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Underlying dynamics of lithospheric plates and their controls on surface topography

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Abstract

The lithosphere forms the mechanically strongest and outermost layer of the Earth, with its thickness varying from approximately 100 km in oceanic regions to about 150 km in continental regions. Lithospheric dynamics govern nearly all tectonically driven geological phenomena, including plate boundaries (sites of intense tectonic activity), mountain formation, and large-scale topographic developments in both continental and oceanic regions. Geophysical observations and geological evidence suggest that the mechanical and thermo-mechanical interactions between the lithosphere and the underlying mantle play a crucial role in shaping different dynamic regimes in the lithosphere, such as convergent and divergent plate boundaries, intra-cratonic rifting, and epeirogenic movements. Consequently, an important area of research focuses on conceptualizing large-scale mantle flow processes, e.g., thermal convection, slab movements, and plume ascent, to better understand lithospheric dynamics. Each of these processes creates a distinct dynamic environment in the lithosphere, characterized by specific geological and geophysical responses. Large-scale surface topography is a prominent manifestation of geodynamic processes in the mantle. However, establishing a quantitative relationship between mantle dynamics and surface topography poses complex challenges, and addressing such problems often requires an interdisciplinary approach. This thesis explores a set of outstanding topographic issues in critical tectonic regimes of Earth's lithosphere, as outlined below.

A part of this thesis deals with the origin of contrasting crustal topography in mid-ocean ridge (MOR) systems. Although there has been a significant research advancement on divergent plate boundaries and their associated phenomena, the problem of MOR axial topography is still inadequately explained. Consequence, this has remained a subject with many open ended questions. A part of the thesis work utilizes an interaction dynamics of the elastic oceanic crust with the underlying mush complexes (MC) to constrain the axial topography of MORs. The effective bulk viscosity (μ_{eff}) of MC beneath MORs is projected as the crucial mechanical factor in modulating their axial high versus flat topography. Based on a two-stage viscosity calculation, utilizing the suspension and solid-melt mixture rheology, this work provides a theoretical estimate of μ_{eff} as a function of melt suspension characteristics (crystal content, polymodality and polydispersity, strain-rate), its volume fraction in the MC region. Subsequently, this study develops a solid (elastic lithosphere) – fluid (melt-rich mantle region) finite model to test the control of μ_{eff} on the axial topography. The model couples an enthalpy-porosity based fluid formulation to implement a one-way fluid-structure interaction (FSI) that transmits the dominating normal viscous force to the overlying lithosphere. The limiting non-rifted topographic elevations (-0.06 km to 1.27 km) of natural MORs are found to occur in the range $\mu_{eff} = 10^{12}$ to 10^{14} Pa s. The higher end (10^{13} to 10^{14} Pa s) of this spectrum produces axial highs, which are replaced by flat or axial valley topography as $\mu_{eff} \leq 5\text{x}10^{12}$ Pa s. The present thesis uses the FSI model to explain the following MOR phenomena: topographic stability, co-existence of melt-poor and -rich conditions in a ridge, and local variations of axial topography in fast-spreading ridges.

Geophysical evidence suggest that MOR systems evolve in strongly heterogeneous stress environments. However, the origin of such stress complexity still awaits a comprehensive explanation, which is the central theme of the present thesis. This study develops a thermo-mechanical model to demonstrate the multi-ordered 3D convective circulations, produced by decompression melting in the mushy region, as the key factor to modulate the MOR dynamics. The model mechanically couples the sub-ridge mushy regions with the elastic crustal layer within a mathematical framework of FSI mechanics. FSI model simulations show that the heterogeneous stress field of a MOR forms characteristic segmented patterns on a time scale of million years, resembling axial as well as off-axis topographic morphologies observed in MORs. This work provides a model calculated estimate of the total stress tensor, focusing on the following components: across- and along-axis horizontal tension / compression ($\sigma^{\perp}$ and $\sigma^{/\!/}$) and across-axis horizontal shear stress ($\sigma^{\#}$) that dominantly control the ridge-axis morphologies. The stress mapping reveals a distinct 30 km wide axial zone of tensile $\sigma^{\perp}$ localization (median < 250 MPa), whereas compressive $\sigma^{\perp}$ localization (median < 100 MPa) in off-axis ridge-

parallel linear belts on either side of the MOR axis. This finding leads to an alternative explanation for the off-axis ridge-parallel second-order hill topography, located at a distance of 20 km to 50 km, as a consequence of compressional $\sigma^{\perp}$ localization. Along-axis compressional $\sigma^{\parallel}$ concentrates in a row of ridge-normal narrow, 10 to 30 km wide stripes, giving rise to segmentation of the stress field on a wavelength of 40-150 km, which conforms to the second-order magmatic segmentation patterns of MORs. From $\sigma^{\#}$ mapping, it is also shown that ridge-transverse discontinuities, including transform offsets and transpression zones originate spontaneously from the FSI interactions during the MOR evolution.

The cause of eastward tilting of the Indian Peninsular (IP) plateau is a lively issue of ongoing debate in geoscience. This thesis invokes a fresh geodynamic perspective, employing extensive topographic analyses to recognize the mechanisms behind this tilting. By analyzing the eastward-flowing river systems in relation to the plateau's tilt, we constructed a series of east-west topographic profiles using digital elevation models (DEM). The DEM findings indicate a steady increase in eastward slopes (θ = 0.008° to 0.3°) from the northern boundary to the southern tip of the plateau. Large-scale thermo-mechanical simulations reveal that the configuration of the Indian plate plays a crucial role in driving this tilt. Specifically, this study finds that the older lithosphere beneath the Bay of Bengal (age ~ 140 Ma) has undergone subsidence at a significantly faster rate than the younger lithosphere beneath the Arabian Sea (age ~ 60 Ma). This differential subsidence has set in westward sub-lithospheric flows beneath the Indian Peninsula, interacting with east-directed mantle flows originating from regions below the Arabian lithosphere. This interaction has resulted in a localized mantle upwelling at the Western IP margin, contributing to the Western Ghats Escarpment (WGE) formation. Furthermore, we examine spatial variations in sub-lithospheric flow patterns to account for the increasing θ towards the south. The present findings suggest that the eastward topographic tilt of the IP originates from sub-lithospheric mantle dynamics, driven by lithospheric density contrasts between the Bay of Bengal and the Arabian Sea. The present thesis provides valuable insights into the drainage patterns in IP.

An important direction of the thesis focuses on the problem of plume-lithosphere interaction, which is thought to be a critical process involved in the development of many continental rift system. Using numerical models, a part of this study explores the structural evolution of a rift formed under the influence of a mantle. Additionally, the response of a pre-existing rift to a specific plume event is investigated to deal with the Indian rift systems. Indian craton comprises a number of old rifts, e.g., the Narmada and the Godavari rifts, which reactivated in multiple stages during the supercontinent breakup events. The latest reactivation of the Indian rift system occurred at the Cretaceous-Tertiary boundary when the Réunion plume interacted with the Indian plate, leading to the massive Deccan volcanism at 66 Ma. Although the plume-driven rift tectonics has been a subject of lively research over past decades, how a pre-existing rift system can modulate the plume dynamics, particularly in continental settings, remains inadequately explored. This study addresses this problem in the context of the Réunion plume encountering the Indian lithosphere. 2D thermomechanical models are developed to simulate plume-rift interactions, systematically investigating the modes of interactions as a function of plate velocity (V_p) and plume–rift (δ) distance. Numerical experiments reveal that small δ (< 250 km) or high V_p (> 1cm/year) conditions redirect a large portion of the plume material towards the pre-existing rift, resulting in significant underplating beneath the rift undergoing reactivation. Increasing δ or lowering of V_p weakens the plume-rift interaction, leaving the pre-existing rift zone almost passive, where the underplated plume materials stagnate beneath the rift with little melting. The model results suggest that the Narmada rift, which was closer to the Réunion plume, caused significant deflection of the plume and its melting with Moho upwrapping. In contrast, the Godavari rift, located at a larger distance from the plume, behaved passively, allowing underplating of the plume at the lithospheric base with no significant melting and Moho downwrapping, as supported by geophysical observations. Finally, this thesis provides a new insight into the differential responses of the Indian rift system during the Reunion plume event.

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