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An Integrated Observational, Experimental and Computational Study of Plume-Ridge Interaction

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Project Summary

The existence of sub-horizontal channels connecting hotspot plumes and spreading ridges has been suggested by recent observationally based studies. These features have important consequences for understanding mantle dynamics and the manner in which the mantle interacts both thermally and chemically with Earth's surface. A striking result has been the importance of a sloping rheological boundary layer, resulting from the combination of variable fluid viscosity and plate spreading, in modulating channel development and evolution. Comparison of results in 2D and 3D experiments clearly indicate the limitations of 2D representations of flows which include both small scale plumes within a larger scale shear flow.

2D experiments investigate higher order physical effects such as thermo-chemical plumes and relative motion between plume source and ridge axis. These effects are best studied first in the more simplified 2D geometry.

Experiments completed to date have significantly increased our understanding of the process of communication between plumes and ridges. This initial stage of funded research has also lead to increased interaction between observation and theory. As an example of this, Kincaid was invited to participate in a data collection cruise to Easter Island-EPR system designed to study plume-ridge interaction.

Background Informatin/Research Objective/Goals

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Mantle plumes and passive upwelling beneath ridges represent the dominant modes of thermal and chemical transport between the Earth's internal and surficial dynamical systems: core-mantle and ocean-atmosphere. Recent observational studies have shed new light on plumes and ridges and, more importantly, the dynamical interaction between ridges and plumes. The existence of sub-horizontal channels linking hotspot plumes and spreading ridges over length scales of up to 1000km is suggested by geochemical and seismic tomography data sets.

The existence of these channels have implications not only for our understanding of mantle evolution but more importantly how the mantle transmits heat and chemical constituents to Earth's surface. Here we present results from numerical experiments which incorporate the essential physics of the plume-ridge-upper mantle system. These experiments clearly indicate that both transient and steady state channels may be established for a range in realistic mantle conditions. By examining the influence of spreading velocity, plume buoyancy and upper mantle viscosity structure we are able to define the controlling factors in plume channel evolution.

Important to LANL's Science and Technology Base and National R&D Needs

The numerical modeling techniques developed for this project have applications in the much broader field of computational fluid dynamics. Areas of interest within EES-5 include modeling of magma chamber dynamics, porous flow and hydrology heat and mass transfer. This research into mid-ocean ridge dynamics is also important to understanding heat transfer from the earth's interior to the ocean.

Scientific Approach, Progress and Results to Date

A series of 2D experiments have been conducted in which the basic model setup consists of a spreading ridge and a stationary source source of compositionally buoyant plume material. Morphological features of these plumes include both the transient plume head and the longer term trailing conduit. Convection within the 2D Cartesian domain is a combination of forced and free convection driven by plate motions and plume buoyancy, respectively. A variable, temperature-dependent viscosity is employed within the convecting fluid to allow for an upper rheological boundary layer (RBL). The thickness and near-axis slope of the RBL are controlled by the parameter, E , which is related to activation energy. Besides RBL slope, or E , other important parameters where plume buoyancy and plate velocity which are governed by a dimensionless compositional Rayleigh

number, RB , and Peclet number, Pe , respectively. We find that in 2D, the development and long term persistence of sub-horizontal channels between hotspot and ridge are possible and are strongly modulated by 1) morphology/slope of upper rheological boundary layer, 2) plate velocity, 3) plume buoyancy and 4) plume- ridge separation distance. Figures 3a and 4 illustrate the role of RBL slope on channel evolution and chemical communication for the range $E=0$ (no RBL; constant viscosity) to $E=30$ (thick, sloping RBL). For the case with a gradual RBL slope, or $E=3$, a transient channel is established (Figure 4b) which is eventually overwhelmed by the divergent large scale flow (Figure 5a). A steady channel which continually feeds plume material to the ridge axis results in the steeply sloping case ($E=30$) as shown in Figures 3c, 4c and 5b. Most striking, however, is the complete absence of transient or steady channels in cases where the fluid has a constant viscosity. As expected increasing plate velocity and/or decreasing plume buoyancy preclude channel development and the plume conduit bends away from the ridge axis, with the large scale flow.

The laboratory portion of this study is just getting under way. The tanks are now built and apparatus for modeling spreading plates have been designed and constructed. Preliminary experiments have been performed which give us confidence the apparatus will be up and running for modeling situations which have been investigated with numerical models.

Planned Work for the Next FY and Beyond

The continuation of this work will involve construction of more elaborate laboratory experiments, investigation of a wider range of parameter controlling plume ridge interaction and continued work on modeling what has been observed at Sally Gomez ridge.