In this issue

Perspectives in Earth sciences – 2010

From the introductory article on the challenges in Earth sciences, it is obvious why we planned a special section titled, 'Perspectives in Earth sciences – 2010'. The lead article, which maps the progress of Earth science and attempts to show the direction in which this discipline might evolve, sets the stage for the succeeding papers in the special section. I wanted this section to be an eclectic mix of manuscripts both from the authors within India and outside that would reflect themes under the grand challenges. I wanted this section to be a showcase of some of the recent progress made in various fields mainly in solid Earth science with a slant towards the work in India, in view of the grand challenges of the 21st century. Often such lofty editorial ambitions get tempered over a period during which time many potential authors would choose to be stoic to the editor's pleas for contributions or go back on the promised deadlines. I may not be completely successful in bringing together all the interesting advances made in the recent past, but, the papers, as one can see, published in this issue manifest the future directions, in some key areas that would jive with some of the grand challenges, besides taking stock of the current status.

Simon Lamb and Tony Watts review (**page 1699**) the advances made in our understanding of the origin of mountains. How does the lithosphere deform to elevate the crustal material to such dizzying heights? What supports such gravity defying act of the Earth? The authors provide the current understanding of such issues. As one of the reviewers of this paper said, this paper not only makes an excellent review of the subject matter but it can also be used as tutorial material for the students. In the next article, Jeffrey Freymueller provides (**page 1719**) a well argued review on plate boundary deformation, based on recent insights gained from a variety of geodetic and geologic studies. The article touches on some topics that are continued to be debated. Ajay Manglik writes (**page 1733**) about the core-mantle boundary (CMB) region, a 200–300 km thick zone in the lowermost mantle bounded between the D″ discontinuity. This boundary plays a significant role in controlling the dynamical processes in the Earth's interior, both in the mantle and in the core. Binod Sreenivasan discusses (**page 1739**) various geodynamo models to explain the workings within Earth's core. Despite progress, there are many outstanding questions on the geodynamo processes such as nature of convection and turbulence in the outer core, field reversals, energy budget and the relation with core processes and the mantle dynamics. We expect to have better understanding on some of these issues from satellite missions and laboratory experiments. Ravi Kumar and Arun Singh present (**page 1751**) an overview of work that has been done to characterize seismic anisotropy beneath the Indian plate using splitting of SK(K)S phases and receiver function analysis and present interpretations of these measurements in terms of mantle deformation processes. The early Earth evolution is always shrouded in mystery. Much of the rock records of that interval (pre-Archean Hadean Period) may have all been destroyed. But meteoritic data, especially the short-lived radionuclides, have proven to be an archive to explore for clues to understand the early Earth – a key period during which time Earth's core and mantle may have been differentiated. G. Srinivasan (**page 1762**) marshals the data on those aspects and show how evolution of Earth and other planets can be constrained using such data. Rapid progress in Holocene monsoon reconstruction employing multiproxy signatures during recent years necessitates a critical review of the new advances and a current synthesis incorporating all new information. R. Ramesh *et al.* provide (**page 1770**) a review of the changes in the Indian monsoon during the Holocene, based on the data derived from various proxies. The geogenic arsenic pollution sourced mainly from the Himalaya has turned out to be a major health hazard in the deltaic areas of the Bengal basin. S. K. Acharyya and B. A. Shah discuss (**page 1787**) the geological setting and aquifer characteristics of the region. Deeper aquifers are relatively free of arsenic compared to shallow aquifers. Therefore, geological aspects are important as they help to find potential sources of arsenic-free water within the pervasive arsenic polluted Bengal delta. Satellite gravity missions (CHAMP, GRACE and GOCE) have contributed much to the understanding of the static and dynamic gravity field of the Earth. V. M. Tiwari *et al.* analyse (**page 1795**) GRACE satellite observations and terrestrial gravity data to demonstrate their applications in studying large scale geological features of the eastern Himalaya where little terrestrial data are available. Their 3D lithospheric density models bring out certain aspects of the structural features of the Himalayan Collision Zone (HCZ) with more clarity than what was available earlier.

The quality of the papers depends also on the standard of the reviews. Each paper in this section has been critically evaluated and many valuable improvements resulted from the reviewers' comments. I have been fortunate in getting the prompt support from the following geoscientists as reviewers. I thank Uri ten Brick (United States Geological Survey), Rolland Burgmann (University of California), Roger Bilham (University of Colorado), Jeffrey Feymueller (University of Alaska, Fairbanks), J. N. Goswami (Physical Research Laboratory, Ahmedabad), Maureen Long (Yale University), D. C. Mishra (National Geophysical Research Institute, Hyderabad), R. N. Singh (National Geophysical Research Institute, Hyderabad), M. S. Srinivasan (Banaras Hindu University, Varanasi), K. Gopalan (National Geophysical Research Institute, Hyderabad), Simon Lamb (University of Oxford), Brian Atwater (United States Geological Survey), Mary Lou Zoback (Risk Management Solutions, California), Michel Diament (Institut de Physique du Globe, Paris), Rajiv Nigam (National Institute of Oceanography, Goa), Hema Achyuthan (Anna University, Chennai), Jayanta K. Pati (University of Allahabad), Mark Jellinek (University of British Columbia), Prosun Bhattacharya (Royal Institute of Technology, Sweden) and John Paul (Memphis University) for their reviews. I also thank Kusala Rajendran (Indian Institute of Science, Bangalore) for promoting the idea of a special section on Earth sciences in *Current Science*.

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EDITORIAL

Arsenic, Bacteria and Mendeleev's Legacy

Gifts, especially when unexpected, are always a source of pleasure. A mischievous and much travelled colleague returned, a few days ago, from a 'working holiday' abroad and presented me with a tablemat, confidently asserting: 'This should help you learn even while you eat and drink'. The tablemat, marketed as part of a 'painless learning' programme had a beautifully produced version of the Periodic Table, laminated so that tea and coffee stains could be readily wiped away. There is something captivating about the Periodic Table, so central to chemistry and indeed, the study of all materials. Biology and life seem to need very few of the over one hundred elements so colourfully depicted in modern versions of the Periodic Table. A handful is all that is necessary to wade through a biochemistry course; hydrogen, carbon, nitrogen, oxygen, phosphorus and sulphur are the major actors, with a few other elements playing limited, albeit essential, roles. Even as I admired my new possession, I could not resist returning to a favourite essay, 'Mendeleev's Garden', in which Oliver Sacks describes his childhood fascination with the elements. In Sacks' words: 'I was convinced that the Periodic Table was neither arbitrary nor superficial, but a representation of truths which would never be overturned, but would on the contrary, continually be confirmed, show new depths with new knowledge, because it was as deep and simple as nature itself. And the perception of this produced in my twelve year old self a sort of ecstasy, the sense (in Einstein's words) that "a corner of the great veil had been lifted" '. (*Uncle Tungsten: Memories of a Chemical Boyhood*, Vintage Books, New York, 2001, p. 211). Having drifted away from the diversity of chemistry over the years, the Periodic Table began to evoke memories of long forgotten courses, where the neatly arranged rows and columns of elements seemed so important. Even as I was musing on the past, my attention was drawn to a report that announced the discovery of 'A bacterium that can grow by using arsenic instead of phosphorus' (Wolfe-Simon, F. *et al.*, *Science*, 2 December 2010; doi:10.1126/science.1197258). This report appeared to dramatically overturn many long held ideas about the chemistry of life. Although we learn that 'six elements make up… the bulk of living matter', the authors note that, 'it is theoretically possible that some other elements in the periodic table could serve the same functions'. I was immediately reminded of a formidable teacher, in the years that I learnt a little chemistry, who would demand aggressively that students answer the question: 'why is silicon not widespread in nature's chemistry although it lies directly below carbon in the periodic table?' I heard this question at a time when science fiction formed the staple of my reading. It seemed so tempting to think of aliens on a far removed planet surviving happily on a silicon enriched and carbon depleted environment. The elements, at first glance, seem so replaceable in Mendeleev's columns, especially if the, often uncomfortable, niceties of chemistry are ignored. The report by Wolfe-Simon *et al.* seemed to raise an interesting question: can arsenic substitute for phosphorus in the chemistry of life? The paper describes a bacterium, somewhat mysteriously called GFAJ-1, which was isolated from a lake in California, which 'is a hypersaline and alkaline water body with high dissolved arsenic concentrations (200 μM on average)'. While in its natural habitat GFAJ-1 undoubtedly has adequate access to phosphate as a nutrient, Wolfe-Simon *et al.* report growing the bacteria in arsenate enriched media, apparently devoid of phosphate. Using the device of increasing arsenate enrichment in the medium, through successive transfers, these authors suggest that the bacterium can 'exceptionally ... vary the elemental composition of its biomolecules by substituting As for P'.

Arsenic is not a popular element. In recent times arsenic toxicity has been a subject of great concern following the contamination of groundwater in Bangladesh, West Bengal and several other locations. In the world of fiction and theater, arsenic was often a poison of choice, with the Broadway play 'Arsenic and Old Lace' being a great hit, converted into a movie in the 1940s. The question of whether Napolean was murdered on St. Helena by arsenic poison has intrigued forensic researchers since the 1950s. Most recently, neutron activation analysis has weighed in against the theory of poisoning. Arsenic, ironically has also been central to the development of chemotherapy and medicinal chemistry. Paul Ehrlich's Nobel lecture in 1908 describes the successful use of arsenic compounds as trypanocidal agents; the first triumph in developing molecules that kill trypanasoma, the parasites responsible for African 'sleeping sickness'. Salvarsan, the first drug for syphilis was another of Ehrlich's discoveries; the result of years of painstaking studies of arsenicals. Despite ushering in the dawn of chemotherapy, arsenic chemistry has not been a glamorous area of research. As I read the

Wolfe-Simon paper, I wondered if this was about to change. If there was compelling evidence for arsenic incorporation into DNA, RNA and ATP would not the tide turn in favour of this relative of phosphorus? Were we about to see a surge of interest in the chemical biology of arsenic? At first glance the paper had all the trappings of modern chemical analysis. The list of techniques used to estimate arsenic in cellular fractions is impressive: inductively coupled plasma mass spectrometry (ICP-MS), nanosecondary ion mass spectrometry (nano SIMS) and synchrotron X-ray using micro X-ray absorption near edge spectroscopy (μXANES). To the average reader, and I must count myself as one, the apparent sophistication of the analytical methodology used must seem reassuring. However, no individual, isolated class of metabolites is analysed in this report. In a surge of optimism, the authors conclude that arsenic atoms have indeed been substituted into the DNA backbone, replacing phosphorus. They go on to add that the arsenylated analogs of a whole host of intracellular molecules are indeed present. They conclude in intriguing fashion: 'How arsenic insinuates itself into the structure of biomolecules is unclear, and the mechanisms by which such molecules operate are unknown'.

The 'arsenic bacteria' paper might have taken some time to attract attention. However, a press release from NASA served to catalyse a remarkable flurry of interest. The space agency, somewhat unwisely, proclaimed: 'NASA-funded astrobiology research has changed the fundamental knowledge about what comprises all known life on earth'. The press release was emphatic: 'The finding of an alternative biochemistry makeup will alter biology textbooks and expand the scope of the search for life beyond Earth'. If I had been forty years younger I might have conjured up visions of arsenic eating Martians, whose very breath was toxic to humans. Unfortunately, age blunts the imagination. The seeds of doubt that must have germinated in the minds of many readers of the *Science* paper quickly found expression in the ever expanding universe of blogs on the internet. A storm of criticism began to appear, with every piece of experimental data being publicly dissected. From bacterial growth curves to X-ray absorption near edge spectroscopy, almost no piece of reported data was exempt from the process of deconstruction. The blogs, and there are many, are both instructive and entertaining. It is here that I was reminded of Frank Westheimer's thoughtful and reflective analysis on 'Why nature chose phosphates' (*Science*, 1987, **235**, 1173). Could nature have used silicates or arsenates? Westheimer noted that arsenate esters breakdown so rapidly in aqueous media that arsenic could hardly provide the requisite stability for the essential molecules of biochemistry. In the concluding section of his commentary Westheimer returns to an oft asked question: 'Why have the choices made by chemists in the laboratory been so strikingly different from those made by nature in living cells?' His answer: 'We can understand the choices made by chemists and by natural selection. They are both correct'.

Ignorant as I am of Twitter and the joys of tweeting and as a bemused entrant to the world of blogs, I found the rapidity and scale of the attack on the Wolfe-Simon paper astonishing. The power of the new media for communication and the rapid nucleation of networks of interested readers are indeed remarkable. Less than a week after the online appearance of the paper, the evidence for biomolecules with arsenic in their backbones seemed to be evaporating, under the heat of technical criticism. NASA blundered in a manner characteristic of governmental agencies worldwide, when it declined to engage the critics in discussion. The reason cited was that it would be inappropriate to debate the results in a paper published in one of the 'most prestigious scientific journals', with bloggers who could hardly qualify as peers. The response was overwhelmingly critical of NASA's 'we know best' attitude. I found the argument, that prepublication refereeing is really 'just a quality filter' while post-publication reaction is 'true peer review', compelling. All the responses to the Wolfe-Simon paper are not negative. GFAJ-1 may turn out to be another wonderful example of adaptation to an extreme environment, revealing new ways by which the microbe handles arsenic. The focus on arsenic may also revive interest in chemotherapy using arsenic trioxide and the biochemical mechanisms involved (Kroll, D., 4 December 2010, cenblog.org/terra-sigillata). The Wolfe-Simon paper appears to be a case where a seductive hypothesis has enthralled a group of enthusiastic researchers. In biology, as practiced in India, I often hear that all good research must be hypothesis driven. There is sometimes a danger in this approach. Researchers can fall prey to the temptation of designing and interpreting experiments to prove a pet hypothesis. Critical control experiments can be overlooked, often overwhelmed by the desire to sustain an engaging hypothesis. This indeed seems to be the trap into which the authors of the 'arsenic eating bacteria' paper have fallen. They may yet resurrect the story they have presented, if the presence of arsenic in place of phosphorus is convincingly demonstrated in DNA isolated from the bacterium.

In thinking of hypothesis driven research and the oft reviled, observational approach to science, I was struck by the fact that two great intellectual syntheses of the 19th century were indeed based on painstaking observation and intense reflection; Darwin's principle of natural selection, as the driver of biological evolution and, Mendeleev's conception of the Periodic Table, as the central organising structure of chemistry, both of which are valuable in thinking of the Wolfe-Simon paper. Arsenic is an element that has never been at the centre stage of modern chemical research. The bacterium GFAJ-1 has provoked a surge of interest in the chemistry of arsenic. Looking down at my tablemat, which so concisely displays Mendeleev's legacy, I could not but help wonder if other elements will also emerge from the shadows.

P. Balaram