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Interactions between mantle diapirs

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Abstract. Experimental, theoretical, and numerical results are presented for the dynamics of interacting and deforming diapirs. The clustering of diapirs may occur as a result of the deformation induced by their mutual interactions. The time required for two diapirs in the mantle to merge can be small compared to their ascent time. The clustering of many diapirs, however, is a relatively slow process and is unlikely to significantly affect their distribution in the Earth's mantle. If coronae on Venus are produced by diapirs, diapir clustering may explain the variation of coronae size, and may be related to the observed clustering of coronae on the surface.

Introduction

Mantle plume heads are thought to be responsible for the formation of large flood basalt provinces, and hotspots are often attributed to conduits or "tails" that follow behind plume heads [e.g. *Richards et al.,* 1989]. Features resembling plume heads followed by tails are commonly observed in numerical and experimental studies of mantle convection, and form naturally at thermal boundary layers.

Most studies focusing on the details of plume dynamics consider single plumes and plume heads. However, *Kelly and Bercovici* [1997] found that diapirs formed by a Rayleigh-Taylor instability were sufficiently numerous that they could interact and migrate laterally to form clusters. *Kelly and Bercovici* [1997] suggest that the long-wavelength spatial distribution of hotspots on the surface may be due to clustering of plumes and that large plume heads may develop from the clustering of many smaller plume heads. Because the amount of mantle entrained by plumes as they rise through the mantle depends on their size relative to the distance they travel [e.g. *Farnetani and Richards,* 1995], clustering would affect inferences of the nature, size, and distribution of geochemical mantle reservoirs.

Here we review theoretical, numerical, and experimental results related to diapir interaction and clustering. We then present numerical calculations that allow us to determine the conditions under which diapir interactions will affect their transit and interaction through the mantle and the resulting distribution of associated features on the surface. We find that small numbers of diapirs may indeed merge within the Earth's mantle, but that their coalescence will not significantly affect their global distribution. On Venus, however, the spatial- and size-distribution of coronae (features often associated with mantle diapirs) may result from diapir interaction and clustering within the Venusian mantle.

Interaction of two diapirs

In figure 1 we show a sequence of photographs of two air bubbles rising and interacting in corn syrup. Relative to the larger bubble, the small air bubble is advected around, and then sucked into the back of, the larger one. These peculiar dynamics are not due to the presence of an inertial wake, because the Reynolds number is about 10^{-3} (i.e. inertial effects are negligible); rather, they are due to the mutual deformation induced by the interaction of the bubbles. Unlike diapirs in the mantle, there is surface tension between the air and corn syrup; in this experiment, however, the bubbles are sufficiently large that surface tension forces are only about 2% of those associated with buoyancy and thus dynamically unimportant [*Manga and Stone,* 1993].

In order to put the dynamics observed in figure 1 in context, we begin by considering the interaction of spherical diapirs [*Manga and Stone,* 1993], shown in figure 2a. Relative to the larger sphere, the smaller one is advected around the larger. The horizontal offset of the

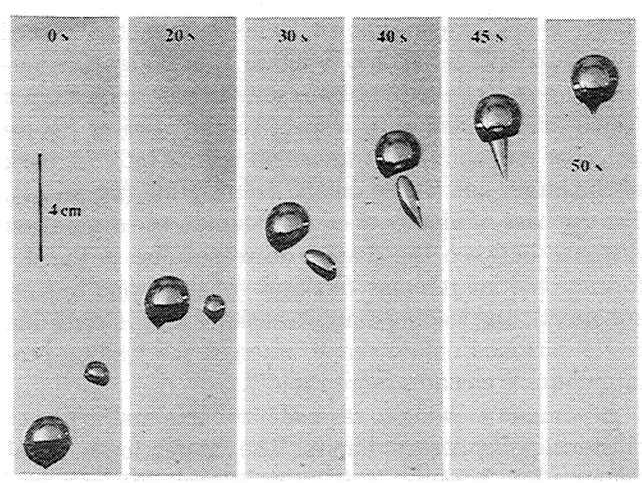

Figure 1. Photographs of air bubbles in corn syrup. Inertial and surface tension effects are dynamically negligible.

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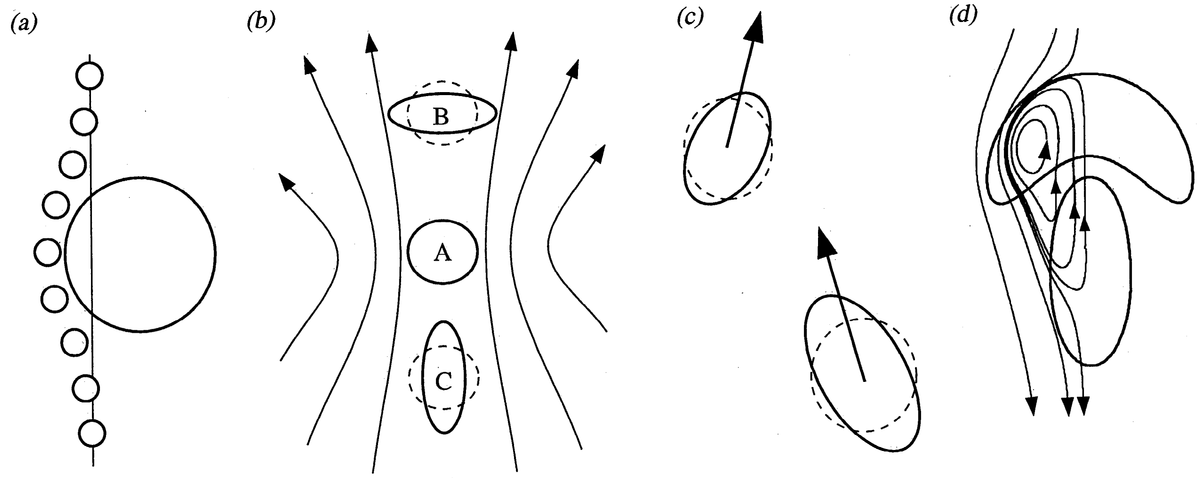

Figure 2. Summary of results for two interacting diapirs [after *Manga and Stone*, 1993]. a) Interaction of spherical diapirs. b) Deformation associated with interactions. c) Deformation of two interacting and horizontally offset diapirs. d) Calculated streamlines (in a frame of reference moving with the larger leading diapir) for interacting and deforming axisymmetric diapirs showing the deformation-induced wake that entrains the smaller trailing diapir.

smaller sphere at a given distance in front and behind the larger sphere must be identical because of the reversibility of Stokes flows. This reversibility is a consequence of the linearity of Stokes equations (equations of motion valid for Newtonian fluids at Reynolds numbers $\ll 1$) and holds provided the spheres do not deform. The idea of reversibility is a powerful and simple tool: here, it allows us to conclude that the separation and relative orientation of two spheres of equal size will remain fixed as the spheres rise. Analytical solutions for the motion of spherical diapirs (for all viscosity ratios with the surrounding mantle) are derived by *Kim and Karrila* [1991, p. 200].

Bubbles in corn syrup and diapirs in the mantle are deformable, however. Consider the flow field created by a translating diapir (diapir A in figure 2b). Streamlines diverge in front of this diapir, whereas they converge behind it. The flow created by diapir A will thus flatten diapir B and extend diapir C. This is, in fact, observed in the experiment shown in figure 1, although the horizontal offset of the bubbles results in deformed shapes which are inclined with respect to the vertical (figure 2c). The entrainment of the small bubble into the back of the larger one is also due to deformation (figure 2d). For the case of diapirs of equal volumes, the separation distance between the diapirs decreases due to the deformation (but remains constant if the diapirs remain spherical): the leading diapir translates more slowly due to its flattened oblate shape, whereas the trailing prolate diapir translates more rapidly.

In summary, owing to reversibility there can be no net clustering of spherical diapirs. The interaction-induced deformation, however, breaks this reversibility, and produces the clustering observed by *Kelly and Bercovici* [1997]. Numerical and experimental results, as well as theoretical results valid for all viscosity ratios, are presented for the interaction between two deformable drops, bubbles or diapirs by *Manga and Stone* [1993, 1995].

Clouds of diapirs

In order to quantify the importance of interactions on diapir dynamics, we performed a set of numerical simulations of the rise, interaction and deformation of diapirs in "clouds" of N three-dimensional diapirs. Because it is the interaction-induced deformation of diapirs which ultimately leads to their aggregation, as discussed in the previous section, we let all the diapirs have the same volume so that changes in their separation distances can be attributed to their deformation and not a spatial redistribution resulting from different rise speeds associated with different radii. *Manga and Stone* [1995] show that the clustering rate is highest for equal-size diapirs.

We randomly position ten ($N = 10$) initially spherical diapirs with radius a in a spherical region with radius $5a$ (so that the volume fraction of diapirs was 8%). The typical separation distance between diapirs is $3a$. Calculations were performed using the boundary integral approach described in *Manga and Stone* [1995] in the limit of vanishing interfacial tension. The numerical technique involves recasting Stokes equations as integral equations (the problem is non-linear because the shape and position of the diapirs must be determined as part of the solution). The shape of each diapir is described by 1044 triangular elements. Each calculation required 5 days on a sparc server 1000. Because of the long computation times, we were limited to the consideration of diapirs which have the same viscosity as the surrounding mantle. However, the calculations and analytical results presented by *Manga and Stone* [1993] indicate

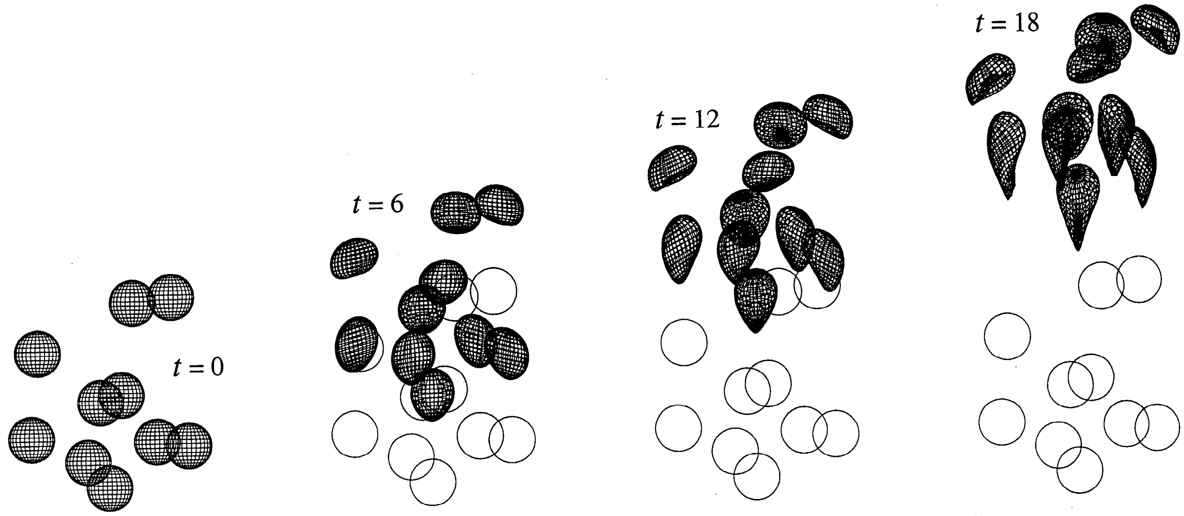

Figure 3. Example of a numerical simulation of diapirs in a cloud of 10 diapirs. Pairwise clustering dominates diapir interactions. Shapes are projections of the three-dimensional shapes. Time is normalized by the advective time scale $\Delta\rho g a/\mu$.

that the dynamical difference between constant viscosity and relatively inviscid diapirs will be small. We assume an unbounded geometry so that boundary effects do not influence the results.

In figure 3 we show a sample calculation. The circles indicate the initial shapes (spherical) and positions of the diapirs. The gridded shapes are projections of the three-dimensional shapes onto a vertical plane. Lengths are normalized by a, and time is normalized by the advective time-scale $\Delta\rho g a/\mu$, where μ is the mantle viscosity, g is gravity and $\Delta\rho$ is the density difference between the diapir and surrounding mantle. The calculations run until the diapirs translate a distance approximately equivalent to the thickness of the mantle, assuming $a = 150$ km. The diapir shapes presented in figure 3 show the same type of interaction-induced deformation found in the experiment (figure 1) and illustrated in figure 2: the leading diapirs are flattened by the trailing diapirs, and the trailing diapirs are extended by the leading diapirs.

In order to quantify the dynamics shown in figure 3, we monitored three quantities. First, we computed the mean separation distance between diapirs and their nearest neighbours in order to determine the rate at which diapirs approach each other:

$$D = \frac{1}{N}\sum_{i=1}^{N} \text{minimum}\{|\mathbf{x}_i^{cm} - \mathbf{x}_j^{cm}| \;\; i \neq j\} \quad (1)$$

where $\mathbf{x}_i^{cm} = (x_i^{cm}, y_i^{cm}, z_i^{cm})$ denotes the position of the center of mass of diapir i. In order to characterize the spatial distribution of diapirs, we computed the mean horizontal and vertical offset, H and V respectively, of diapir centers of mass from the center of mass of the "cloud," $\mathbf{X}^{cm} = (X^{cm}, Y^{cm}, Z^{cm})$,

$$H = \frac{1}{N}\sum_{i=1}^{N} \left[(X^{cm} - x_i^{cm})^2 + (Y^{cm} - y_i^{cm})^2\right]^{1/2} \quad (2)$$

$$V = \frac{1}{N}\sum_{i=1}^{N} |Z^{cm} - z_i^{cm}| \quad (3)$$

Both $\mathbf{x}_i^{cm}$ and $\mathbf{X}^{cm}$ are normalized by the diapir radius a. If clustering occurs, all three quantities D, V, and H should decrease with increasing time.

We performed a total of 10 numerical simulations for different random initial diapir positions. Evaluating the time derivatives of (1)-(3) at time $t = 15$, we find

$$dD/dt = -0.0065 \pm 0.0058 \quad (4)$$

$$dH/dt = -0.0018 \pm 0.0012 \quad (5)$$

$$dV/dt = -0.0099 \pm 0.0022, \quad (6)$$

where the $\pm$ denotes standard deviations for the 10 calculations. These quantities are negative, as expected if clustering is occurring. The large standard deviations indicate that the detailed dynamics for each simulation are highly variable. The rate of clustering is slow compared to the translation speed $\Delta\rho g a^2/\mu$ of the diapirs used to normalize (4)-(6).

Application to the Earth

The preceding numerical calculations and experiments show that, although rising diapirs will form clusters (in particular the pairwise clustering shown in figure 1), the rate of clustering is small compared to the rate at which diapirs rise (figure 3, equation 4). As a result, clustering of many diapirs should only be "significant" if the diapir radius a is small relative to the thickness of the mantle L. To estimate the mean change in the minimum separation distance as the diapirs traverse the mantle, we can multiply (4) by L/a. For the Earth's mantle, assuming $L = 2700$ km and a conservatively low value of $a = 150$ km [*Richards et al.,* 1989; *Griffiths and Campbell,* 1990; *Farnetani and Richards,* 1995], the average separation distance between diapirs decreases $(L/a)dD/dt \approx 10\%$ during their journey through the mantle. These results apply to thermally buoyant diapirs because the Peclet number (the ratio of advection to thermal diffusion) $Ua/\kappa \gg 1$, where U is the diapir rise speed and κ is the thermal diffusivity.

The horizontal distribution of diapirs within the cloud changes very little $(dH/dt \approx 0)$, indicating that on average the horizontal drift of diapirs due to interactions must be relatively small compared to their vertical rise speed. Thus the long-wavelength spatial distribution of hotspots is probably not related to diapir interactions. Instead, the distribution of hotspots on the surface may reflect advection by large scale flow, a thermal instability of a very low viscosity layer in D" [*Ribe and de Valpine,* 1994] or long-wavelength structure of flow in the lower mantle caused by a viscosity increase in the lower mantle [*Bunge and Richards,* 1996].

Application to Venus

If coronae on Venus are associated with diapirs [e.g. *Stofan et al.,* 1991; *Squyres et al.,* 1992], then the typical radius of the diapirs reaching the surface is 35-150 km [*Koch and Manga,* 1996]. The smaller radius relative to terrestrial diapirs could be caused by a higher Rayleigh number, instabilities associated with partial melting in upwellings [*Tackley and Stevenson,* 1991] or diapirs that form from a chemical rather than a thermal boundary layer. Applying the numerical results to diapirs with a radius of 35 km, we find that the average interaction-induced migration of diapirs is $\approx 50\%$ of the separation distance between the diapirs. Thus, the variable size of coronae-forming diapirs may be a results of varying degrees of clustering and merging of smaller diapirs.

Spatial clustering of coronae on Venus is also observed. *Stefanick and Jurdy* [1996] find that the density of coronae near extensional features called chasmata is almost twice as great as that for a random distribution. The concentration of coronae near chasmata may be a consequence of diapir advection by large scale upwellings. Alternatively, if clouds of diapirs form from a Rayleigh-Taylor instability [*Kelly and Bercovici,* 1997], the large scale flow induced by the diapirs may be responsible for the formation of chasmata. Stratigraphic relationships indicate that coronae formation and extension are in fact interrelated [*Baer et al.,* 1994].

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