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Interface Deformation in Low Reynolds Number Multiphase Flows:
Applications to Selected Problems in Geodynamics

Carl Gable, LANL

R. J. O'Connell, Harvard University

H. A., Stone, Harvard University

B. J. Travis, LANL

Project Summary

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Flow in the mantle of terrestrial planets produces stresses and topography on the planet's surface which may allow us to infer the dynamics and evolution of the planet's interior. This project is directed towards understanding the relationship between dynamical processes related to buoyancy-driven flow and the observable expression (e.g. earthquakes, surface topography) of the flow. Problems considered include the ascent of mantle plumes and their interaction with compositional discontinuities, the deformation of subducted slabs, and effects of lateral viscosity variations on post-glacial rebound.

We find that plumes rising from the lower mantle into a lower-viscosity upper mantle become extended vertically. As the plume spreads beneath the planet's surface, the dynamic topography changes from a bell-shape to a plateau shape. The topography and surface stresses associated with surface features called arachnoids, novae and coronae on Venus are consistent with the surface expression of a rising and spreading buoyant volume of fluid. Short wavelength viscosity variations, or sharp variations of lithosphere thickness, have a large effect on surface stresses (thus, dynamic topography and geoid).

This study also considers the interaction and deformation of buoyancy-driven drops and bubbles in low Reynolds number multiphase systems. Applications include bubbles in magmas, the coalescence of liquid iron drops during core formation, and a wide range of industrial applications. Our methodology involves a combination of numerical boundary integral calculations, experiments and analytical work. For example, we find that for deformable drops the effects of deformation result in the vertical alignment of initially horizontally offset drops, thus enhancing the rate of coalescence.

Background Informatin/Research Objective/Goals

Flow in the mantle of terrestrial planets produces stresses and topography on the planet's surface which may allow us to infer the dynamics and evolution of the planet's interior. The first part of this project is directed towards understanding the relationship between dynamical processes related to buoyancy-driven flow and the observable expression (e.g. earthquakes, surface topography) of the flow. Problems considered include to ascent of mantle plumes and their interaction with compositional discontinuities, the deformation of subducted slabs, and the effect of lateral viscosity variations on post-glacial rebound.

The second part of this study considers the interaction and deformation of buoyancy-driven drops and bubbles in low Reynolds number multiphase systems. Applications include bubbles in magmas, the coalescence of liquid iron drop during core formation, and a wide range of industrial applications.

The goal of the proposed research is twofold: we would like to study numerically the effect of buoyancy, geometry and rheology on simple mantle and volcanic processes, and also develop simple relationships between these parameters and observable geophysical and geological phenomena. To this end, a combination of numerical, experimental and analytic work will be required. The properties of buoyancy, geometry and rheology can be considered to be zeroth order governing parameters for a number of geodynamic processes since they may play a dominant role in dynamic behavior.

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

Many of the effects we are interested in studying often cannot be studied in the more conventional and complicated thermal models because unrealistically high chemical diffusivities must be assumed. Our numerical boundary integral approach offers a stable method to calculate multiphase flows with zero diffusion.

Since an important part of this work deals with developing methods to describe deformable interfaces, the techniques developed in this study may eventually be integrated into more complicated geodynamic models which include thermal effects and phase changes. While we are interested in geodynamic processes, the methods and results are directly applicable to problems in chemical engineering, petroleum extraction, the behaviour of cells and suspensions in biological systems, and with some modification to a much wider class of problems including problems in hydrology.

Scientific Approach, Progress and Results to Date

Approach

The work completed to date has involved a combination of numerical, experimental and analytical methods. We use a boundary integral method for the numerical calculations: two-dimensional, axisymmetric and three-dimensional geometries are considered. The advantage of the boundary integral formulation

is the reduction of problem dimensionality: volume integrals are converted to surface integrals and only the deformation of interfaces needs to be evaluated. Not only does this reduce the amount of CPU time and computer memory required, it also allows us to study very detailed geometries with a resolution not possible with finite-element or spectral methods.

Part of study involves performing complementary laboratory experiments to verify the reliability of the numerical results and to consider geometries, rheologies and boundary conditions which cannot be studied numerically. During the past year, we have successfully done preliminary work comparing experiments and calculations for both plumes and slabs in a compositionally layered mantle, and studies of two-drop interactions. Experiments were done with corn syrup and glycerin solutions.

Results

During FY93 we have focussed on the ascent of mantle plumes and their interaction with compositional discontinuities, the effect of lateral viscosity variations on post-glacial rebound, the deformation of subducted slabs, and the interaction of bubbles in magmas and lavas.

i) Plumes and compositional discontinuities

We find that rising plumes passing from the lower mantle to a lower-viscosity upper mantle become extended vertically before impinging on the surface. As the plume spreads beneath the planet's surface, the dynamic topography changes from a bell-shape to a plateau shape. The topography and surface stresses associated with arachnoids, novae and coronae on Venus are consistent with the surface expression of a rising and spreading buoyant volume of fluid.

ii) The effect of lateral viscosity variations on mantle flow

Short wavelength viscosity variations, or sharp variations of lithosphere thickness, have a large effect on surface stresses (thus, dynamic topography and geoid). Sea-level change data, which is often collected near ocean-continent boundaries will be particularly sensitive to variations of lithosphere thickness associated with the ocean-continent boundary or the presence of a continental tectosphere.

iii) Deformation of subducted slabs

Using a combination of numerical and experimental methods we studied the time-dependent deformation of subducted lithospheric slabs. We find that a wide range of styles of slab deformation may arise depending on the density of

the slab relative to the lower mantle and the viscosity contrast between the slab and mantle. For sufficiently thin slabs and large viscosity contrasts, slabs will buckle.

iv) Interaction of bubbles in magmas

Our methodology involves a combination of numerical boundary integral calculations and experiments for large deformations, and scaling analyses and a perturbation solution for small deformations. An example of an experiment for two air bubbles in corn syrup is shown in figure 1, and an example of a calculation for two drops is shown in figure 2. We find that for deformable drops, the effects of deformation result in the vertical alignment of initially horizontally offset drops, thus promoting the rate of coalescence.

Planned Work for the Next FY and Beyond

During the summer of FY 1993 we have successfully developed and tested a three-dimensional boundary integral code. We are now able to begin studying some inherently 3D problems, figure 3. For example, we will consider the distribution of stresses in subducted slabs -- we will study the effect of radial viscosity variations in the mantle, viscosity contrasts between the slab and mantle, geometric effects (variable slab length, width, thickness, shape, etc.) and the effects of background mantle flow on the magnitude and distribution of stresses within the slab. Calculated stresses can be compared to observed stresses inferred from deep earthquakes.

We also intend to continue studying the behaviour of drops and bubbles in multiphase systems. The completed preliminary work has focussed on a simple model two-drop problem. We will extend these results to many-drop systems. We will also study the effects of external flows, such as shear flows, on the interaction of drops in multiphase systems.

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