with its highly diversified geomorphology, hydrology, chemistry, and climate. For example, my recent preliminary work on the Indian stygofauna has brought to light the order Bathynellacea[8], which has remained unreported from South Asia; the copepod family Parastenocarididae[9] which was hitherto unknown from India, and a host of new taxa, which are yet to be described and published. The Indian stygon thus holds a huge serendipitous potential not only for taxonomists and phylogeneticists, but for ecologists, physiologists and other interested biologists as well. All in all, stygology deserves to be treated and pursued as a distinct branch of biology.

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RESEARCH NEWS

Recent concepts about heat source from the earth's core

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Heat from the interior of the earth is basic for several geological processes like plate tectonics, earthquakes, volcanism, mountain-building and more importantly, for propelling the geodynamo creating the magnetic field. The earth's heat energy is believed to arise from the decay of radioactive elements present in the crust and the mantle, from primordial heat that is still left and from the secular cooling of the liquid outer core. Terrestrial heat flow is estimated to be about 45 TW (1 TW = 10^{12} W) and of this, radioactive heat, which must have been much more in early earth times, accounts for about 30 TW presently. When the total heat flux at the surface is budgeted, it is found that it is about twice that can be produced by K, U and Th in the silicate portion of earth. The source of this excess heat is thought to arise from concentration of radioactive elements in the lower mantle. But now, experimental studies indicate that at least a part of this excess heat may be accounted by K as well as U and Th in the earth's core where, hitherto, their presence according to their conventional geochemistry, was not expected.

The 3500 km thick core lies deep in the interior of the earth, beyond the mantle zone and carries a third of the total mass of the planet, but forms hardly 14% by volume. It is liquid in its outer 2100 km (outer core) and solid for the rest of the 1400 km (inner core; Figure 1 *a*). Apart from these features regarding its structure, which is fairly well made out, quite a few other aspects of the core have remained enigmatic and not fully understood. Even though some pertinent inferences have been deduced from comparative studies on meteorites, from seismic data and through several laboratory experiments and computer simulations, answers for instance, on the age of core formation, its density deficit, source of heat, anisotropy and spin of inner core are still controversial. Compositionally, the core is supposed to be essentially iron or iron–nickel compound and the inner core of solidified iron, and according to some[1], it is nickel silicide. However, for such a composition, the density of the core is about 10% lower than it should be, a disparity that is attributed to incorporation of certain low-density elements during its formation. Though the normal geochemistry of such light elements – H, Si, O, S, K, Mg and C – forbids their presence in the core, experiments on the solubility of some of them demonstrated feasibility of O, S or alkali-metals to exist in the core[2–4].

Core formation was the first major event to take place in the earth's evolution. Current views consider that the kinetic energy of the impacting accreting bodies was sufficient to heat up the earliest earth to a partly or completely molten state, even as the accretionary phase continued[5,6]. As a result, all elements

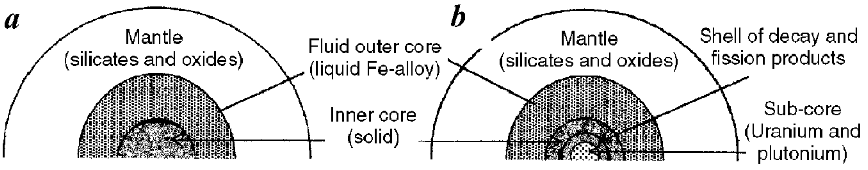

Figure 1. Two views of the core: ***a***, Traditional view with inner core consisting of solid iron or iron and nickel surrounded by a fluid outer core of iron and nickel, plus one or two light-density elements; ***b***, Georeactor model with inner core of solid nickel silicide enclosing a sub-core of uranium with decay and fission products.

present in the materials that accreted were incorporated into this molten sphere, which differentiated in the course of time. Dictated by the geochemical preferences, these elements partitioned into the new phases that formed in this melt. Certain elements belonging to the siderophile group (Fe, Ni, Co and noble metals) having strong affinity for the metallic Fe-phase that developed first, separated from the melt along with iron to form the core. Other elements like Al, Si, Mg, alkali elements, halogens, REE, U and Th, that remained in the essentially silicate-oxide melt left behind after the segregation of core forming elements became part of the early or primitive mantle[7]. While the depletion of iron along with other siderophile elements from such a mantle is expected, the observed deficit in a few of the non-siderophile elements, particularly the alkali metals, were baffling. Initial explanations attributed this to their low volatility and escape during early earth times. But, recent experiments[3,4] suggest that one or more such elements could have as well entered the core, and which also explained the observed density deficiency of the core. In experiments carried out in 1996, it was shown how the non-siderophile alkali metals like K, Rb and Cs, which normally do not combine with core-forming transition metals like Fe, Ni or Co, do so under high pressures and can enter the core[3]. Subsequent studies also found that K and Na preferred to enter the Fe-phase in the presence of sulphur in the early core-forming liquid[2] and this reaction transported, besides the alkali metals, significant amounts of another core lightening element – oxygen[2,4].

Cooling of the outer core of Fe-rich fluid alloy led to solidification of Fe, which gravitationally sank to form the solid inner core. This process released latent heat and at the same time, liberated the alloyed light constituents. The heat arising from the inner core set large-scale fluid motion or convection in the liquid outer core. This convection resulted not only from the thermal buoyancy forces arising from latent heat of crystallization of the inner core, but also from compositional buoyancy from the liberation of light elements during solidification of the inner-core[8,9]. According to the traditional explanation, these convective motions of the electrically conductive iron transferring the heat to the mantle layers, were fairly rapid and operated the geodynamo creating the earth's magnetic field.

The earth's geodynamo appears to have been in operation producing the magnetic field from very early geological times. This inference is derived from the records of magnetization acquired by Fe-bearing minerals in igneous rocks (orientation of these minerals along the earth's prevailing N–S magnetic axis, i.e. palaeomagnetic data) that had congealed during those geologic periods. Oxidized magnetic mineral – hematite (Fe_2O_3), in 3.45 b.y. old dacitic rocks (volcanic equivalents of granodiorites) belonging to the early Archaean member of Pilbara Craton, W. Australia[10], has preserved palaeomagnetic poles that prove the existence of geomagnetic field at least by 3.5 b.y. ago. This would suggest that core separation must have taken place rapidly, soon after the earth was formed, an inference agreeing with thermal history of the core computed as a function of heat flux conducted to the mantle through time[11]. However, estimating the age of formation of the core is a topic that has generated considerable research activity and interpretations based on highly reliable Hf–W chronometry, which have yielded ages between 10 and 50 m.y. within the earth's accretionary history[12,13].

The contrasting geochemical behaviour of Hf and W during core formation is well-suited to date some of the early earth events like core formation. Hf is lithophile and prefers to stay with the silicate phase (mantle), while W is moderately siderophile and prefers the metallic phase forming the core. This behaviour results in large fractionation of Hf from W between the silicate mantle and metallic core. The decay system of ^{182}Hf, with its short half-life of 9 m.y., decaying to ^{182}W which drains into the core, therefore helps to infer when the core separated – very early, as considered by some, or late. This is arrived through Hf–W studies of several types of meteorites, undifferentiated as well as differentiated metallic ones, analogous to the evolution of the earth's core. In this manner, estimating both initial ^{182}W and whatever ^{182}W came from Hf decay in them, one team concluded that core formation took place about 60 m.y. after the beginning of the solar system[12]. Now, using the same Hf–W chronometry, another group[13] recently put this core formation at a much shorter time span of 29 m.y. and suggested that core formation was a continuous process, and that the main metal–silicate separation took place in a relatively short time of ~ 10 m.y.

Palaeomagnetic records available so far[10] have revealed that the earth's geodynamo must have been fully operating by the time the earth was 1 b.y. old, which implies that the inner core must have already formed to generate convection currents to run this geodynamo. But, the present heat output from the core, estimated to be around 10 TW, demands a rate of cooling considered too high if the core attained its present size at a constant rate over 4.5 b.y. Hence, it is felt that either the core should be much younger or there should be another heat source like radioactive heat[14]. Gessmann and Wood[4] (University of Bristol, UK), who recently demonstrated the feasibility of heat producing K to enter into the core in the presence of S, believe that this K in the core could account for some of the excess heat through decay of ^{40}K. Their calculations, based on experiments on the partition coefficients of K and Na between metal and silicate phases, indicate that at some point in the early earth, as much as 250 ppm K may have entered the core, from oxygen and sulphur-rich Fe-sulphide liquid magma gathering at the base of the mantle. This is sufficient to generate just 1.7 TW as against the calculated 4 TW required for an inner core nearly as old as the earth. It is, therefore, pointed out that there may be more than just 250 ppm K in the core or other heat-producing radioactive elements like U and Th alloyed with iron[14].

Yet another contender claiming to be the earth's main heat source, and by implication the prime mover of earth's magnetic-field generation, is the perceived existence of a 'steady-state planetary-scale reactor, continuously operating through geologic time'. The author of this ingenious theory[15], Herndon (Transdyne Corporation, San Diego, USA) originally proposed this nuclear process to explain the unaccounted radiation of energy (albedo) from some of the outer planets like Jupiter, Saturn and Neptune[16]. Subsequently, this idea gained momentum from the discovery of the underground natural fission reactor, now extinct, that had operated about 2 b.y. ago, for several million years, in uranium ore deposits at Oklo and Bongombé, Franceville Basin, Gabon, Africa[17]. Here, the proportion of ^{235}U was high enough in the uranium deposit for triggering nuclear chain reaction which was moderated by groundwater. This natural reactor produced additional fissile materials, which kept the reactor functioning for millions of years.

On the same analogy, Herndon considered the possibility of a planetary-scale natural fission reactor existing at the centre of the earth's core. Teaming with Hollenbach (Oak Ridge National Laboratory), Herndon carried out theoretical simulations and confirmed viability of such a georeactor to function at the centre of the inner core. According to them, a small sphere ^{235}U and ^{238}U at the centre of inner core (Figure 1 *b*) inside a shell of Ni-silicide (instead of the classic view of Fe and Ni) operated like a fast-breeder reactor releasing heat energy from uranium and fissionable plutonium, a fission-product of the nuclear reactions. This energy radiating to the outer core served to propel the geodynamo or as the authors feel, generate magnetic field through a variety of charged particles or ionizing radiation from fission reaction[15].

Critics of this georeactor theory have pointed out that uranium and thorium are strongly lithophilic and show preference for oxygen, and hence are likely to have partitioned into the silicate-oxide phase of the crust and mantle rather than into the metallic phase forming the early core. But Herndon argues that the 'relative mass of the earth's core is consistent with the earth having been derived from highly reduced matter like that of certain enstatite chondrites' like the Abee meteorite[18], an enstatite chondrite, that fell over Canada in 1952 and having the composition of the earth's core. In these enstatite chondrites, much of the U and some Th occur alloyed with iron. Herndon has estimated that considerable percentage of the earth's U (as much as 64%), enough to start nuclear reaction, went into the core alloyed with Fe-sulphide, and gravitationally settled into the inner core. In further support of this nuclear georeactor theory, the author draws attention to the abundance of ^{3}He in the Hawaiian basalts[19]. According to him, these basalts are plume-delivered from deep mantle, and ^{3}He in such rocks can originate only as a by-product of nuclear fission reactions and not from any pockets of primordial ^{3}He (ref. 20). Such primordial ^{3}He, he points out, is unlikely to exist now and must have been degassed early in the earth's history. In fact, interplanetary dusts raining continuously on the earth and having ^{3}He/^{4}He ratio distinctly extraterrestrial, are the main source for most of the ^{3}He reported presently from certain marine and other sediments[21]. Herndon feels that the distinctly different and much larger ^{3}He/^{4}He ratio (34 times the atmospheric ratio) in the Hawaiian basalts is from the nuclear fission reactions of the conceived reactor in the core.

Presence of potassium in the core has now been experimentally proved as a viable proposition and could undoubtedly account for part of the unresolved excess heat flux. With the possibility of U entering into the core alloyed with Fe-sulphide, the heat flux budget would call for suitable revision. But the quantum of K, U and Th that could explain the observed net heat output, appears to be speculative. Needless to say, all these are closely linked to the timing of core formation, the manner of its formation as well as the solidification of the inner core. Current views are somewhat inconsistent and hazy on these matters, to arrive at a unified view about the core's role in the earth's heat flux and the associated operation of the geodynamo. Against this backdrop of uncertainties, the viability of a georeactor operating at the centre of the earth, as proposed by Hollenbach and Herndon, which physicists admit is theoretically quite acceptable, calls for greater examination and debate.

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