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Review Article

Current Trends of Geodynamic Research in India: A Review of Theoretical and Experimental Studies

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This paper presents a review of the geodynamic studies, giving a special emphasis on the recent theoretical and experimental work in India. The geodynamic research has progressed broadly in the three major areas- physical states of Earth's interior, thermo-mechanical processes, and lithospheric slab dynamics. Understanding the physical properties of minerals under extreme pressures and temperatures is one of the major challenges in solid earth geophysics. This review provides an account of the theoretical studies in mineral physics in India, which primarily use ab-initio calculations to characterize the high-pressure behaviour of silicates and oxides, and discusses their implications in predicting geophysical discontinuities. A number of researchers in India are actively engaged in performing physical as well as numerical model experiments to study a range of thermo-mechanical processes, such as plumes in Earth's mantle, subduction of lithospheric slabs in convergent tectonic settings and evolution of the mid-oceanic ridges in divergent tectonic boundaries. This review summarizes the outcome of these studies in the perspective of current research trends in geodynamics.

Keywords: **Lithospheric Discontinuity; Thermo-Mechanical Flows; Mantle Plumes; Subduction Zones; MOR Segmentation**

Introduction

The subject - *geodynamics* has witnessed a remarkable development in the last couple of decades for a comprehensive understanding of the solid earth processes, and to account for their underlying mechanisms. Despite an enormous diversity of the geodynamic research, the subject trends broadly in three major directions- physical states of Earth's interior, thermo-mechanical processes, and lithospheric slab dynamics. I discuss here, albeit succinctly the progress of geodynamics in these principal directions.

A range of thermodynamic models have been proposed to describe the thermal state in Earth's interior. The adiabatic temperature gradient is the most common model, although there are large uncertainties of various thermodynamic parameters, such as specific heat and co-efficient of volume expansion under high pressure and temperature conditions akin to planetary interiors. To obtain a more accurate estimate of the adiabatic temperatures it is necessary to develop a better mineralogical constraint for different rheological models. In recent time various experimental techniques, such as multi-anvil, diamond anvil and laser shock have been developed to perform mineralogical experiments under extremely high pressures and temperatures. A new line of theoretical mineral physics involves *ab-initio* calculations within the framework of density functional theory to calculate their thermodynamic properties (Dutta and Mandal 2012a, b, c, d; Dutta and Mandal 2013; Das *et al*., 2016).

The work of planetary dynamics has accelerated in the last few decades with the development of a new branch, called *computational geodynamics*. With this development in geodynamics, new research fronts have evolved to address various issues in solid earth geosciences, such as prediction of thermal heterogeneities, geochemical mixing on planetary scale, mantle flow and associated seismic anisotropy and global surface velocities. In recent years workers have

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extensively used computational fluid dynamic (CFD) models to simulate complex three-dimensional convection structures in numerical models with Boussinesq approximation of fluids. The dynamics of mantle convection has a direct control on upwelling and downwelling of mantle materials, resulting in plate generation and destruction along divergent and convergent tectonic boundaries, an issue widely discussed in the theory of plate tectonics. The present review specifically aims to highlight studies dealing with complex processes involved in plate generation along mid-oceanic ridges (divergent tectonic boundaries) and plate destruction along subduction zones (convergent tectonic boundaries).

I present this review to cover some recent advancement/progress in the theoretical and experimental geodynamic studies in India in the following way. A number of important geodynamic phenomena are chosen to constitute the next section. We will try to bring out the key questions addressed in these studies. A short outlook is then provided, with an aim to show the future trend of geodynamic research in India.

Geodynamic Phenomena

Lithospheric structure

The lithosphere is an active component of the geodynamic system, showing a thermo-mechanical interaction with the mantle. A large number of Indian geophysicists, mostly working in the field of seismology are engaged in deciphering the lithospheric structure of the Indian plate (Uma Devi *et al*., 2011; Rai and Ramesh, 2012; Kumar *et al*., 2013). Their studies provide estimates of lithospheric thickness of the Indian craton. Based on broad band seismological data, Jagadeesh and Rai (2008) first showed a spectacular variation in the thickness of Indian lithosphere, ranging from 120 km in the southern extremity to nearly 180 km in the north. Using converted wave techniques (P and S receiver functions) and a novel stacking analysis Kumar *et al*. (2013) later predicted somewhat lower thicknesses of the lithosphere; 70 km in the south, increasing to nearly 170 km close to the Himalaya in the north. Interestingly, both the seismic studies converge to a point- the Indian lithosphere progressively thins as we move from north to south. There is a characteristic seismic discontinuity in the Indian lithosphere, called Hales discontinuity, widely reported from many other cratons across the globe. The Hales discontinuity has been attributed to a lithological transition from spinel to garnet peridotite, marked by an increase of S wave velocity from 4.52 to 4.77 km/s, amounting to about 4% increase across the discontinuity. On the other hand, P waves show a velocity jump by about 3%. The origin of Hales discontinuity is not well understood as it is hard to establish the spinel to garnet transition unequivocally from other cratons. Using first-principles calculations within density functional theory the discontinuity was later interpreted to be a consequence of a transition in cation ordering of bivalent cations- Mg and Fe in the octahedral sites of olivine lattice structures as a function of pressure and temperature (Fig. 1A, B; Mandal *et al*. 2009). Their calculations reveal that this ordering transition results in a substantial change in the elasticity, leading to jumps in P- and S-wave velocities by 2 to 4%. Their estimated depth required for this transition perfectly matches with the Hales discontinuity, observed in the Indian craton (Fig. 1C). This study provided a completely new insight into the origin of the lithospheric seismic discontinuity.

In India a strong research front of geodynamics has been established in recent time to study the lithospheric deformations in the Indian Ocean, which display a complex configuration of the plate boundaries. A research group of the National Institute of Oceanography, India has explained the nature of strain accumulation in the diffuse plate boundaries between the Indian and the Capricorn plates, which was reported by Krishna *et al*., 2009. The strain accumulation occurs on two spatial scales: reverse faulted blocks with 5-10 km spacing, and 100-300-km-wavelength folding of the oceanic lithosphere. Using the estimates of India-Somalia-Capricorn plate rotations and seismic reflection data they have described the history of India-Capricorn convergence. Their study also shows that new India-Capricorn plate rotations started between 18 and 14 Ma, which is consistent with marine seismic evidence for the onset of deformation at 15.4-13.9 Ma. In continuation of this study they have recently explained the origin of the Ninety East Ridge in the context of the spreading records (Krishna *et al*., 2012).

A large number of Indian geoscientists have been working on the Himalayan-Tibet Mountain system in

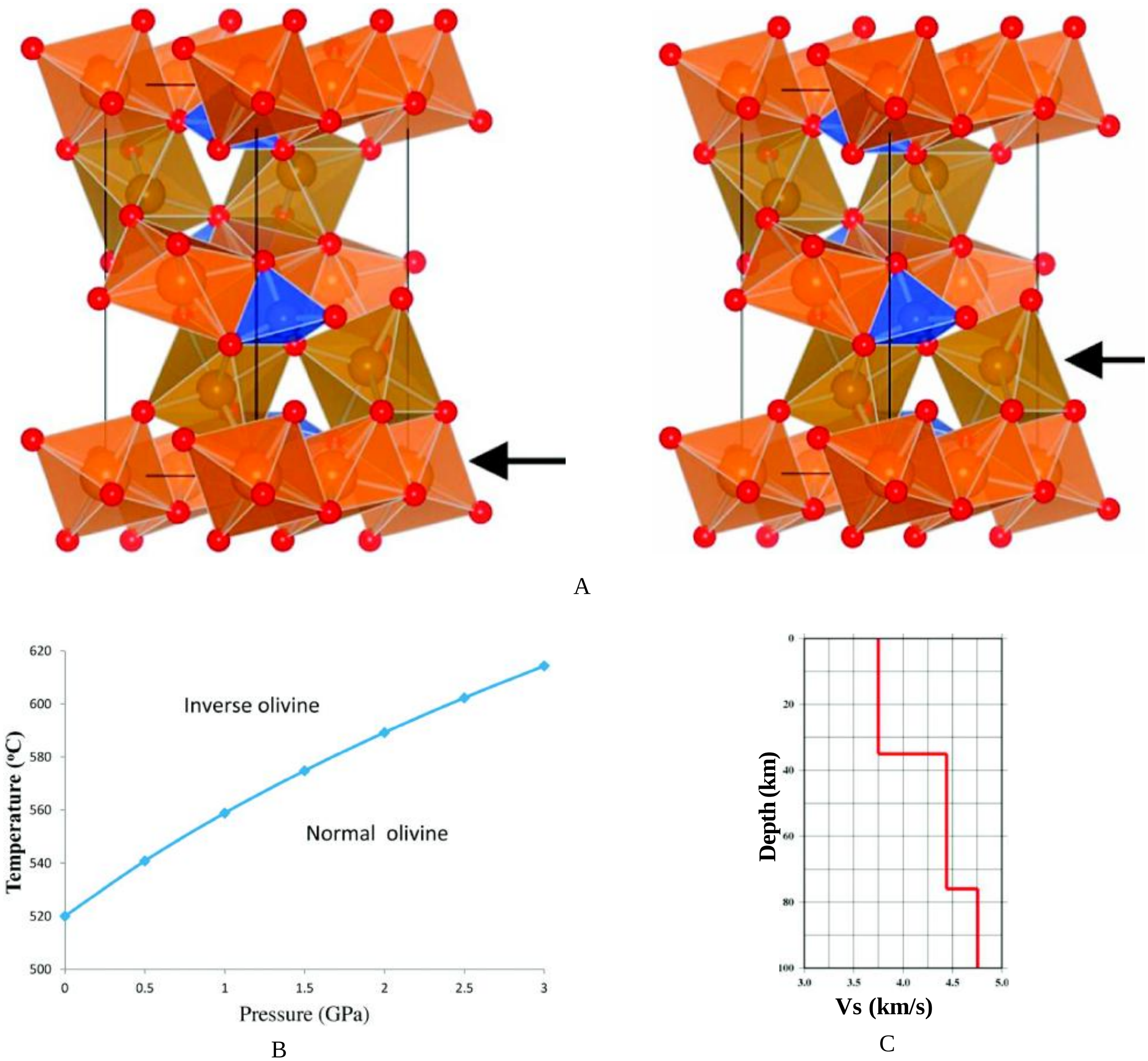


Fig. 1: (A) Inversion of Fe2+ordering in M1 and M2 octahedral sites in Mg-Fe olivine structures with orthorhombic symmetry (B) Fields of normal and inverse cation ordering in P-T space (C) Jump in shear wave velocity at different depths in Indian lithosphere, where the jump nearly at 80km marks the Hales discontinuity

a geodynamics perspective. This review highlights some of the important studies that connect the Himalayan tectonics with the planetary scale geodynamics. In a recent study Uma Devi *et al*. (2011) have investigated the nature of collision and subduction of the Indian plate against the Asian plate. They have used the S receiver function technique to synthesize broad-band seismic data from the northeast India and Eastern Himalayan regions and reconstructed the geometry of Indian Plate collision. Their study reveals that the Indian lithosphere is 90 km thick beneath the Shillong plateau, but thicker (~135 km) on either side of the plateau. The structure indicates a doming of the lithosphere, which explains the plateau uplift. According to their study, the Indian Plate steepens to subduct beneath Tibet just south of Bangong suture zone.

Evolution of Mid-oceanic Ridges

This review discusses a theoretical work by Sarkar *et al*. (2014), which provides a comprehensive thermo-mechanical model to show the dynamics of melt formation and migration, coupled with solidification processes. They have chosen random thermal perturbations (RTP) in the upwelling zone, and simulated the melt pathways, leading to magmatic segmentation, as observed globally along MORs. The model employs an enthalpy based formulation to tackle phase change problems in fluid flow, developed and numerically implemented by Voller and his co-workers in the late 1980s (Voller and Prakash, 1987). The most fundamental step is to represent the computational cells, attributed to a phase change in terms of the mean latent heat content, ΔH, ranging between L (latent heat of the phase change) and 0. The partially molten system is treated as a pseudo porous media, with porosity changing from 1 to 0 as ΔH varies from L to 0. This theoretical approach accounts for the zero velocity for the phase in solid state as well as reduced velocity in the case of solid-melt mixture using a parameter A in the momentum equation in the form of a source term. The melt flow through the porous media is regulated by this 'Darcy' source term. The Darcy term dominates over other terms when there is complete solidification, leading to a zero velocity condition in the system. They have developed their model using the following governing equations.

Conservation of mass,

$$\nabla .v = 0 \tag{1}$$

Conservation of momentum,

$$\rho \frac{\partial}{\partial t} v + \rho v \nabla v = -\nabla p + \mu \nabla 2v + S_g + S_D \tag{2}$$

Enthalpy equation,

$$\frac{\partial}{\partial t}(\rho H) + \nabla .(\rho v H) = \nabla .(k \nabla T) - S_h \tag{3}$$

where p is the pressure, ρ is the density, and μ is the coefficient of viscosity. H stands for the enthalpy. S_g, S_D and S_g are external source terms. S_D is a source term used in Eq. 2 to modify the momentum equation in the mushy regions. This can be defined as,

$$S_D = -Av \tag{4}$$

The expression of the parameter A can be obtained in the following way. Considering the Darcy law for the mushy region flow, we have

$$v = -(K/\mu)\nabla p, \tag{5}$$

where K is the permeability, which is a function of porosity. As mentioned earlier, the mushy zone can be treated as a fictitious porous medium, where the porosity decreases from 1 to 0 as the mean latent heat content, ΔH decreases from L to 0, and so does the liquid fraction β. The Carman-Kozeny equation, derived from the Darcy law is given by

$$\nabla p = -C \frac{(1-\beta)^2}{(\beta^3)} v, \tag{6}$$

where C is a mushy zone constant. The source term in the momentum equations (Eq. 3) introduces the effect of advection in the solid-melt system. They consider a Boussinesq approximation to deal with the buoyancy-driven fluid flow or natural convection in the present model. This kind of thermo-mechanical problems employs the Boussinesq approximation; with this approximation we can neglect all the effects of thermally driven density fluctuations, except in the gravity source term S_g of the momentum as,

$$(\rho_v - \rho)g \approx -\rho g \theta \Delta T \tag{8}$$

where ρ_v is the variable density of liquid and ρ is the reference density. ΔT represents the temperature fluctuations with respect to the reference temperature. θ is the co-efficient of thermal expansion. The source term then follows,

$$S_g = \rho g \theta \Delta T \tag{9}$$

Using the enthalpy (Eqn. 4) and the continuity equations (Eqn. 1), the enthalpy source term S_h can be expressed as

$$S_h = \frac{\partial \rho \Delta H}{\partial \tau} + \nabla .(\rho v \Delta H) \tag{14}$$

With this approach the governing equations can be written with a predicted mushy velocity term, v:

$v = v_l \in$ *liquid phase*

$\beta v = v_l \in$ *muzhy zone* (*solid-melt mixture*)

$0 \in$ *solid phase,*

where v_l is the velocity corresponding to the liquid phase. β is the liquid fraction, a parameter ranging between 0 to 1 for entirely solid and liquid phases, respectively.

In their calculations they have chosen the viscosity of melt in the order of 10^3–10^4 Pa s. Using a power-law function they have varied the viscosity with temperature as,

$$\mu = \mu_0 \left(\frac{T}{T_o} \right)^n$$

where, *n* is the temperature exponent (negative), and the subscript denotes the values of viscosity corresponding to the reference temperature. They have modeled the overlying crust as a high-viscosity layer (10^{20} Pa s), attributed to a zero velocity condition, i.e., the layer is treated as a solid phase.

Their RTP models show that the upwelling develops discrete melt zones, forming mushroom patterns (Fig. 2). These melt zones are grossly aligned along the MORs, but displaying a segmented structure, as reported from several mid-oceanic ridges, like Mid-Atlantic ridges. The magmatic segments show remarkable lateral offsets, on a scale of several kilometers. The magma flow field is strongly heterogeneous, where two adjoining magmatic segments have flows in the opposite directions, diverging or converging to each other. The map of the flow field show spectacular delineation of the magmatic segmentation pattern. According to this model, magmatic segments evolve through local convection of melts, forming a characteristic pattern. It is interesting to see the melts to upwell not in the form of a single, homogeneous magma chamber, as typically conceived in pluton tectonics, but in the form of melt channel aggregates. These channel-like structures probably explain the formation of crustal layers with abundant sills and dykes. Using the RTP model Sarkar *et al*. (2014) reproduced transform-like structural discontinuities in their numerical simulations; the magnitude of offsets along them is in the order of 10 to 15 km (Fig. 3). Their model explains the development of transform faults as a spontaneous phenomenon, coupled to the upwelling processes. In a recent study Baruah *et al*. (2014a) have used a reaction diffusion (RD) model to show the melt front migration in a partially molten system. Using diamond-graphite transitions under high pressure and temperature experiments they also provided an estimate for ascent rates of kimberlite magmas generated in mantle, and showed a mechanical model required for the rapid ascent processes (Baruah *et al*. 2013).

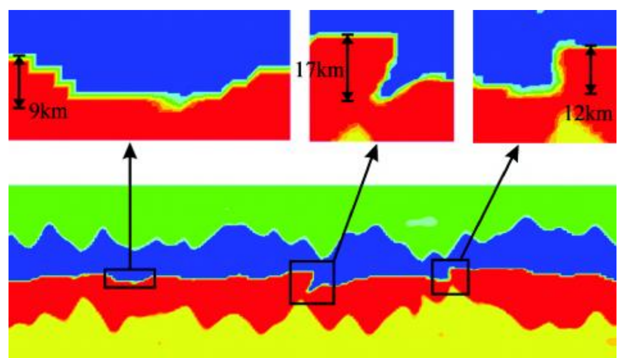


Fig. 3: Offset pattern of mid oceanic ridges in numerical simulation (after Sarkar *et al*. 2014)

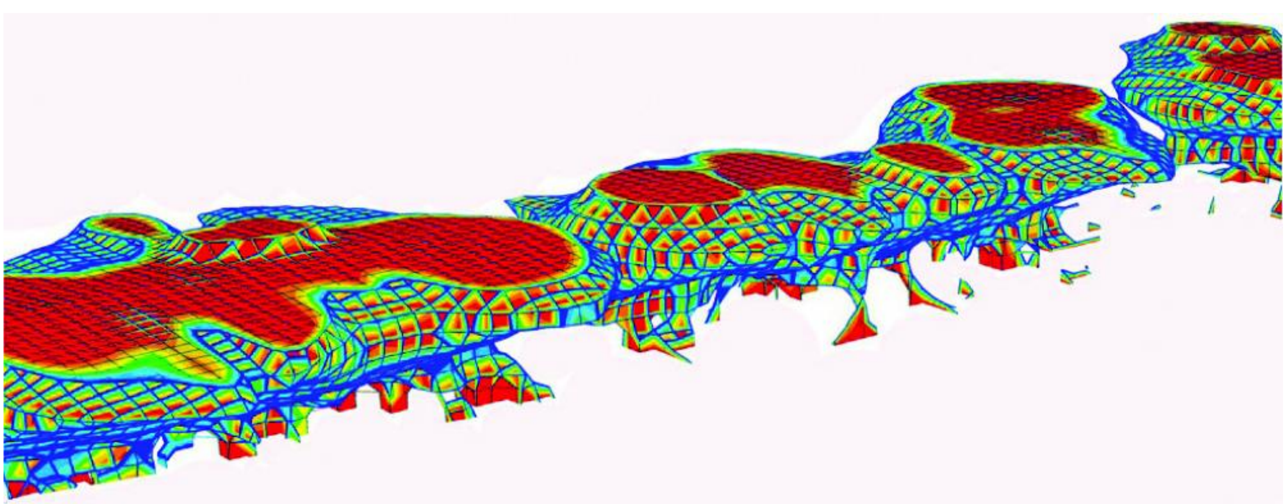


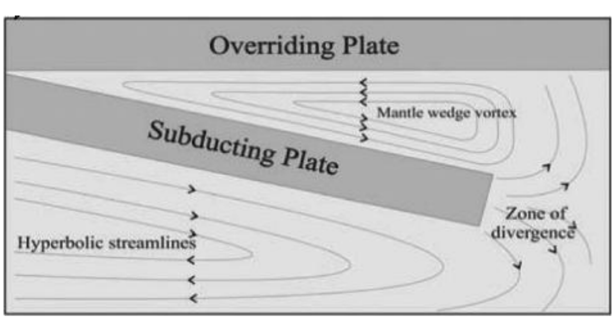
Fig. 2: Melt upwelling patterns along mid oceanic ridges obtained from Random Thermal Perturbation (RTP) models

Subduction Zones

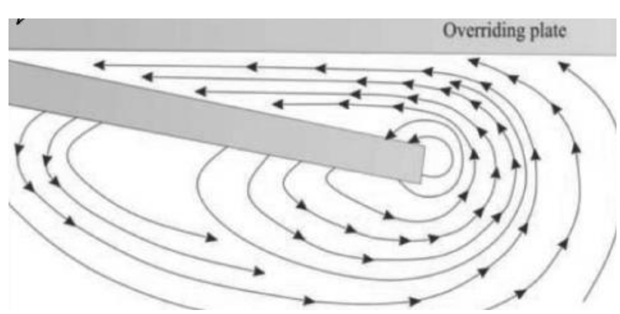
In recent years a new wave has surged up in theoretical and experimental modeling of lithospheric subduction processes, owing to growing interests for a wide range of subuduction-associated geological as well as geophysical phenomena, like island-arc volcanism, trench dynamics, topographic evolution and deep-focus earthquake mechanics. Some of the geoscientists in India have initiated this research; an outline of the theoretical and experimental studies is presented here.

Using finite element (FE) models the Geodynamic research group at Jadavpur University has been engaged in simulation experiments on subduction, accounting different physical factors, such as density contrast. They have considered Maxwell type visco-elastic rheology to develop a subduction model, covering a horizontal distance of 6000 km and a depth of 1600 km, and performed three types of numerical experiments. *Type 1 experiments*: the slab moves downward with a uniform velocity, maintaining a constant subduction angle. These experiments aimed to show independently the effects of subduction rate (*Vs*) and angle (α) on the patterns of flow induced by the subducting lithospheric slab. *Type 2 experiments*: the slab undergoes flexural bending, simulated by applying differential forces across the subducting slab. Type 2 models investigate the role of flexural motion on the local flow in the ambient mantle. *Type 3 experiments*: this was aimed to investigate the nature of flow produced by a detached slab moving downward freely, a phenomenon widely reported in literature as slab detachment. Corner flow model is the most well-accepted flow model to describe the flow patterns in the mantle wedge of a subduction zone. This flow model show a harmonic vortex motion, where the sense of vorticity is consistent with the downward movement of lithospheric slabs. However, the simulations suggest that a typical corner flow pattern develops essentially under specific kinematics of the slabs, characterized by along-slab translational movement, as in their Type 1 simulation experiments (Fig. 4A). Using Type 2 simulations they have demonstrated that flexural motion of lithospheric slabs dramatically transforms the corner flow pattern, and develops large vortices with their centers located at the slab edges (Fig. 4B). They also show varying flexural deformations accounting the effects of depth-dependent density variations in the lithosheric slab and the ambient mantle, which in turn leads to complex flow patterns, developing a secondary downwelling zone.

Scaled analogue experiments are extensively used to study the subduction processes under a given set of boundary conditions. This experimental approach focuses mostly upon the mechanical aspects of lithospheric subduction as there are serious limitations in attaining the thermal structure approximated for Earth's mantle in such experimental condition. In Jadavpur University, a research group is actively engaged in laboratory experiments to deal with the mechanics of subduction. Using analogue fluid models they simulate subduction zones, and investigate the deformation behaviour of lithopheric slabs as they dip into the mantle (Fig. 5). Their experiments bring out possible modes of subduction, and their implications for interpretation of the evolution of natural subduction zones. This group is also employing computational fluid dynamic simulations of subduction processes on real scales.



A



B

Fig. 4: Flow patterns around subducting slabs undergoing (A) translational motion and (B) flexural motion

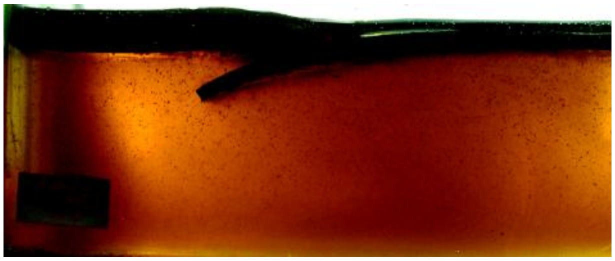


Fig. 5: Laboratory experiments of subduction zones with scaled analog models

Understanding the lithospheric subduction processes is an important issue in the perspective of the geodynamic setting of the Indian plate, the northern and the eastern margins of which are delineated by active convergent plate boundaries. A group of workers from Indian School of Mines have been working on the Indian plate subduction against the Burmese plate. Using seismic data they have constructed a series of E-W profiles of the Benioff zones in the Burma-Java subduction margin, and showed steepening of the subduction angles moving from north to south. This study deciphers the evolution of Andaman convergent tectonics in two phases at 11 Ma and 4-5 Ma. The younger phase is attributed to a steeping subduction angle and trench retreat, leading to an extension required for active back-arc extension, as reported in their earlier publication (e.g., Khan and Chakraborty 2009). Khan (2011) has provided a dynamic analysis of the subducting lithospheric slab to explain the 2004 Sumatra mega-earthquake event, accounting the slab pull versus resistive forces. His study shows that an unbalanced dynamic state has led to such an earthquake event.

Thermal Plumes

Plumes are probably the most important process of heat advection in various earth systems, ranging from atmosphere and solid earth. Geoscientists have dealt with this thermal process owing to its implications in interpreting large scale geological phenomena, like hotspots, large igneous provinces and melt supply to mid-oceanic ridges. A line of geodynamic studies in India has a particular focus on mantle plumes, mainly to explain the spectacular large igneous provinces in Indian craton, such as Decan and Rajmahal traps. Despite a long standing debate on the plume model (Seth, 2005; Sen and Chandrasekharam, 2011), there is a strong view that these large igneous provinces received magmas from melting of thermal plumes originated in the present location of Reunion Island in the Indian Ocean. Here I review some of the studies to show the recent development in experimental and theoretical studies in India.

The Geodynamics research group at Jadavpur University is actively involved in laboratory experiments of plume structures. Their laboratory experiments use analogue fluids, accounting a scaled down approach to the physical properties of the corresponding natural prototype. The viscosity of fluids chosen in this type of experiments is generally in the order of 10 Pa s. Their experiments produced plume-like thermal structures as the relatively hot fluid upwelled in a relatively colder medium (Fig. 6). The research group investigated a specific problem of plume ascent- ballooning versus curling, giving rise to either balloon- or mushroom-like geometry. The mushroom-type has been widely reported from both physical experiments and numerical simulations. However, seismic tomography rarely detects this type of plumes. Dutta *et al*. (2013) have addressed this issue- why mushroom type plumes are rarely detected in Earth's mantle (Fig. 7). They have used a computational fluid dynamics (CFD) approach to simulate thermal plumes in numerical models. Their CFD models were developed employing a volume-of-fluid (VOF) formulation for describing the two-phase fluid system. The fundamental step of the VOF is to define the phase boundary with the help of a function, called phase indicator function, where the

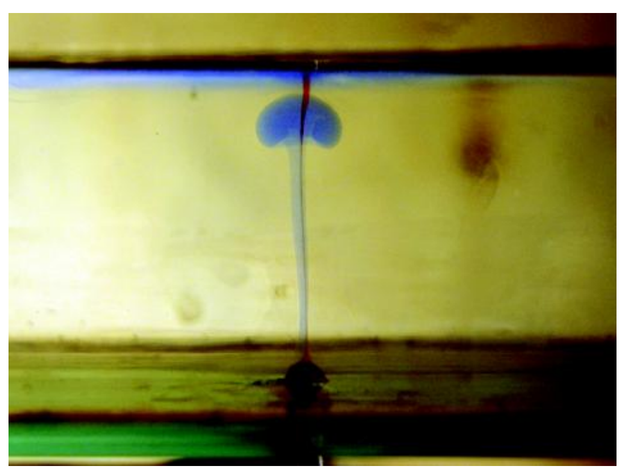


Fig. 6: Laboratory simulation of thermal plumes by injecting a hot fluid into a relatively colder, stationery viscous fluid

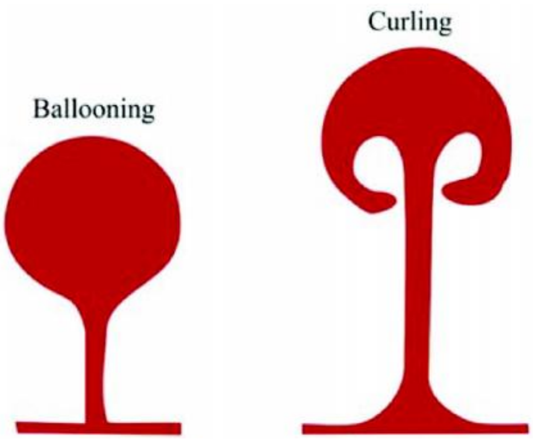


Fig. 7: Two principle types of thermal plumes: balloon- and mushroom- shaped heads

function is assigned to 0 and 1 for the end-member fluid phases, and to a value between 0 and 1 at the interface between the two phases. Their CFD models show that the shapes of a plume defined by the thermal boundary significantly differ from that defined by a phase boundary (Fig. 8). This finding suggests that seismic tomography possibly reveals thermally defined shapes, which do not show any strong mushroom geometry.

In many cases plumes evolve in pulses forming pinched-off structure, as reported from a wide range of physical settings (Dutta *et al*., 2013). The research group at Jadavpur University also focused their study upon the mechanics of jet ascent, with a motivation for explaining the factors leading to transitions of typical balloon or mushroom-shaped to pinched-off geometry of jets. In a recent study they investigated the ascent behavior of non-breaking bulbous jets. Using the VOF method they have shown that the ascent process of jets can undergo transformation from a continuous mode (called *Mode 1*) to a pulsating mode (called *Mode 2*). Mode 1 gives rise to either balloon or mushroom-shaped plumes, whereas Mode 2 produces plumes with plumes with pinched-out tails. They have shown these contrasting modes of ascent behaviour as a function of viscosity ratio and Reynolds number (Fig. 9).

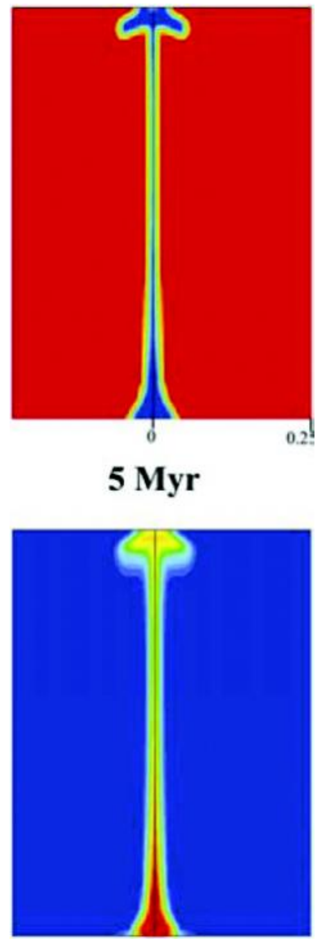


Fig. 8: VOF simulations of thermal plumes in numerical models

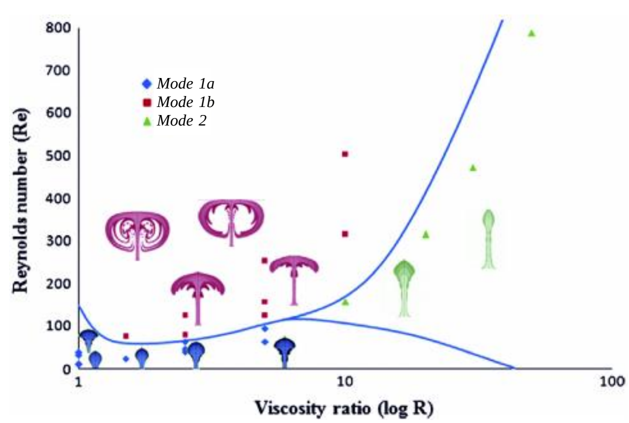


Fig. 9: Conditions of continuous (Mode-1a: ballooning and Mode-1b: curling) and pulsating (Mode-2) plumes

An Outlook

Most of the geological phenomena, ranging from surface topography to craton formation are governed by the processes operating in Earth's deep interior. A large part of the subject- geodynamics looks at how these processes operate and what are their governing factors. Geodynamics has thus gained an enormous importance in earth sciences across the globe, leading to new research fronts with a multi-disciplinary approach, where researchers from different branches of sciences, like physics, mathematics and engineering join their hands to tackle complex problems on a wide range. With this development we now have a better understanding of thermo-mechanical processes involved in the plate dynamics and its role in controlling different geological phenomena, e.g. earthquakes and volcanisms.

The geosciences in India are traditionally driven by field observations and their post-processing. In recent years this trend has taken a new turn, with the applications of geodynamic models in interpreting crustal processes. This direction has further strengthened with geophysical studies, especially in seismology. For example, we have now a better constraint on the subduction pattern of Indian lithospheric slab beneath the Himalaya-Tibet Mountain system. A line of research groups in India are engaged in geodynamic studies with a theoretical and experimental approach. Their work provides new insights into thermo-mechanical processes, like plume ascent and melting-solidification processes in mid-oceanic ridges. This trend of geodynamics in India is expected to strengthen in near future since a significant number of young geoscientists have started their research career in the field of theoretical and experimental geodynamics.

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