WHITE PAPER

VITALIZING INDIAN EARTH SCIENCE WITH CROSS-DISCIPLINARY RESEARCHES

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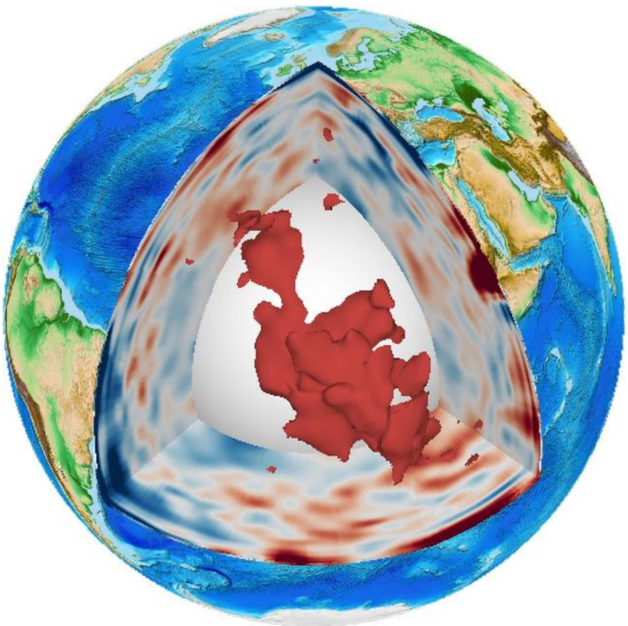

Deep-Earth scape holds the clue to planet Earth's core-driven thermodynamics

3D representation of seismic tomography model S40RTS (Ritsema *et al*., 2011 [1]), visualized using GPlates (Müller *et al*., 2018 [2])

Image Courtesy: Paula Koelemeijer

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WHITE PAPER

Vitalizing Indian Earth Science with Cross-Disciplinary Researches

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Summary

This white paper is the result of a discussion meeting[1] sponsored by the Indian Academy of Sciences with the objective of exploring means and conditions for ushering in a culture of cross-disciplinary research in earth sciences in our academia and research institutions. In particular, it was considered important to raise the national intellectual capital constituted by young graduate students by exposing them to the adventure and excitement of cross-disciplinary approaches to better define the parameters of earth structure and processes that are fundamental to understanding its core-driven thermodynamics. The meeting held in October 2024, attended by 7 scientists and an equal number of young researchers[2], focused on the enquiry-driven approach to model earth system dynamics from first principles. Its deliberations began by recounting how the emergence of the science of the earth as well as its subsequent development had happened, based on the scientific method of hypothesis formulation and testing. Over the past two centuries, this approach has revolutionized our knowledge of the structure and workings of the planet, some of which were also contributed by the first scientists at the Geological Survey of India, which was established around the middle of the 19th century. A deliberate initiative to reinfuse Indian earth science with this vital sap should therefore prove fruitful in enriching our current endeavours with enquiry-driven research.

[1] A discussion meeting on “Vitalizing Indian Earth Science with Necessary Cross-disciplinary Contents” was held on 25 and 26 October 2024 at the Indian Academy of Sciences, Bengaluru. For details please refer to the Appendix (Preliminary Report of the Meeting) enclosed at the end of this paper (after References).

[2] Participants of the meeting – please refer to the above-mentioned Meeting Report (Appendix).

Discussants at the meeting finally resolved that a potentially effective way to catalyse enquiry-driven education and research in the country would be to initiate the following two steps concurrently. (i) Formulate a few research programmes of deep significance guided by First principles science to enrich their perspective. These may then be submitted to an appropriate funding agency for their consideration and support. (ii) Inspire a band of interested young researchers to embrace the exciting intellectual challenge of studying and analysing a complex system that planet Earth is, and empower them with the pre-requisite conceptual understanding of the physical and analytical bases, through a few rounds of intense learning programmes, over the next few years. Such an exercise could then be conducted as a special initiative of the Academy for which it may seek additional funds from the Government.

Enquiry-Driven Beginnings and Emergence of the Science of the Earth

Science of the Earth was born and grew from keen observations by curious minds who sought rational explanations to explain the origin and processes that created the wondrous wealth of its heirlooms displayed on mountain cliffs, river valleys, sea coasts, and deserts; even counterfactual assumptions. The earliest knowledge of the Earth's round shape was deduced from the shape of its shadow cast on the moon's surface, and its dimension was calculated by designing an experiment based on the scale-free symmetry of similar triangles. Indeed, ideas about symmetry observed in many natural phenomena became an intuitively grounded understanding in the minds of *Homo sapiens*. Thus, piecing together, the patterns of stars and landforms on the Earth, the Greco-Roman thinkers postulated the existence of a southern continent symmetrically disposed at the south pole to balance the Arctic under the constellation of Arctos (Ursa Major). They called it Antarctica, which, in fact, appeared in the Orontius Finaeus map created in 1531 (Figure 1), becoming an inspirational driver of explorations to discover it. Amazingly, the Hindu Cosmology states the age of the Earth to be 4.32 billion years[3] (equal to one Brahma Day). Even as the way to its calculation remains obscure, we know that this number is intriguingly close to the value (4.543 billion ± 1%) determined by the disintegration rates of radioactive nuclei, which was discovered by the Physicist Henry Becquerel in 1896.

Definite ideas about the Earth's dynamical processes, however, began to form in the 18th century when natural philosophers, on finding many of their kinematic expressions exposed to view, began to question its assumed static

[3] *Srimad Bhagavatam*, Canto 3, Chapter 11, with translation and commentary by A. C. Bhaktivedanta. *Surya Siddhanta*, a treatise on Astronomy and time reckoning, written by Aryabhata around the early 5th century describes several features and dimensions of the Earth, based on observations.

Figure 1. Terra Australis (Circulus Antarcticus) was imagined to exist over 200 years before it was actually discovered in order to satisfy the symmetry conditions about the equator. (Reproduced from Oronce Fine's *Nova, Et Integra Universi Orbis Descriptio*, 1531, woodcut double-cordiform map.)

nature. A treatise on *Theory of the Earth* [3] based on reasoned arguments to explain the existence of fossil-bearing sea beds, raised high on cliffs, and themselves intruded by later material flows from below, appeared in 1795, about 80 years after Newton's Principia. Its author, James Hutton, had correctly concluded that the sequence of long deposition followed by Earth deformation, re-submergence, fresh deposition, and uplift, deduced from such exposures (Figure 2), attested to the operation of a cyclic process in the Earth's history and, looking at their currently observed rates, to its great age.

Indeed, Hutton's rigorous mind considered it essential to state, at the very outset, the logical premiss of his interpretation: "the forces and processes observable at the Earth's surface are the same that have shaped its landscape throughout natural history". This is the first explicit statement of the universal principle of symmetry of physical laws with respect to space and time, which was elevated to the status of an axiom by Einstein, in his 1905 paper [4]. Later in 1918, Emmy Noether proved that every conservation law in nature is a consequence of some aspect of universal symmetry [5]. The story of how a search for the symmetry principle associated with the conservation of electric charge, led to the identification of

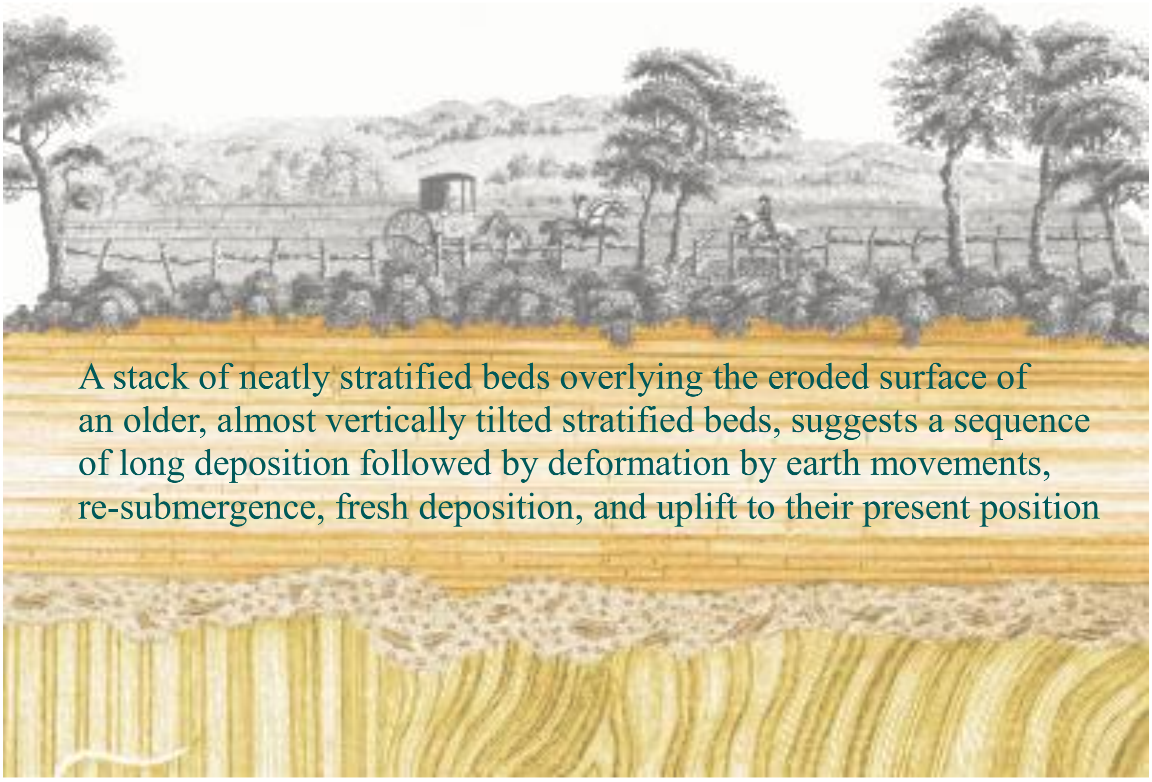

Figure 2. Hutton's saw the space–time symmetry of physical laws written in the syntax of geological forms leading him to hypothesize that the Physical laws operating in the past were the same as they do now. (Reproduced from James Hutton, *Theory of the Earth*, Vol. 1, 1795.)

Gauge symmetry, already implicit in Maxwell's equations, is a veritable tribute to the belief in the universal consistency of the laws of physics and the power of logical reasoning in pointing to the existence of deeply buried tautologies.

The revolutionary character of these developments greatly excited Charles Darwin, who packed a copy of Lyell's *Principles of Geology* [6] that included numerous observations of the type noted by Hutton, in his personal baggage, when he sailed on the Beagle in 1831. Indeed, Darwin used the time afforded at every port of call to go out and add many more examples of uplifted fossil-studded sedimentary deposits, to affirm the great age of the Earth – a fact that was needed for his theory of evolution based on the extremely slow process of natural selection.

Over the next seven decades, the analytical formulation of heat flow, the principles of molecular makeup and breakup, and the laws governing transaction costs of energy transformation, together with Newton's laws and the theory of mechanics, provided a significant armoury of interdisciplinary science for a reasoned study of the Earth's physical fields, and its chemical and biological processes. Thus, the scene was set for testing plausible hypotheses suggested by evidences gleaned from its archives, both present and past, to model the Earth's intertwined structure and hierarchy of processes, by designing revelatory experiments and numerical predictions.

By the mid-18th century, a chain of magnetic observatories had been established to investigate the nature of the Earth's elusive dipolar magnetic field, including one at Colaba, Bombay, in 1841, and triangulation surveys established in India to determine the ellipticity of its oblate spheroidal shape proposed by Newton, by taking advantage of the continuous occupiability of the 78°E longitude from Kanyakumari to Mt Everest. An early result based on the difference between the observed and calculated pendulum measurements and their orientations with respect to stars, led to the prediction and later discovery of lower-density, deep roots of elevated mountainous regions, dug by the Earth to maintain a hydrostatic balance in its deeper, warmer, yielding layers (Isostasy). Concomitantly, experimental works, such as James Hall's [7] melting of igneous rocks and cooling under controlled conditions to reproduce their crystalline structure, showed how the Earth's crust covered by great expanses of crystalline rocks, were differentiated from hot, rising plumes of iron- and magnesium-rich materials from the subjacent mantle underneath, leading to the appearance in 1928 of N. L. Bowen's book, *The Evolution of Igneous Rocks* [8]. Based, in large measure, on his laboratory melting experiments on simple models of silicate systems, it proved the power of experimentation for understanding the diversity of igneous rocks. Shortly, thereafter, the concept of *free energy*, identified by Josiah Gibbs as the difference between the oppositely tending (negative change in Enthalpy and positive change in entropy) drivers of spontaneous reactions, was used to constrain the stability of individual minerals as well as their assemblages in the pressure–temperature–composition space. The latter, in turn, yielded estimates of equilibration pressure and temperature of metamorphic and igneous rocks and the nature of the geotherm that shed light on heat flow processes through the Earth's mantle and crust. At the same time, application of the theory of elasticity to the fracture of Earth materials allowed geologists to infer the stress configurations responsible for the observed fracture zones in the Earth's brittle crust and those of the resulting earthquakes and patterns of their radiated energy calculated from ground motion records made by seismographs, to model the Earth's internal structure (Figure 3). These have been progressively refined over the past few decades with revolutionary designs of instrument systems, the growing stock of high-density and quality of data and computational algorithms to realize their information potential.

The 20th century witnessed the development of revolutionary ideas to explain the workings of planet Earth's solid and fluid spheres in the framework of a thermodynamic heat engine. This was made possible by testing hypotheses to explain the geographical pattern of long, narrow belts of globe-girdling fracture

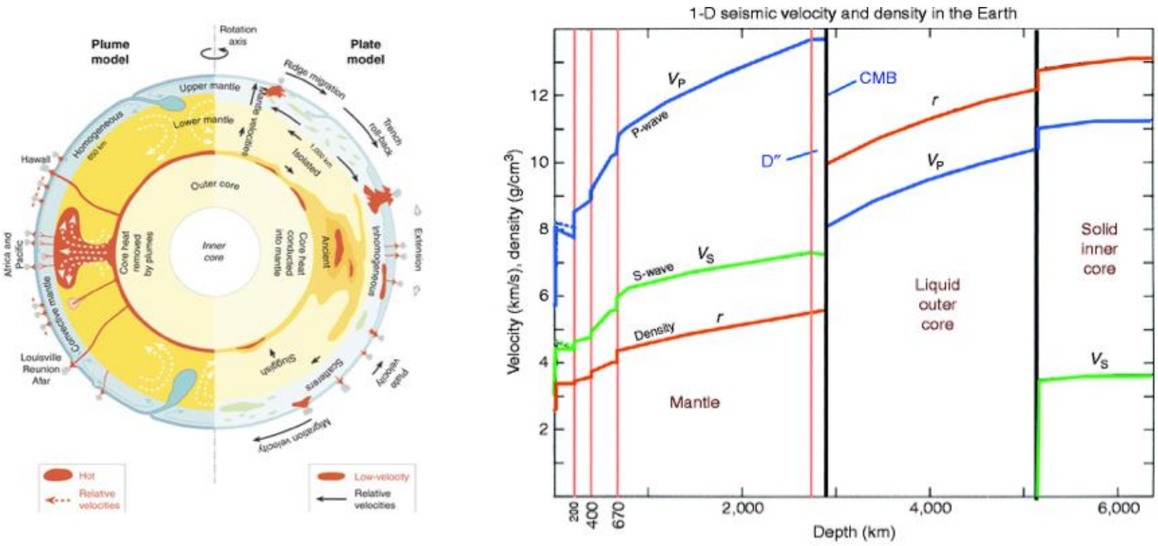

Figure 3. Left: A cartoon section through the Earth's diameter, showing the boundary layer between the fluid outer core and the visco-elastic mantle above, as well as the deeper shaded boundary between the outer core and the inner, by Jean-Paul Montagner. Right: The spherically averaged longitudinal and shear wave velocity variations down to the earth's centre and the density is shown by the red line (both the figures are reproduced from the revised edition of the *Encyclopedia of Solid Earth Geophysics* – J. P. Montagner, 2021. Earth's Structure, Global. In: *Encyclopedia of Solid Earth Geophysics*, Gupta, H. K. (eds), Encyclopedia of Earth Sciences Series. Springer, Cham, doi: https://doi.org/10.1007/978-3-030-58631-7_13).

zones marked and characterized by earthquake locations and mechanisms. Their global connectivity with the high heat-flow submarine ridges on either side of which the ocean floors were discovered to be marked by zebra stripes of oppositely polarized magnetization, eventually resulted in the formulation of the Plate Tectonic theory, but not until several of its predictions described by Figure 4 had been proved to be true.

Earth Sciences in India

Empirically learned skills for locating ore deposits, and the operations and processes for both mining and metallurgy of copper and iron ores, apparently dating back to a dim past, had reached a high level of accomplishment in India (Will Durant's *The Story of Civilization*, 1935 [9]) by the Gupta period (3rd to 6th century AD). Scientific studies of the Earth as related above, however, began with the establishment of the Geological Survey of India (GSI) in 1851, and the first academic appointment of Henry Benedict Medlicott, formerly of the British Geological Survey, as Professor of Geology at the then Thomason College of Civil Engineering at Roorkee. Later, in 1892, graduate studies in geology took root in the Presidency College of Calcutta. The GSI established by the East India Company primarily to prospect for coal deposits to feed the Railways, however, quickly matured into a world-class scientific organization under its first superintendent, Thomas Oldham, who progressively widened its scope to mapping of rock types, their structures, age, and relationship to earthquake hazards.

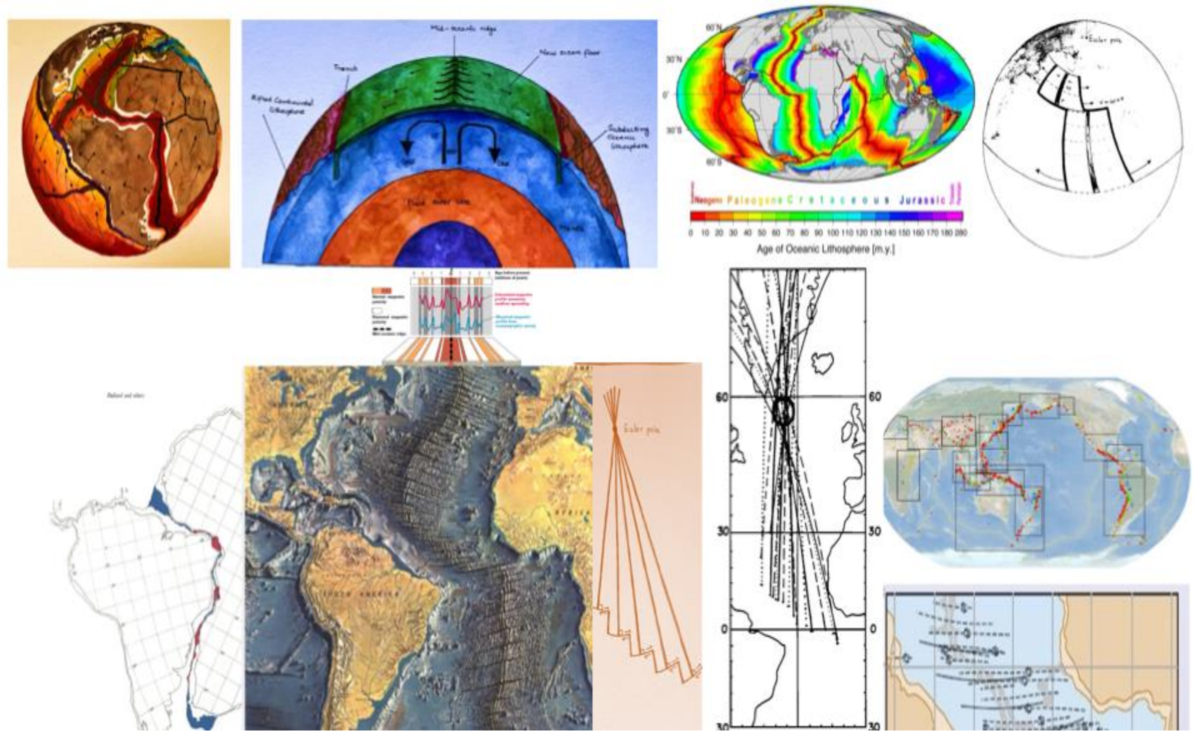

Figure 4. Top left: The first two panels show a cartoon of the Plate Tectonic thermodynamic engine of the earth powered by the latent heat released by the progressive solidification of the boundary between the solid inner core and the fluid outer. The uppermost ~100 km thick colder, brittle cap is a mosaic of fractured shells in relative motion determined by the traction at their base exerted by ascending and descending limbs of the viscoelastic mantle convection, and marked by the corresponding earthquake mechanisms: extensional or compressional (corresponding earthquake epicentres in the middle panel on the right – Courtesy: U.S. Geological Survey Map). Hot ascending sheets of molten rock continue to upwell through the vent created at the time of their first surface outpourings forming a ridge whilst new rising streams push the preceding sheets of quenched material spreading a new created ocean floor symmetrically on either side of the ridge. Since the earth's magnetic field episodically reverses polarity every few million years, now chronicled by radioactive dating, alternatingly spreading sheets of about 100 km width gets branded by the direction of the prevailing magnetic field as the material cools below the Curie point (middle panel between the spreading centres of Atlantic and the schematic – Courtesy: U.S. Geological Survey. Source: https://pubs.usgs.gov/gip/dynamic/stripes.html). The continental fragments rifted apart at the time of their first breakup, continue to drift away on either side of the spreading ridge creating a growing oceanic crust richer in Fe-Mg content (bottom second figure from left – Reproduced by Courtesy of Studio Berann. Source: MapCarte 78/365, Atlantic Ocean floor by Heinrich Berann, 1968.), until the densifying, ageing ocean floor at their first welded junction with the rifted continents becomes gravitationally unstable and dives underneath, forming the descending limb of the mantle convection. Ocean floors are thus predicated to die young. Radioactive dating of ocean floor rocks, do indeed show their progressive ageing with distance from the parent ridge, nowhere older than ~200 million years (upper last but one from the right – Reproduced with permission from AGU Publications. Source: R. D. Müller, M. Sdrolias, C. Gaina, and W. R. Roest, 2008, Age, spreading rates, and spreading asymmetry of the world's ocean crust, *Geochem. Geophys. Geosyst.*, Vol. 9(4), Q04006, doi: https://doi.org/10.1029/2007GC001743) providing one of the tests of the theory. Another hard test was provided by synthetically closing the ocean by moving the opposite sides of the rifted continents that were once together (bottom first figure from left – Reproduced with permission from The Royal Society (U.K.). Source: Edward Bullard, J. E. Everett, and A. Gilbert Smith, 1965, The fit of the continents around the Atlantic, *Philos. Trans. R. Soc. A*; doi: https://doi.org/10.1098/rsta.1965.0020) according to geometrical constraints of displacement over a spherical base (Euler's theorem requires only scissor like displacements, shown in the upper rightmost panel). Finally, transform faulting perpendicular to displacement as the continents move as arms of a scissor are found to intersect over a small region (lower middle panels) marking the Euler pole of rotation (bottom first and second figures from right – Reproduced with permission from AGU Publications. Source: W. Jason Morgan, 1968, Rises, trenches, great faults, and crustal blocks, *J. Geophys. Res.*, Vol. 73(6), https://doi.org/10.1029/JB073i006p01959).

Oldham's initiatives starting with his own project to compile the first catalogue of Indian earthquakes from the earliest times, began making seminal contributions to global knowledge about Earth structure and processes. Medlicott, who, in 1876, succeeded Thomas Oldham at the GSI, discovered the iconic sequence of variegated fluvial and lacustrine sedimentary rocks several kilometres thick, deposited in depressions of the oldest basements in east-central India. Their rock facies bearing signatures of a changing climate during the few tens of million years during which they were deposited, naturally, hosted a variety of economic deposits as well as a veritable archive of the Earth's changing environment. He called these the Gondwana series to honour the ethnic Gond culture of the region. By the 1880s, evidence had accumulated to show the existence of this extraordinary formation of similar ages in five other continents, attesting to their having shared a connected geography. It led Eduard Suess, a Professor of Geology at Vienna University, to propose a long-connected assembly of the five southern continents of Antarctica, Australia, India, Africa, and South America which had remained together for several hundred million years between 400 and 200 Ma. He called it Gondwanaland (Figure 5).

Another path-breaking contribution to earth science that kickstarted analytical seismology, leading to images of the Earth's internal structure, was made by Richard Oldham, who, in 1879, had joined the Geological Survey as an Assistant Superintendent. He clearly identified the distinct wave phases on ground motion records generated by earthquakes, with the Earth's longitudinal and torsional modes of vibrations predicted by the equations of elasticity that had been worked out a few years earlier (Figure 6). Thus confirming that the Earth could be treated like an elastic body, he proceeded to use the theory to show how earthquake waves could be used to create Earth scans and, in this way, produced the first evidence that its core had a fluid character.

Over the coming decades, the enquiry-based Earth Science at the Geological Survey led by the Oldhams inevitably yielded place to geological mapping and mineral prospecting, the original mandate of the Survey. This resulted in the construction of high-quality maps of India's varied terranes and their distinctive character, as well as a spurt in mineral exploration and mining. These knowledge products proved to be a valuable heritage for Independent India set on a course of industrialization.

The 20 or so academic departments of Earth Sciences that were established in various Universities before independence also shaped their endeavours on geological field mapping and classifications, and characterization of terranes, rock facies, and mineral assemblages.

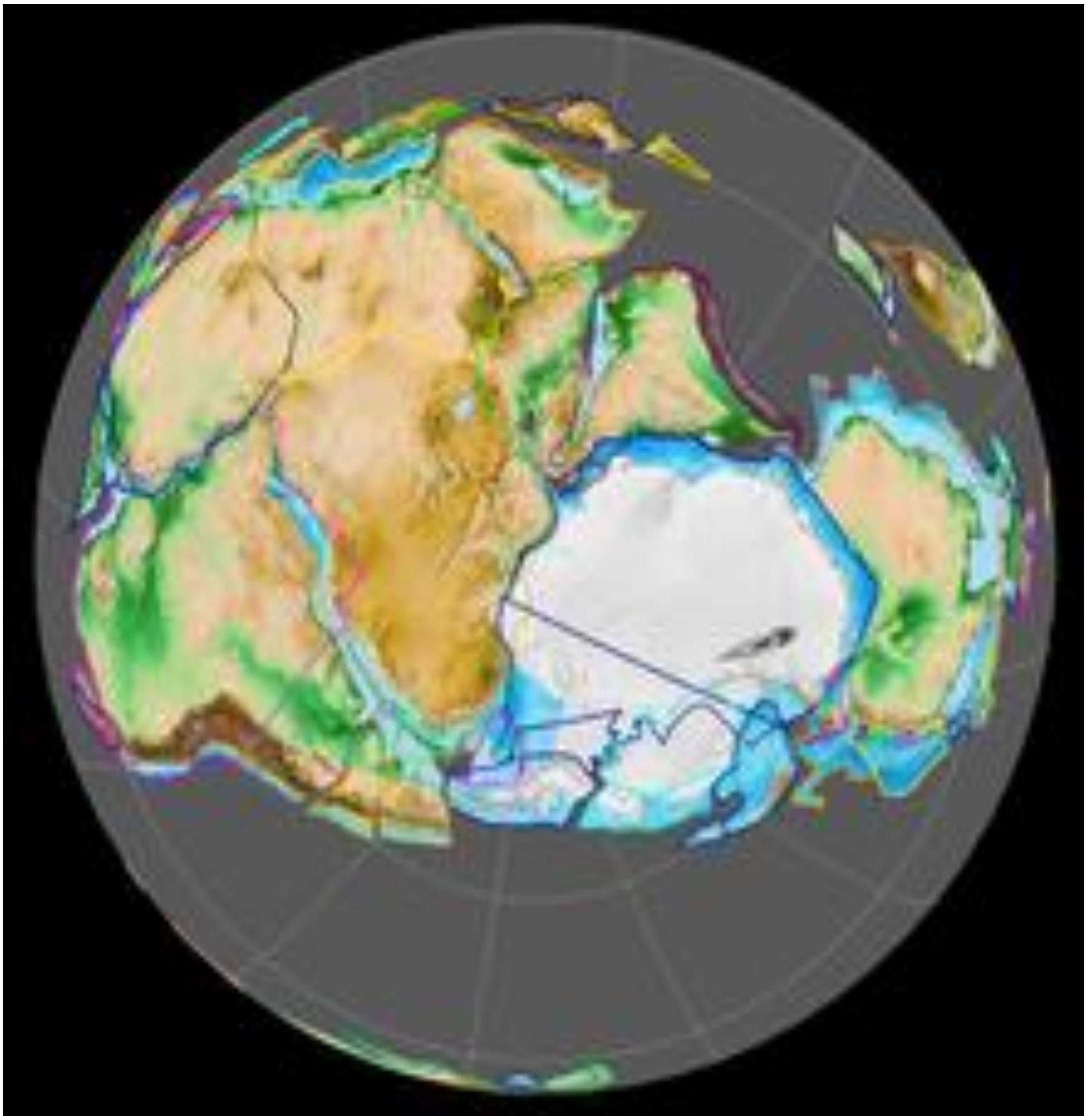

Figure 5. Eduard Suess proposed (1885) the existence of a continental assemblage comprising Antarctica, Australia, India, Africa, and South America, covering about 2/3rd of the continental Earth, which remained geographically connected for several hundred million years (400–200 Ma), based on the identification of formations in all these continents, with that of Medlicott's Gondwana series (Reproduced from Fama Clamosa, Gondwana at 420 Ma. View centred on the South Pole; available under CC BY-SA 4.0, https://en.wikipedia.org/wiki/File:Gondwana_420_Ma.png).

A notable one being the recognition and study of an extraordinary knee bend of a whole stack of geological formations around Nanga Parbat in northwestern Himalayas by D.N. Wadia whilst teaching Geology at Jammu University (Figure 7). He carried out a fine-scale mapping of the bent formations on either side of the Syntaxis, even after he had joined the Geological Survey in 1921. Ten years later, he convincingly showed that the Syntaxis was produced by a loop-like bending of the new evolving Himalayan formations around a strong ancient promontory of the stolid Indian continent.

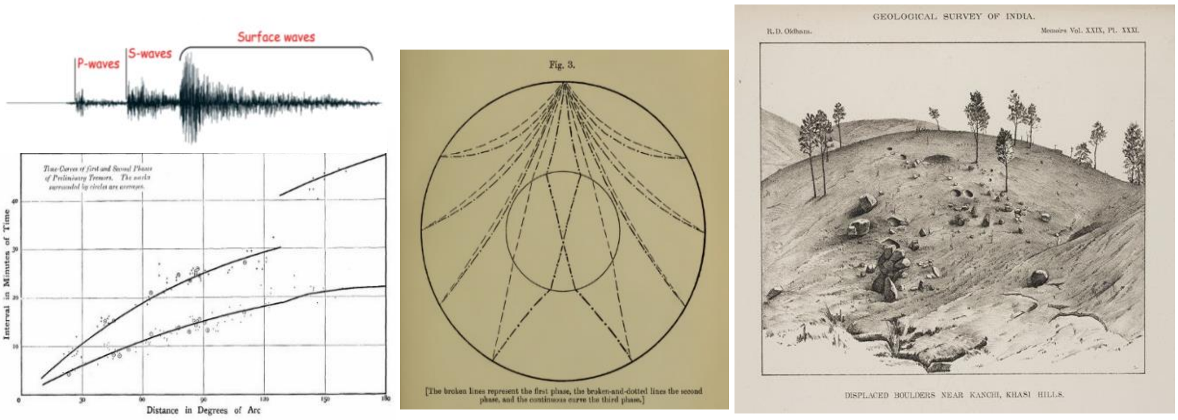

Figure 6. Upper left: shows a classical ground motion record created by earthquakes. It shows 3 distinct wave trains that Oldham identified with the longitudinal (P) and shear waves (S) as well as those of surface waves, travelling with different velocities, as predicted by the theory. He derived the travel time–distance function (lower left), using station records from just over a dozen sites in Australia, New Zealand, USA, Russia, and Japan, created by about 14 earthquakes. He then used these functions to chart the course of these waves through the Earth, revealing in the process, the existence of a fluid core (middle panel) (lower left and middle figures – Reproduced from R.D. Oldham, 1906, The constitution of the interior of the Earth, as revealed by earthquakes, *Quart. J. Geol. Soc. London*, Vol. 62, pp. 456–475). He further used his keen observations of displaced boulders ejected from their original muddy seats nearby, during the Great Assam earthquake of 1897, to calculate the maximum causative ground acceleration (right panel – Reproduced from RD Oldham, 1859, *Memoirs of the Geological Survey of India*, published by order of the Governor-General of India, Vol. XXIX, plate XXXI.) which turned out to be to close to that of gravity.

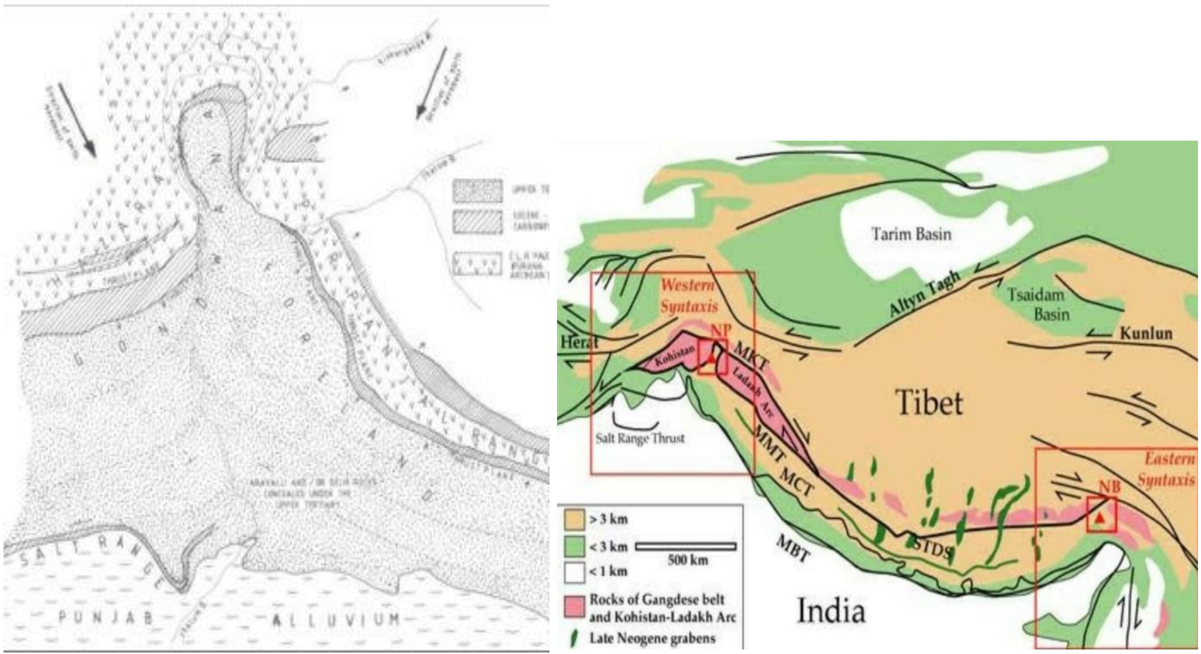

Figure 7. Map of Hazara, Pir Panjal in NW Himalaya, mapped by D.N. Wadia (figure on left: Reproduced from D.N. Wadia, 1928, The geology of Poonch state (Kashmir) and adjacent portions of the Punjab. In: *Memoirs of the Geological Survey of India*, Vol. 51, Part 2, Calcutta Government of India Central Publication Branch), showing how the SE-NW trending Pir Panjal range along with the entire assemblage of rocks and their fracture zones, has been bent into a knee around the Nanga Parbat (figure on right: Reproduced from Peter Zeitler *et al.*, January 2021, Erosion, Himalayan Geodynamics, and the Geomorphology of Metamorphism, *GSA Today*, pp. 4–9).

A study of the evolution of Earth science research in Indian institutions over the last 175 years points to the high desirability of catalysing the emergence of First Principles Earth Sciences in the country by restoring its essentially interdisciplinary character.

Promising Prospects of First Principles Earth Sciences

The Earth is a thermodynamically open system that comprises a hierarchy of open subsystems powered by the constant outflow of its internal heat from below and the daily radiation from the sun. The latter has spawned a rich assemblage of hydro-biological ecosystems of which the human system is a part. Each of these subsystems tend to preserve its temporal identity by developing a transitional boundary layer that is known to evolve definite structures (e.g. the thermal boundary layer on Earth's surface and animal cell boundaries).

Earth-scans made possible by earthquake waves, distinguish 3 first order, nearly spherical, quasi-homogeneous shells separated by 3 internal phase boundaries, apart from the free surface boundary with the atmosphere. All three layers are distinctly structured, essentially by the geographical distribution of heat fluxes across their nearly spherical surfaces; the source of all these being the secular cooling of the Earth's outer core and latent heat released by the freezing of the inner core. The one nearest to us lies at an average depth of ~100 km that separates the top nearly solid lithosphere from the viscous upper mantle, and is the best characterized (vide the right panel of Figure 8, showing it in cross-section beneath a 1400 km long E-W profile across the Atlantic). The second, that separates the viscoelastic mantle from the outer fluid core, lies at a depth of ~3000 km and shows an intriguing structure which has been broadly imaged (middle panel, Figure 8). The deepest one at a depth of ~5000 km lies at the base of the outer fluid core. The latent heat outflow from this layer, estimated to be ~80 mW/m^2, and the efflux of light elements power convection in the outer core, whilst the solid inner core grows by about 1 mm/yr. The structures in the boundary layers have been carved by the interplay of geographically differentiated heat fluxes across them and the quantum mechanical wave functions of materials traversed by them at different depths (temperature–pressure conditions) during their passage to the Earth's surface. Specifically, the Core–Mantle Boundary (CMB) exhibits two large regions of low seismic velocities, one beneath Africa and the other under the Pacific, indicating the location of warmer material and lower heat fluxes across the outer core. Albeit less sharply imaged, the inner-outer core boundary shows two regions of higher velocity, one beneath Asia and the other beneath the Atlantic. Expectedly, these geographically asymmetrical structures, being the consequence of a shared process, must bear some relationship. A recent study at the IISc strongly suggests

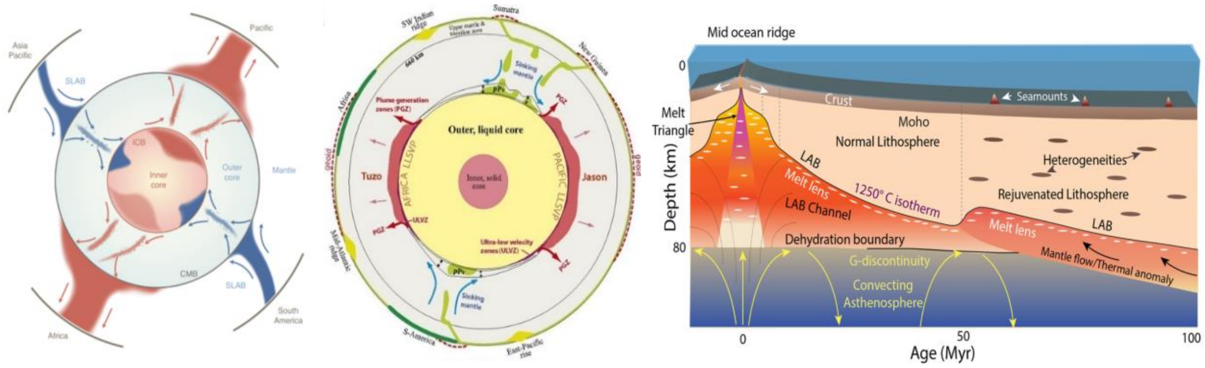

Figure 8. Left: shows the 3 thermodynamic phase boundaries within the earth (Reproduced from W. Wang and J. E. Vidale, 2022. An initial map of fine-scale heterogeneity in the Earth's inner core, *Nat. Geosci.*, Vol. 15, pp. 240–244; doi: https://doi.org/10.1038/s41561-022-00903-8) which are azimuthally structured, essentially by the geographical distribution of heat fluxes across their spherical surfaces. The uppermost lithosphere-asthenosphere boundary (LAB) at a depth of ~100 km separates a largely solid brittle lithosphere from the viscoelastic upper mantle below. It is structured by ascending magma sheets whose surface outpourings continually build new landscapes and oceanic lithospheres, and the descending limbs of their cold, denser ageing slabs, often diving deep to the base of the mantle (right panel – Courtesy: Satish Singh, IPGP, Paris). The second called the Core-Mantle Boundary (CMB) separates the viscoelastic mantle from the fluid outer core. Seismic imaging of this layer, distinguish two regions (middle panel – Reproduced with permission from *PNAS*. Source: Trond H. Torsvik *et al*., Deep mantle structure as a reference frame for movements in and on the Earth, June 17, 2014, *PNAS*, Vol. 111(24), pp. 8735–8740), one under the Pacific and the other beneath Africa as being characterised by large region of low seismic velocities, indicating the location of higher heat fluxes from the outer core. The deepest at ~5000 km, marks the uppermost freezing layer of the inner core that underlies the fluid outer core above. Albeit not sharply imaged, this layer too shows high velocity colder patches, one beneath Asia and the other under the Atlantic.

that the CMB structure induces an east–west dichotomy in outer core convection [10], which in turn can control the geographical distribution of freezing at the outer surface of the inner core. An important question in the theory of Earth and planetary magnetism is whether the preference for the axial dipole field is due to a purely hydrodynamic process influenced by rotation or due to a magneto-hydrodynamic process influenced by both rotation and the self-generated field. Recent studies at IISc have shown that the back-reaction of the magnetic field on the convection manifests as hybrid magnetostrophic waves which are essential for dipole formation [11]; the suppression of these waves under strong forcing likely results in polarity transitions.

Recently, the Indian Academy of Sciences, encouraged by the work of some broadband Academy Fellows and Summer Fellowship interns, engaged with the problems of deep-Earth structure and processes – the prime mover of landscape formation and mineral repositories at its surface, sponsored a discussion meeting aimed at working out an intermediate term programme (3–4 years) that would catalyse the evolution of First Principles Earth Sciences in the country by bringing to bear cross-disciplinary approaches to the subject. For example, a more accurate estimate of material density in the deep Earth needed for modelling most geodynamic processes could be potentially constrained using a combination of Neutrino tomography and free oscillations seismology which is currently absent in the country and the results independently tested using the Density Functional Theory.

Discussion at the meeting which described itself as ‘work in progress’, was finally distilled to bring out the following promising approaches that the Academy may help catalyse. To implement these, however, the Academy will need to organize necessary support systems with additional financial assistance:

1. Scientists from TIFR, IMSc, IISc, NCESS, IISER Kolkata and Pune, and IOP Bhubaneswar enthusiastically greeted the prospect of using the science of Neutrino physics, Helioseismology, Density functional theory, Convection and dynamo modelling, Information theory, and magmatism to enrich research endeavours aimed at understanding Earth dynamics. The initiative would enhance the potential of an expanding repertoire of cross-disciplinary approaches to earth science problems from First Principles.

2. Creating a critical mass of expertise and interest in these fields would, however, be necessary to kick-start this new composite endeavour starting from the small fledgling ones that are currently underway but without the resources for joining hands.

3. This can best be accomplished by an Academy Initiative to (a) hold priming schools of up to 2 weeks’ duration in the following areas along the lines already honed by its decades of experience, and (b) nucleation of two modern observatories new to India.

   (a) Priming Courses:

   (i) Convection and dynamo modelling; understanding the response of the Earth’s core to azimuthally distributed heat fluxes in the mantle.

   (ii) Normal mode seismology for characterizing deep Earth structures, especially density.

   (iii) Neutrino Physics and the Earth’s density structure.

   (iv) Modelling of advected heat fluxes associated with large mantle plumes-generated lava flows in the past.

   (v) Density Functional Theory towards testing of stable lattice structures of minerals in the deep Earth.

   (b) Establishment of the first modern experimental observatories in the country to inspire imaginative research initiatives amongst graduate students and young researchers in (i) Ultra-long period seismology and (ii) Neutrino physics.

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Preliminary report on a Discussion Meeting on Vitalizing Indian Earth Science With Necessary Cross-disciplinary Contents

Indian Academy of Sciences, 25 & 26 October, 2024

The Academy sponsored a Discussion meeting proposed by Professors Binod Sreenivasan and Vinod Gaur, aimed at working out an intermediate term programme (4–5 years) that would catalyze the development of deep earth researches using the science of (i) convection modelling of the core, (ii) neutrino tomography, (iii) normal mode seismology which is currently absent in India, (iv) the density functional theory based on quantum mechanics and (v) the chronology and quantitative estimates of the azimuthal distribution of advected heat fluxes through large magma outpourings in the past. The proposal had grown from a year-long discussion between scientists working in the above fields to interpret the azimuthal distribution of heat flux proxies mapped as low seismic velocity structures[1] in the core-mantle boundary layer, and those gleaned from convection modelling[2]. It had acquired force from the appearance of a recently grown small number of adventuresome young graduates who have begun to work in these areas: convection modelling at IISc, Bengaluru, density functional theory applied to mineral physics at IISER, Kolkata, normal mode seismology at the CSIR Fourth Paradigm Institute, and neutrino tomography of the earth at TIFR.

The discussion meeting was held on 25 & 26 October, 2024 with a select group of 14 participants (Annexure I) who had been identified as potential contributors to the programme, including 7 young researchers. It began with an introductory note by Binod Sreenivasan, outlining the rationale behind the meeting and brief statements by participants about their science, and pointers to potentially new knowledge that could be aimed at, to characterize structures in the deep earth. It was followed by a most supportive address by Dr M Ravichandran, Secretary, MoES, and later by detailed presentations and discussions that could result in the formulation of some collaborative research proposals over the coming months.

Discussions were centred on ways to understand and define the fundamental dynamics of earth processes and the density structures created in their wake, especially those in the boundary layers of this far-from-equilibrium system, which is known to be primarily driven by the latent heat released by the freezing of the outer region of the inner core. Details of the spherical distribution of heat fluxes across the two deep boundary layers - the CMB D” layer and that separating the outer core from the inner, thus pose as the major parameters that still await a more definitive knowledge.

The afternoon session, which began with online greetings by the President of the Academy from S. Korea and his brief exchanges with Secretary M Ravichandran, set the tone for subsequent deliberations. Accordingly, the discussions were focused on the key steps necessary to create a critical mass of researchers and to inspire young graduate students to the excitement of researching the wondrous processes and phenomena exhibited by the most remarkable natural laboratory in the solar system. The process would begin by formulating some cross-disciplinary research proposals to be tested by funding agencies and the preparation of an expert-vetted white paper that would spell out a road map for proceeding forward with a built-in critical process to ensure the integrity of approach as the endeavour moves forward.

In particular, it was felt that the following steps should prove fruitful in advancing this exciting genre of research in exploring earth structures and processes over their wide-ranging space-time scales:

i) Holding priming schools of up to 2 weeks' duration in the following areas along the lines already honed by decades of experience by the Indian Academy of Sciences:

a) Convection modelling and quantification of azimuthally distributed heat fluxes across the earth's deep boundary layers.
b) Normal mode seismology for characterizing deep earth structures, especially density.
c) Neutrino Physics and the earth's density structure.
d) Modelling of advected heat fluxes associated with large mantle plumes-generated lava flows in the past.
e) Density Functional Theory towards testing of stable lattice structures of minerals in the deep earth.

ii) Establishment of the first modern experimental observatories in the country to inspire imaginative research initiatives amongst graduate students and young researchers in

a) Ultra-long period seismology
b) Neutrino physics

In the aftermath of the meeting, work on the formulation of the following collaborative research proposals is currently in progress:

(i) Models of core dynamics with boundary layer heterogeneity refined by mineral physics.

(ii) Relating Earth's core fluxes to density anomalies reconstructed by neutrino tomography.

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Annexure I

LIST OF PARTICIPANTS

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