active beneath the sea[1]. This statement applies to all primary gold deposits in the Archean greenstone belts the world over. These greenstone are the metamorphosed equivalents of basalt, andesites, etc. of volcanic origin. The best examples in India are the Kolar and Hutti gold belts.

Some examples from ground realities are the following: (1) The uranium-bearing quartz pebble conglomerates have gold associated with them at the following places in Orissa[2] – Mayurbhanj district (0.2 to 0.8 g/t) and Keonjhar district (1.0 g/t). (2) In the Jaduguda uranium mines in Singhbhum shear zone, gold is an associated metal in the range of 1.5 to 4.58 g/t (ref. 2). (3) In the Chikkamagalur district (Karnataka) at the base of the Bababudan iron ore formation, uranium and pitchblende occur as detrital grains along with gold[3]. (4) Uranium and thorium are associated with gold in the well-known pyritiferous quartz pebble conglomerates in the Rand gold mines in South Africa. (5) Boyle[4] suggested uranium and gold association at several auriferous tracts all over the world. Some important areas are Canada (Au, U deposit at Claff lake, Saskatchewan), Mexico (Guadalupe), USA (Plumas country, California), and Australia (Jubiluka U, deposit in Northern territory).

In the light of the above evidences on the common association of uranium and gold, it is suggested that in Meghalaya an attempt may be made to evaluate the gold contents also of the pyroclastics. The gold may or may not be of any economic significance, but it will confirm whether the pyroclastics are auriferous or not. Since the Atomic Minerals Division (AMD) has a regional office at Shillong, it should not be difficult to determine gold content of the pyroclastics. This will not only enhance the importance of the AMD investigation but also throw light on the source of gold in Brahmaputra river which drains the northern part of Meghalaya.

1. *Gold News*, March/April 1999.
2. Radhakrishna, B. P., *Gold in India*, 1999, p. 143.
3. Radhakrishna, B. P., *Mineral Resources of Karnataka*, 1996, p. 160.
4. Boyle, R. W., *The Geochemistry of Gold Deposits*, 1979, p. 138.

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Reply

We are thankful to the suggestions made by J. V. Subbaraman. Though the genesis and age of the uranium deposits referred by him are different, however, association of uranium with gold is well-known. Our discovery of pyroclastics in the Mahadek Formation attributes volcanogenic character to the uranium mineralization and volcanoclastic nature to the sediments. Therefore, we also suspected the presence of gold, silver and other volcanogeic metals. We have sent some samples for analyses and the results are yet to be received.

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RESEARCH NEWS

Deformation-assisted percolative core formation in early earth

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The earth was formed from accretion of bodies or planetessimals of the solar system 4.55 billion years (b.y.) ago. In course of time, these bodies melted and differentiated to form the core, mantle, crust and atmosphere. The earth's core, which is 3400 km in diameter, is essentially made up of iron, its inner 1300 km being solid and the outer 2100 km being liquid. Silicate mantle with a thin outer crust surrounds the core (Figure 1). Though many of the models advanced on the earth's evolution have helped to understand the early thermal history and its role in the development of the internal structure particularly of the core, some aspects of the growth of the latter still remain only vaguely understood. For example, the classic view visualizes that the earth underwent homogeneous accretion, wherein the impacting silicates and metal alloys were mixed before melting and separation of core-forming elements. But, how the accreted planetessimals of silicate and metallic composition melted in the first place, and what mechanism brought about the partitioning of elements from this melt to form the metallic core are still under considerable discussion. This is understandable since these events that took place so very early in the earth's history have left hardly any direct or unambiguous evidence. Various theories, therefore, about the earth's primordial differentiation have come mainly from experimental work on the behaviour of elements under high pressure and temperature, as well as through geochemical studies on deep mantle samples[1–6]. Undoubtedly these have provided insights into the physics and chemistry

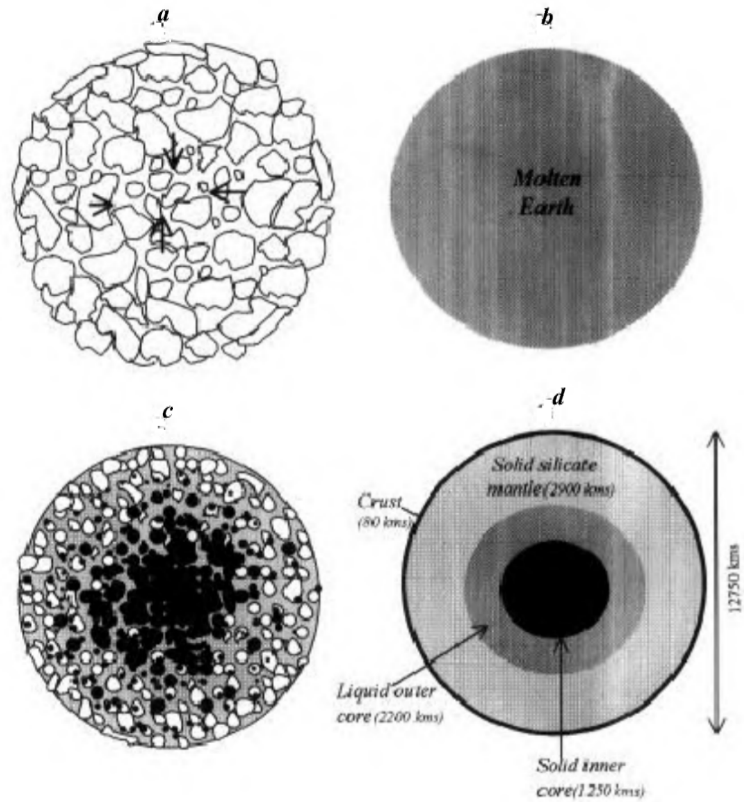

Figure 1. Classic view of formation of earth's interior. (***a***) accretion of planetessimals leading to (***b***) production of a molten earth and differentiation by (***c***) gravitational sinking of metals like Fe, Ni, Co, noble metals, etc. (black circles) to form the core and separation of crust-forming elements like Si, Al, O, K, Rb, REE, etc. (clear circles and other forms) towards surface, and (***d***) internal structure of the present earth.

behind the evolution of the earth's inner structure. At the same time, they have also highlighted a few puzzling facts, for example, the unexpected solar abundance ratios of certain siderophile and refractory lithophile elements in the earth's deep interior disagree with normal differentiation trends as well as with the data from high-pressure partitioning experiments.

Though the melting of planetessimals and separation of elements are accepted as essential requirements for the earth's early differentiation, there has been no unanimity among scientists about how and at what stage of protoearth's evolution these developments took place. One view considers that early earth underwent steady increase in its internal temperature through impacting planetessimals as well as from heat released by the decaying radioactive elements in them. This rise in temperature, at certain point of time, was high enough to melt the metallic minerals and alloys at a depth of 400 to 800 km. These minerals and alloys with low-melting point but having high melt density, could easily segregate gravitationally towards the centre of earth to form the core[2,3,7] and the processes are believed to have happened by the time the earth was 1 b.y. old. Another view considers the earth to have melted while the accretionary process was still active. The kinetic energy of the impacting bodies, most of them large and massive, was sufficient to keep the earth melted partially throughout or perhaps repeatedly, to form an ocean of magma[6,8]. Core formation is thought to have commenced when the earth reached a radius of about 3300 km (half its present size) and one-tenth the present mass[9,10], through separation of melts of iron and its alloys by liquid immiscibility. The latter Fe, Ni and Co-rich melts moved gravitationally to the base of the magma ocean and accumulated at the junction of present upper and lower mantle[6]. After equilibration with silicates there, the molten layer sank diapirically to the centre of the planet to form the core (Figure 2 *a*). All these processes are believed to have been completed 4.55 b.y. ago[5,6]. Apart from these processes, it is believed that significant quantities of the impacting planetessimals, which had already differentiated extra-terrestrially to core-forming metals, may have settled into the earth's core directly without interacting with the silicates[1].

Now, a mechanism of core formation by percolation of metallic melts through solid matrix, proposed[11] as early as 1963 but rejected as unfeasible, is again getting attention. Unlike the other processes, percolative core evolution does not invoke development of a magma ocean followed by geochemical fractionation of elements. Instead, the metallic melts, the first to form in early earth undergoing steady heating, are believed to have trickled through the solid silicate grain matrix towards the centre of the earth to form the core. But, this mode of drainage is known to be effective only if the melt can wet the edges of the solid silicates. This wetting property or simply surface tension is controlled by molecular forces in operation between the boundaries of the phases in the system – here the solid (silicates) and molten (Fe, Ni) phases. In fact, several experiments conducted to study this vital property have confirmed that such percolation through solid silicate matrix is not possible since these high-density melts have high surface energies relative to solid/solid and solid/melt interfaces, which prevent wetting and interconnection of melt pockets to enable the flow[12–15].

Studies at a pressure range of 2 to 20 GPa, on interfacial energies in two-phase systems that can develop during melting of early earth have stressed the important role of geometry of the melt with respect to the solid grains. Expressed as the dihedral angle θ or the angle between two neighbouring grains, this is determined by the interfacial energies of solid surface/melt surface relative to solid/solid interfaces in the matrix[15,16]. When θ is $> 60°$, due to large relative values of solid/melt interfacial energies, the melt does not wet the grains, but when the value decreases to less than 60°, even at small melt fractions, interconnection of melt pockets through wetting is achieved and percolation becomes possible. The experiments have revealed that this dihedral angle for liquid alloy in solid matrix at a pressure equivalent to the earth's upper mantle, is on an average 108°, which is too high for percolation and hence the melts remained isolated at junctions between the solid minerals (Figure 2 *b*). This mechanism of core formation was, therefore, not favoured as a viable process except under certain conditions that can bring about decrease in the melt/solid interfacial energy and induce wetting of the grains, like when the melt fraction is very high or when under increased pressure or in the presence of small amounts of oxygen and sulphur which can reduce the surface tension of liquid iron[9,15]. Recently, the various physical restraints to wetting and percolation were reinvestigated under a revised set of experiments incorporating conditions close to real mantle. They have shown that percolative core formation through solid silicate matrix could indeed have taken place in early earth aided by deformation-produced channels[16].

The latest study by researchers at the University of Minnesota (USA) has brought to light an important aspect overlooked by earlier workers studying melt percolation through solid matrix. They had kept static mantle conditions in their experiments, whereas in nature, the mantle is dynamic with upwelling and downwelling convection currents set in motion due to high thermal gradient prevailing between its upper and lower portions. The researchers at Minnesota argued that the resultant density differences between the cold (more dense) upper portions of the mantle and the hot (less dense) lower portions would generate differential buoyancy forces, which could trigger shear stresses within the mantle. Considering the fact that the earth was hotter early in its history, these buoyancy forces must have been quite active to develop shear channels extensively and assist melt drainage through interconnection of the isolated melt pockets[16,17]. In fresh experiments, keeping mantle conditions dynamic, the Minnesota team subjected a mixture of metal (Au, Fe–Ni–S) and polycrystalline olivine to high pressure and shear stresses at 1250°C in gas medium apparatus. They found development of different types of microstructures with a characteristic value of θ ~30°, exhibiting distinct alignment of melt pockets. The deformation of the mineral grains led to the elongation of trapped melt pockets, aligning them along directions of grain orientation and establishing their interconnection to enable drainage (Figure 2 *c*). The team concluded that such deformation-assisted percolative core formation must have been a viable process operating during early earth times. Pertinently, they have drawn attention to the speculation that the core of Mars may have formed through such percolation of melts, a view that has gained currency after recent discoveries of several shear stress channels and lineations, all believed to be associated with active plate tectonism in the planet's early history[16,18,19].

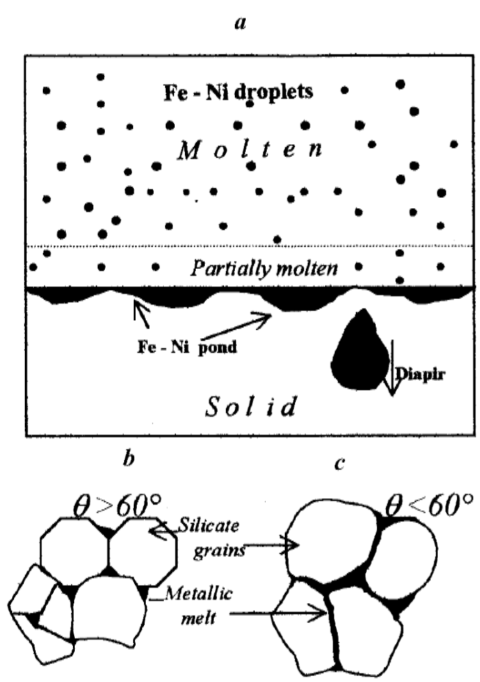

Figure 2. Mantle–core formation outline. ***a***, Fe–Ni alloy droplets (black dots) separate from magma ocean to form an alloy pond at the base of the ocean and later descend diapirically into the developing core (adapted from ref. 4); ***b***, non-wetting metallic fluid remaining isolated at the triple junction of silicate grains where θ > 60°; ***c***, Interconnection of metallic melt pockets and their percolation through solid matrix into the growing core where θ < 60° (***b*** and ***c*** adapted from ref. 14).

The significance of the deformation experiments is that it envisages core-forming metal segregation in early earth without invoking silicate melting to form an initial magma ocean. In fact, some geologists have argued against this ocean magma concept in view of solar system abundance ratios (as in chondrites) exhibited by some siderophile (Ni, Co) and refractory lithophile (Sc, Sm) elements in deep mantle samples[20,21], a feature unlikely to prevail after fractionation of the magma ocean. But subsequent workers[4,22,23] have justified such chondritic abundance ratios after experiments with Allende CI chondrite (known for its primitive composition). They have shown how siderophilic elements like Ni and Co become less siderophilic under high pressure (20 GPa) and temperature (2800°C) and can attain metal–silicate equilibrium at 28 GPa, the value at upper mantle–lower mantle junction. This geochemical change, they claim, explains the solar Ni–Co ratio in the mantle samples. Further, such abundance is also possible under certain conditions like entrapment in the magma which is considered to have crystallized and not fractionated, leaving refractory lithophile and siderophile elements at chondritic abundance ratios[6,10,24]. Nonetheless, a number of questions still remain unanswered. For example, could it be possible that the core-forming metals that had equilibrated, segregated and collected at the bottom of the magma ocean as a layer, may have traversed later through the solidified and possibly sheared core–mantle boundary zone by percolation? Such a process would satisfy both concepts of core growth. Or, did the core evolve through different routes at different times? Only future experimental studies can answer these enigmas and unify many of the existing postulates.

1. Murthy, V. R. and Karato, S., *Phys. Earth Planet. Inter.*, 1997, **100**, 81–95.
2. Ringwood, A. E., in *Origin of the Earth* (eds Newsom, H. E. and Jones, J. H.), Oxford University Press, 1990, pp. 101–134.
3. Murthy, V. R., *Science*, 1991, **253**, 303–306.
4. Li, J. and Agee, C., *Nature*, 1996, **381**, 686–689.
5. Karato, S. and Murthy, V. R., *Phys. Earth Planet. Inter.*, 1997, **100**, 61–79.
6. Drake, M. J., *Geochim. Cosmochim. Acta*, 2000, **64**, 2363–2369.
7. Walter, M. J., *Nature*, 1996, **381**, 646–647.
8. Wetherill, G. W., *Science*, 1985, **228**, 877–879.
9. Stevenson, D. J., in *Origin of Earth* (eds Newsom, H. E. and Jones, J. H.), Oxford University Press, 1990, pp. 231–249.
10. Tonks, W. B. and Melosh H. J., in *Origin of Earth* (eds Newsom, H. E. and Jones, J. H.), Oxford University Press, 1990, pp. 151–174.
11. Elasser, W. M., in *Earth Science and Meteorites* (eds Geiss, J. and Goldberg, E.), North Holland, Amsterdam, 1963, pp. 1–30.
12. Von Bergen, N. and Waff, H. S., *J. Geophys. Res.*, 1986, **91**, 9261–9276.
13. Ballhaus, C. and Ellis, D. J., *Earth Planet. Sci. Lett.*, 1996, **143**, 137–145.
14. Minarik, W. G., Ryerson, F. J. and Watson, E. B., *Science*, 1996, **272**, 530–533.
15. Shannon, M. C. and Agee, C. B., *Geophys. Res. Lett.*, 1996, **23**, 2717–2720.
16. Bruhn, D., Groebner, N. and Kohistedt, D. L., *Nature*, 2000, **403**, 883–886.
17. Walter, M. J., *Nature*, 2000, **403**, 839–840.
18. Connerney, J. E. P., *Science*, 1999, **284**, 794–798.
19. Gaetani, G. A. and Grove, T. L., *Geochim. Cosmochim. Acta*, 1997, **61**, 1829–1846.
20. Kato, T., Irfune, T. and Ringwood, A. E., *Geophys. Res. Lett.*, 1987, **14**, 546–549.
21. Kato, T., Ringwood, A. E. and Irfune, T., *Earth Planet. Sci. Lett.*, 1988, **89**, 123–145.
22. Righter, K., Drake, M. J. and Yaxley, G., *Phys. Earth Planet. Inter.*, 1997, **100**, 115–134.
23. Tschauner, O., Zerr, A., Specht, S., Rocholl, A., Boehler, R. and Palme, H., *Nature*, 1999, **398**, 604–607.
24. MacFarlane, E. A., Drake, M. J. and Rubie, D. C., *Geochim. Cosmochim. Acta.*, 1990, **57**, 5161–5172.

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From the archives

CURRENT SCIENCE

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History of Science as related to civilization*

Although the current century has witnessed a greatly increasing occupational absorption of men trained in various branches of science, their fraction of those engaged in all employments taken together must remain very small. It is therefore reasonable to ask, is it profitable for the State to provide an expensive form of school-training framed as if all those who receive it were embryo professional scientists? There can be no question that every individual who is privileged to vote should have some knowledge of the fundamental relation of science to the State, but cannot this be conveyed without giving him at the outset a training he might expect to receive if destined to embark on a scientific career?

*Sri Krishnarajendra Silver Jubilee Lecture by Sir Martin Forster, F.R.S.

The basic idea underlying the new movement is that a more generally useful approach to scientific method and scientific ways of thought is the historical one. Every intelligent mind finds attraction in biography, because when faithfully presented this offers the encouraging picture of shortcomings besides virtues, and thus makes us feel more at home even with outstanding personalities. An honest biography levels while it stimulates, and if with these effects the true bearing of science on civilization be conjoined, this form of instruction can be made most fruitful. It fortunately happens that the history of science, more readily than general history, lends itself to this treatment because its duration, or at least the period of most flourishing development, extends over little more than a century. Consequently its basic facts are more surely ascertainable, many being within the recollection of living people. If this advantage were applicable to general history, much of the rubbish unseasonably uttered about the superiority of the 'good old times' would be self-condemned, and much of the discontent prevailing now, as it has prevailed throughout the history of the world, being avoidable, might be avoided.

In designing a course on the history of science appropriate for students who will not for the most part become specialists in science it will be desirable to select the biographies of men whose discoveries may be definitely correlated with improvement in our ways of living and our outlook on life. If examined from this standpoint the whole subject will yield some surprises. Let us take an example that was very much in all our minds two years ago, being the centenary of Michael Faraday's discovery of electro-magnetic induction on 29th August 1831. It has been claimed that 'no other experiment in physical science has been more fruitful in benefit for mankind'. All scientific men will agree that the claim is defensible, but the biography of Faraday may be less impressive in a course of science-history for the normal student than it is for the professed scientist. Because although his experiments were fundamental, an equally fundamental experiment in the same field had been made by the Danish philosopher Oersted in 1820, he having in that year discovered that a magnitude needle is deflected by a voltaic current; while several other contemporaries of Faraday, notably Arago, Ampère and Humphry Davy were fruitfully engaged in similar studies. In fact, Sir Ambrose Fleming has recorded that 'nothing is more remarkable in the history of discovery than the manner in which Ampère seized upon the right clue which enabled him to disentangle the complicated phenomena of electrodynamics and to deduce them all as a consequence of one simple fundamental law, which occupies in electrodynamics the position of the Newtonian law of gravitation in physical astronomy'.