Index No. 55/19/Geol. Sc./26

MECHANICS OF INSTABILITY-DRIVEN GEODYNAMIC PROCESSES: A THEORETICAL AND EXPERIMENTAL STUDY

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Abstract

A variety of geodynamical phenomena originate from mechanical, thermo-mechanical, and thermo-chemical instabilities in Earth's interior. These dynamic instabilities are triggered by inherently or induced unstable mechanical states of a system, tending to achieve a stable mechanical state under a given set of physical conditions. These destabilizing actions set in motion, which in turn operates tectonic activities on different scales, ranging from local to planetary scale. The present thesis focuses on four major types of instability-driven geodynamic processes, with an objective to explain the evolutionary dynamics of lithospheric scale tectonic systems.

A direction of this thesis concerns the problem of primary plumes originating from deep-mantle sources (buoyant layers) located at the core-mantle boundary. Their formation is subject to Rayleigh-Taylor (RT) instabilities, which critically determine the initiation of a plume and its subsequent growth. Previous studies investigated the mechanics of RT instabilities, taking into account various physical parameters, such as density, viscosity, and the relative proportions of layer thickness between the denser overlying layer and the buoyant source layer. None of these studies, however, addressed a crucial question- how the presence of horizontal unidirectional global flows in Earth's mantle can influence the plume mechanics. A part of this thesis combines the results from 2D computational fluid dynamics (CFD) model simulations with a linear stability analysis to resolve the issue, showing that the global flow acts as a counter factor to dampen the growth rate of instabilities. At a threshold global flow velocity, the dampening effects completely suppress instabilities, allowing the entire system to advect in the horizontal direction. Furthermore, the stability analysis predicts a non-linear increase in the instability wavelength with increasing global flow velocity, implying lowering of the spatial plume frequency in kinematically active regions of Earth's mantle. This study leads to a new hypothesis for unusually large spacing between major hotspots scattered around the globe. The present thesis investigates another important gravitational instability to explain the development of "same-dip" double subduction systems. Understanding the dynamics and evolutionary pathways of such complex tectonic systems is pivotal to unravel the enigmatic and anomalous geological observations from both paleo and presently active convergent plate boundaries. This study aims to explore the coupled evolution of two subduction zones that are spatially separated, but mutually influencing each other. Using CFD models it is demonstrated that they can initiate spontaneously and evolve self-consistently, but in a competing mode depending on the tectonic settings. The initiation and stabilization of a second subduction zone switches transformation of a single subduction into a self-sustaining double subduction system, or vice versa. Three plate tectonic settings considered for this double-subduction modelling yield the following results. 1) Oceanic setting: the second subduction initiates within a large oceanic plate, 2) oceanic-continental setting: the second subduction initiates at the margin between an oceanic plate and a continental block, and 3) multiple continental setting: double

subduction initiates in the presence of multiple continental blocks but reverts back to a single subduction setting due to slab detachment. The effects of dynamic variations of the double subduction system on the Moho boundary of the descending slab and the temperature distribution along the slab's top surface are also investigated. The modelling establishes a set of distinctive imprints of double subduction systems that can be used to reconstruct the evolution of tectonic plate configurations. For validation, the thesis compares the model findings with real-world examples of same-dip double subduction systems.

The geological history of the Himalaya-Tibet Mountain Range reveals two significant extensional tectonic events driven by gravitational collapse, which is a consequence of topographic instability. It has been shown from geological evidences that a north-south extension occurred in the Himalaya-Tibet transition zone, active from 22 Ma to 11 Ma, coupled with another extensional tectonic event, but in the east-west direction that occurred in southern and central Tibet, starting at around 18 Ma and persisting until approximately 4 Ma. The E-W extension had a time overlap with the north-south extension for about 7 Ma. This thesis investigates the driving factors of these two extensional tectonic events. It is demonstrated from laboratory experiments that a decrease in the India-Asia convergence velocity resulted in a gravitational collapse of the Tibetan plateau, which in turn initiated both extensional events, but in different mechanisms. In the southern Tibet region, pressure relaxation in the underlying Himalayan wedge caused gravitational collapse, leading to north-south extension between 22 and 11 Ma. In contrast, the rigid Tarim block in north-western Tibet induced differential topographic uplift from west to east during the initial rapid stage of the India-Asia collision (dating back to over 22 Ma), which subsequently underwent gravitational collapse, setting in eastward crustal flows and E-W extensional tectonics between 18 and 4 Ma.

The final part of the thesis is dedicated to examine mechanisms of strain localization in the perspective of an instability-driven geodynamic process, with an aim to address the problem of secondary shear band formation and their spatial patterns in ductile shear zones under simple shear kinematics. Field studies in Eastern India, reveal the presence of extensive deformation bands (C-bands) parallel to the shear direction on both micro- and macro scales. Interestingly, laboratory-scale simple shear experiments with wet sand (Coulomb) and putty (visco-plastic) showed different band structures: low-angle and high-angle shear bands in sand, and a single set of low-angle shear bands (LSB) in putty. To explore the cause of this discrepancy, 2D CFD models are employed based on viscoplastic rheology. The models revealed that the C-band and LSB formation compete with each other and their competing growth depends on the shear zone parameters: geometric (shear zone thickness), kinematic (shear rate), and rheological (bulk viscosity). Two non-dimensional factors are identified, a dynamic factor (Ω) and a geometric factor (δ), to constrain the conditions of LSB and C-band formation. A theoretical analysis is presented to predict the shear band orientations as a function of these factors.

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01.08.2023

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