeing the beginning of the democratization of Earth science. Thanks to the tools like Google earth, any curious adventurous amateur could explore and appreciate the wonders of the earth's surface, information previously guarded as secrets held by individual governments. Global comparisons using remotely located data are possible at a faster and cheaper rate due to the easy availability of the internet[1]. Lay persons are also going to get involved in all these issues due to the immediacy of the social implications of such problems.

A case in point is the recent discussion on the content of the thousands of e-mails and documents released without authorization from the University of East Anglia's climatic research unit. Here climate scientists were put on the defensive for their data handling. The issue related to the Himalayan glaciers included in the Fourth Assessment Report of the IPCC also attracted public attention and criticism, leading the IPCC to admit its oversight in quoting from a non-peer reviewed piece of literature that the Himalayan glaciers are retreating 'faster than in any other part of the world', and chances of them disappearing completely by 2030 is very high.

Another interesting blog discussion was between Robert Laughlin, a condensed matter physicist and a Nobel laureate with Milan Ilnycky, a man with a Master's degree in International studies (burycoal.com/blog/2010/07/19/robert-lauglin). It is educative to see how Milan Ilncycky questions and corners the Nobel Prize winner on his statement on climate change in the summer issue of the magazine '*The American Scholar*'. Laughlin made light of the global warming and argued that 'Earth will fix things in its own time and its own way', because according to him the geologic records show that Earth had gone through greater cataclysmic events and still it regained its balance. What this scientist has probably forgotten is that the Earth he was talking about was an Earth without humans, and the centrality of human welfare is the underlying key issue in the debate on climate change. In this case, a scientist of high calibre was questioned for his rather senseless statement on a blog by a lay person. The bottom line is that even Nobel Prize winners can be rather foolish outside the area of their specialization.

Along with democratization and public participation, the Earth sciences are also going through a globalization process where international collaborative programmes and unrestricted data sharing will become a norm rather than exception. In fact India has made a revolutionary break with its colonial past in enacting the 'Right to Information'. It is only logical to include in this the accessibility to scientific data. A fine example of open access is the Indian journal *Current Science*. Few leading scientific journals in developed countries have followed this model. Current Science's counterparts in the US (*Science*) and the UK (*Nature*) thus remain off-limits to most scientists in emerging economies. However, when it comes to open access to Earth science data, Indian Earth science needs to follow the fine examples set by US seismology and geodesy. To address hazards as international as tsunamis, there is no choice but to share all such data in real time. We should come of age by breaking out of the colonial mould and be forthcoming in sharing data and data products. I can see changes in the attitudes in many organizations. They have become more proactive in sharing and making Earth science data easily available. The Indian National Centre for Ocean Information Services (INCOIS) offers an excellent website through which all kinds of ocean data are made available. The Ministry of Earth Sciences (MoES) is also in the process of organizing all available data sources related to the atmosphere, geophysics, etc. in a similar fashion. It certainly encourages young minds to generate newer ideas. This bodes well for the Earth science research in the country.

Rapid advances in digital technologies and a concomitant increase in data generated through a variety of instruments and sensors are creating revolutionary changes in data gathering. According to a recent report prepared by the National Academy of Engineering and Institute of Medicine (of the United States), it is an important duty of all the stake holders to ensure the integrity and accessibility of data. Equally important is to find means to archive and index the data in accessible formats. India should wake up to this important aspect, and it is worth remembering that 'Earth and space science data are a world heritage', to quote from a position paper of the American Geophysical Union. A similar sentiment is also emphasized in the final report of the IUGG Working Group[16]. Here, India should immediately take steps in framing more liberal policies, which will in fact in the long run improve the Earth science research within the country. Any policy regarding data generation and storage should be grounded in an underlying philosophy of full and open sharing of Earth and space science data. The University of East Anglia debacle is also a pointer to the need for transparency in all the aspects of scientific research.

In search of new paradigms in solid Earth sciences: fundamental questions

According to the report on a workshop on Computational Geophysics held at Caltech in March 2009 the major paradigms that developed the solid Earth sciences to what it is today are 'essentially geodynamics concepts'[11]. The first of these paradigms is plate tectonics, the well-known processes that underline the crustal evolution. The second paradigm is centred on the mantle convection – the fundamental process that determines the planet's internal workings. The third paradigm, according to the report, is the 'dynamical relationship between faulting and earthquakes' and the geodynamo that controls and sustains the magnetic field forms the fourth paradigm. All researches in solid Earth sciences are grounded essentially on these paradigms. Although these paradigms explain varied Earth observations, it is worth remembering that there are many unanswered questions that impinge on these processes. We are still trying to resolve the linkages of geodynamics and other earth processes such as climatic evolution and variability and their association with the evolution of life. These challenges are certainly going to form the to-do-list for the 21st century Earth sciences.

A major issue in solid Earth science is that we still do not have a unified Earth model. This issue has been brought out nicely by Anderson[17] in the preface of his book, *New Theory of the Earth*. The fact remains that geologists, geophysicists and geochemists are still talking differently in spite of the emergence and success of plate tectonics theory. He points out that 'in spite of the fact that there is only one Earth, there are more Theories of the Earth than there are of astronomy, particle physics or cell biology where there are unaccountable samples of each object'. Seismologists and geochemists still talk differently on the mantle structure. While seismologists support whole mantle convection, geochemists favour layered convection. We are still away from the answers on the relative roles of pressure and temperature in the evolution of the Earth's mantle. The biggest challenge for the Earth sciences in the current century would be to bring together the diverse data and methodologies to bear on the unified model of the Earth.

There are unresolved issues with regard to workings of the geodynamo and the Earth's magnetic field. Much depends on the resolution of the initial conditions of the Earth. What was the nature of Hadean and Archean mantle? How do we map the thermal history and the heat budget of the Earth? Kelvin's heat paradox still raises some uncomfortable questions. Hutton's uniformitarianism does not explain all that had happened during the Earth's history. Some of the boundaries of the geological epochs epitomize major extraterrestrial catastrophes. There are many significant questions that need to be answered to reach a logically sound Earth model. Along with Earth-bound studies, planetary studies will also supplement our understanding of the evolution of the Earth. We have only scratched the surface and there is much to be done.

Challenges in solid Earth science research: Global scene

Recently, a group of US earth scientists authored a report on their view of the fundamental research topics for solid Earth sciences in the 21st century[7]. They identified 10 grand challenges.

1. Questions on the formation of Earth and sister planets: the consensus is that the planets evolved from a common nebular cloud, but we still do not know why the chemical composition of the planets differs. These questions require further study of solar system material like meteorites or lunar rocks or other extra-solar bodies.
2. The nascent stage of Earth's evolution – the first 500 million years – the Hadean Eon is still shrouded in mystery. This period witnessed a collision with another Mars like planet causing the debris to form the Moon and the Earth itself melted down to its core. This is the time when the atmosphere and the ocean probably developed. Are there any rocks from this period preserved anywhere, which would allow us to understand the earliest 'dark ages'?
3. One enduring question that challenges our civilization is about the origin of life. The breakthroughs in molecular biology provide ingenious models of elementary life. But the geology should now provide the answers on when, where and how did life emerge on the Earth. Mars could be a target planet where the sedimentary record, predating the rocks on the Earth, would preserve the earliest forms of life.
4. The Earth's interior has always been a subject of debates. It is known that the mantle and the core are

in constant convective motion. The core convection generates the magnetic field and the convection in the mantle facilitates global tectonics. We still are not in a position to build predictive models so as to know how this mechanism evolved and would evolve in the future.

5. Like life, plate tectonics seems to be unique to Earth. How did plate tectonics evolve and how is it related to the abundance of water, oceans, continents and life itself?
6. Macroscopic processes like plate tectonics and mantle convection are controlled by the microscopic properties of Earth materials at atomic levels. Understanding material properties is essential to make predictive models of the Earth and the planetary processes.
7. Earth's climate managed to maintain its temperature in a narrow range throughout her 4.5-billion-year history, making life possible. There were short intervals when climate went to extremes. Study of the geological archives on sudden climate change will help us to constrain these phenomena better.
8. The linkages of geology and biology have to be understood better. The questions include: What was the role of life shaping up the atmosphere? How weathering and erosion have shaped up earth surface? How did geological events cause mass extinctions?
9. Can earthquakes and volcanic eruptions be predicted? Although some impressive advances have been made on volcanoes, scientists still do not yet know whether occurrences of the earthquakes can be predicted in terms of exact place and time.
10. Our knowledge of fluid flow through both subsurface and surface mediums is still in its infancy. We lack excellent predictive mathematical models that would tell us how these natural systems will behave in response to fluid flow. Questions include how fast they flow, how they transport dissolved and suspended materials and how they are affected by chemical and thermal exchange with the medium.

Another parallel report titled, 'Grand challenges in Geodynamics' poses questions on the generation of plate tectonics, the thermo-chemical evolution of the mantle and core, role of water in tectonics and climate, dynamics of the continental roots, interiors and margins, earthquake dynamics, geology of the core–mantle boundary and origin of Earth's changing magnetic field[11]. To this list one could add the study of alternate Earths (extra-solar planetary interiors and their surfaces)[11]. This study will essentially look into the thermal evolution of the Super Earths, based mainly on spectra. The inferences will have implications on whether these extra-solar planets have plate tectonics and the atmosphere (CO_2-rich or not).

Reliance on quantitative modelling

Resolution of many of these questions will lead to the unified model of Earth. Future work will likely rely on numerical modelling as a tool to integrate observational and laboratory data in system processes. One may fairly assess that data modelling so far has attempted only the 'do-able models'. But, advances in technology might help us to change that situation. The quantitative techniques would certainly need high resolution numerical 3D codes, which require that the Earth science researchers work more closely with the mathematicians and modellers[18]. The IUGG report on future geoscience researches[16] specifically mentions that methods in continuous and discrete dynamical systems, stochastic processes, homogenization, ergodic theory, renormalization, inverse problems and quantification of uncertainty are required to address the problems in Earth sciences. The paradigmatic shift in computing from the conventional 'client-server' system to internet-based multiple systems is on the anvil. The new protocol called Cloud computing is going to usher an era of sharing data and processing codes from remote locations to unprecedented levels.

As Olson *et al.*[11] also point out in their report on grand challenges in geodynamics, the new generation students will require a broad understanding in advanced continuum physics, material science, mineral physics, fluid dynamics, thermodynamics and statistical mechanics, inverse theory, numerical methods and high performance computing, besides proficiency in geology, seismology and the environmental sciences (including ocean and atmosphere). To match the progress in computational techniques there will be an improvement in hardware resources. A major recent development in hardware is reported to be new GPU (Graphical Processor Unit) technology, which create many fold increase in computational power[11]. Of equal importance is the establishment of experimental facilities especially for geodynamics research. Global positioning satellites and satellite altimetry already facilitate Earth observation on a real-time basis.

Setting up research priorities in India

Building a culture

The recent vision document of the Indian National Science Academy emphasizes that: 'The pursuit of basic science is a fundamental expression of human activity. No national scientific enterprise can be sustainable in the long term if it does not contain generous room for curiosity-driven research. . .'[19]. With all the pressure that is likely to build up from society to deal with the questions on sustainability and global warming, Earth scientists should not lose sight on the fundamental research. The motivational strength, however, for conducting cutting edge research in Earth Sciences in India is rather weak.

There are cultural as well as structural reasons for that, and this problem may not be specific just to Earth science[20]. The mediocrity in Indian Earth science research has been discussed before[21]. How do we leapfrog this hurdle? What are the most compelling Earth science challenges in this century that have special reference to India? What are the major questions that Indian Earth scientists need to address in the coming decades?

All of the above issues should attract the highest degree of attention in India. A related issue is the languishing Earth science education in the country[22,23]. How do we attract the best minds in India to address the problems in Earth sciences? As the INSA vision document[19] pointed out 'the vitality of a scientific community springs from many sources. One lies in its capacity to identify, attract and nurture gifted individuals.... Another lies in its success in promoting a culture of science, which places premium on accomplishments'. I think professional societies have a key role in helping establish and nurture a culture of excellence in academic research in Earth sciences. There are many examples set by the American Geophysical Union and Geological Society of America in terms of open scientific forums accessible to students, researchers and teachers alike. One major mistake India made in the beginning was to isolate the research organizations from the universities. Throughout much of Western Europe and North America, the primary research work is carried out in Universities by both professors and the students we mentor. We have to find ways of linking these organizations with teaching and research in the universities.

It is also important that we think globally, which means while addressing the Indian problems we may have to step out of the national borders and set up experiments in other parts of the world (missions in Antarctica and Artic notwithstanding). A major issue that hampers such ambitious research programmes in India is the dearth of a motivated and capable group of younger generation researchers, a problem not specific to India alone. Time has come to open up the gates of educational institutes in India for the unrestricted entry of foreign students and faculty on a competitive basis; the interactive relations that could develop with the local students would improve the robustness of the educational system. It is heartening that the new recruitment policies of the Indian Institutes of Technology take this fact into account. And, what is required is a kick start that would energize the system in one go. We have to realize that Earth science has converted itself into a highly interdisciplinary endeavour akin to the transformation that impacted classical Biology.

Research priorities

A recent report by the MoES is a tentative step in identifying certain research areas for the coming decades[24]. In fact it should be expanded to bring out a vision document for the entire Indian Earth sciences community for the next century by identifying the most challenging areas in an Indian context. India is a fantastic natural laboratory for studying many of the surficial processes and geodynamic challenges that I have listed above. For example, the Himalaya offers the natural location to study the lithospheric deformation, the Andaman region can provide lessons on lithospheric dynamics and earthquake cycles and the Deccan Traps of central India could facilitate studies on magma genesis and fractionation. The Indian shield is an area where early Earth conditions remain fossilized and nothing much has been done here from these perspectives. What is the nature of suture zones and their imprints in the mantle below the cratons? The Bengal ocean basin with its enormous amount of Himalayan sediments can tell us not only about mountain building and climate evolution but also on the potential impacts on an ocean floor that is weighed down by thickening pile of sediments.

The landscape is a net outcome of two forcing mechanisms: climate and tectonics and there is always a 'chicken or egg' question that challenges the enquirer as is common to strongly coupled systems[25]. The Himalaya, a tectonically active mountain chain, responds to the heavy monsoon rain-induced erosion. The southern flank of the mountain which suffers the monsoon brunt grows in stature with concomitant increase in tectonic activity, internally resonated by the southward channel flow of deep crustal material from underneath the Tibetan plateau to the range front. Understanding the linkages between surface processes, mass fluxes, biogeochemical cycles and the landscape evolution is an area that needs attention in India. Some of these secrets are locked up in the deep ocean sediments.

India hosts many major earthquake sources and is ideal to host concerted programmes in earthquake studies. We have to identify two or three potential source zones and conduct focused geological and seismological studies in those areas. A widening window of opportunities exists in planetary sciences as the efforts on lunar and Martian studies continue to unfold in the years to come. The Indian Space Research Organization has already mapped out the exciting possibilities of planetary exploration including harnessing of lunar resources. The next mission to the Moon (*Chandrayaan-2*) is scheduled to be launched in 2013 and the Mars missions are also planned. Lunar studies should give us more information on the early Earth conditions. It is now known that Mars once had water or even oceans. It may have facilitated growth of life much before it started on the Earth. Who knows; it was probably brimming out with life in the early period. The next few decades are going to be a most exciting period for the planetary sciences. The students who come out of at least the elite institutes in the country should be able to take up these research challenges. It will also be worthwhile to ask the researchers themselves to come up with compelling questions that their sub-discipline can address in the next decade.

In the end

While we welcome the advances in experimental and theoretical aspects of Earth science research, it is worthwhile to remind ourselves that the core of the geosciences research will continue to be the direct observation of the Earth. Models have their limitations although they constitute the most important predictive tools for historical sciences. The computer models can determine only the consequences of a hypothesis under a small number of hypothetical conditions[26]. Whether it is regarding snow ball Earth or the extinction of dinosaurs, direct observations will continue to throw up surprises and field studies will continue to be the source of new discoveries leading to new boundary conditions.

Further, as Kastens *et al.*[15] put it, the field experiences provide the opportunity to develop a 'professional vision. . . and a community of practice', shaped by, and now embody, a distinctive suite of experiences, approaches, perspectives, and values', whether it is in a geology field camp, on a research vessel or in a spacecraft. In the end nothing beats the experience of identifying a meaningful geological feature amidst the 'visual complexity of nature', be it a fault or a rip current or a meteoritic crater. The human mind will continue to be most important single tool of generating explanatory narrative of Earth's evolution and processes, ever celebrating the Earth Science's unique mode of reasoning.

The current century will also probably put some of us (Indians or non-Indians) on the Moon and Mars, and we might see more mind dazzling geological field studies in such exotic locales. This will open up new vistas of celestial understanding and may answer some of the eternal questions on our context in the greater scheme of things. I hope excitedly that the astrogeologist, and a field geologist *par excellence*, Eugene Shoemaker's wish of banging an asteroid with a rock hammer may come to pass by the end of the 21st century. While his ashes on the lunar surface would be churned eternally by cosmic 'winds that blow through the starry ways', to use an imagery by Yeats, that intriguing English poet, the future beckons us to go beyond.

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