GEOPHYSICAL RESEARCH LETTERS, VOL. 16, NO. 5, PAGES 437-440, MAY 1989

THE ADJUSTMENT OF MANTLE PLUMES TO CHANGES IN PLATE MOTION

Ross W. Griffiths

Research School of Earth Sciences, Australian National University

Mark A. Richards

Department of Geological Sciences, University of Oregon

Abstract. The relative motion of hotspots and lithospheric plates implies a velocity shear in the underlying mantle, causing horizontal advection of mantle plumes as they rise toward the lithosphere. Consequent tilting of plumes parallel to the direction of plate motion indicates that plumes must undergo a period of readjustment after the velocity vector for plate motion is altered. Thus the shape of bends in the surface tracks of hotspots, resulting from changes in plate motion, will reflect the plume adjustment. Laboratory experiments, as well as computations using a simple theory developed in Richards & Griffiths [1988] for the dynamics of continuous plume conduits, demonstrate that the bend in the surface track has a radius of curvature approximately equal to the maximum horizontal deflection of the conduit. Thus the sharpness of the bend at an age of 43Ma in the Hawaiian-Emperor volcanic chain implies that the deflection of the underlying plume in that case was small (<200 km). This small deflection is expected for plumes carrying large buoyancy fluxes, and it indicates that tilting of the conduit is unlikely to be sufficient to cause diapiric instability.

Introduction

Hotspot volcanic activity at the Earth's surface has been attributed to a presence of underlying plumes of upwelling hot material from deep in the mantle [Morgan, 1972]. There has been considerable speculation about the nature and dynamics of these plumes, and various suggestions have been put forward. The plumes are generally viewed as either narrow conduits (perhaps tens of kilometers across) or a sequence of diapirs. However, apart from seismic evidence for a possible boundary layer at the bottom of the mantle, which some have interpreted as the source of plumes, the only information available at present about mantle plumes is that deduced from their effects at the surface. For example, plumes must supply a buoyancy flux sufficient to generate the observed broad swells which surround the major hotspots and associated island chains [see, e.g., Davies, 1988]. Another key observation is that the lithospheric plates appear to move over mantle plumes while the plumes remain almost fixed relative to each other [Molnar & Stock, 1987]. The relative motion of plume sources and lithosphere implies a shear throughout at least some of the mantle and we can expect plumes, whatever their morphology, to be deflected horizontally by this shear [Skilbeck & Whitehead, 1978]. If the inclination of the plume conduit due to shear is sufficiently great, it may even lead to an instability which can break a continuous conduit into a series of discrete diapirs [Whitehead, 1982].

One feature of hotspot traces which has not been fully utilised in constraining the nature of plumes is the sharp bend in the Hawaiian-Emperor chain. The age of this bend (approximately 43Ma) marks a change in the motion of the Pacific plate [Clague & Dalrymple, 1987]. Hence the geometry of the bend should contain information on the adjustment of the plume to the change in plate motion. In particular, from the radius of curvature of the bend we should be able to constrain the extent to which the plume conduit was displaced by horizontal flow in the mantle. The deflection, in turn, may enable us to determine whether the plume was unstable to diapirism. The radius of the bend in the Hawaiian chain is less than 200km and we immediately notice, as did Whitehead [1982], that this is remarkably small compared with the likely depth of the plume source.

The path followed by plume conduits in a shear flow is governed by a rather simple principle: one which has been confirmed in laboratory experiments with plumes in a linear velocity profile generated by a moving lid [Richards & Griffiths 1988]. The conduit path through the mantle, and its adjustment to changes in plate motion, are adequately given by considering each elemental length of the conduit to be passively advected by the ambient shear flow and adding to this a constant vertical velocity. The vertical velocity results from the displacement of surrounding mantle material as the inclined buoyant conduit pushes upward and generally will be much smaller than the speed of plume material flowing along the conduit. Like the Stokes velocity of a sphere, it scales with the density difference $\delta\rho$ between plume and mantle and with the square of the conduit radius a. In experiments where a rigid lid and the underlying fluid were held stationary, plume fluid rose vertically through a conduit from the base to the lid and spread horizontally in an axisymmetric fashion against the lid. When the lid was moving, the plume was advected with the surrounding horizontal flow. After an adjustment time the conduit reached a steady parabolic shape in which the plume curvature and horizontal displacement from source to lid depended on the ratio of the lid speed to the Stokes velocity of the conduit.

In this paper we investigate the adjustment of a plume to a change in the direction of plate motion, with emphasis on the shape of the plume track relative to the overlying plate. Because each element of the conduit can be regarded as rising through its surroundings almost independent of the rest of the plume, we inferred that that the time required for plume adjustment must be given by the rise time for plume elements from the source. The radius of curvature of an adjustment arc along a plume track should therefore be similar to the maximum horizontal deflection of the plume. Here we present the results of new experiments, along with calculations of the shape of a surface track based on the simple parameterisation established in our earlier paper. The simple theory developed in Richards & Griffiths [1988] predicts the experimental plume tracks accurately, and some implications of the sharpness of the bend in the Hawaiian-Emperor chain are discussed.

Experimental Apparatus

The experiments reported here are an extension of those with a single direction of plate motion described by Richards &

Paper number 89GL00442.
0094-8276/89/89GL-00442$03.00

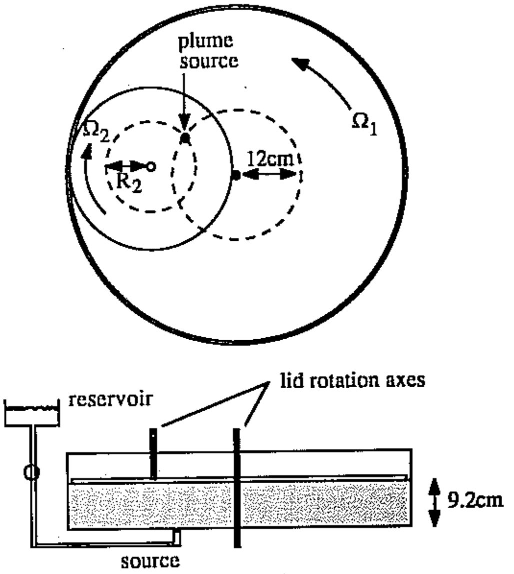

Fig. 1. Sketch of plan and side views of the laboratory apparatus. The lid is shown in the position at which the rotation axis was changed. Broken circles indicate the paths traced out by the plume source (relative to the lid) as the lid rotated about first the primary axis and then the secondary axis.

Griffiths [1988]. A very viscous fluid (glycerol, kinematic viscosity ν=9 cm^2/s) was placed in a cylindrical Perspex tank of diameter 60 cm. A new Perspex lid (2 mm smaller in diameter than the tank) fixed to a central vertical shaft was placed in contact with the fluid. This lid could be rotated at a constant speed by an electric motor via a constant speed motor and a belt and pulley. The distance from base to lid was always 9.2 cm. As in the earlier experiments, the motion of this lid generated an azimuthal velocity in the fluid which decreased linearly with depth at positions sufficiently far from the side wall. Changes in the magnitude of a plate velocity could be modelled by simply changing the speed of rotation of the lid. However, in order to change the direction of the plate and fluid motion, a circular portion of the lid was removed and replaced, as shown in Figure 1, by a disc which was fixed to the remainder of the lid via a bearing at the centre of the disc. This disc was free to rotate about its own centre, relative to the main lid, driven by a stepper motor via a small wheel in contact with the rim of the disc. The disc was flush with the base of the lid, was centred 15.5 cm from the axis of the tank and was 29.5 cm in diameter. Its rotation generated an azimuthal velocity profile (about the disc axis) which decayed linearly with depth everywhere beneath the disc excepting in regions close to its edge.

With the introduction of the second axis of rotation for the lid it was possible to change both the magnitude and direction of the horizontal advection velocity by stopping the rotation of the lid about the axis of the tank at a time when the whole of the inclined plume was in a suitable position beneath the inset disc, and simultaneously starting rotation of the disc about the second axis. By carefully choosing the two rotation speeds (Ω_1 and Ω_2) it was possible to achieve a change in direction without a large change in lid speed (V_1 and V_2) over the plume. We concentrated on the case of direction changes in the vicinity of 90°. In all runs the rotation rate of the primary lid was 5.2×10^{-3} rad/s, giving a lid speed $V_1 = \Omega_1 R_1 = 0.062$ cm/s over the source. In each run the plume flow and initial rotation of the lid about the tank axis were maintained for a lengthy period (but necessarily for less than one complete revolution of the lid) before the inset disc passed over the plume. When the disc reached a suitable position relative to the plume, the lid rotation about the primary axis was stopped and rotation of the disc about the secondary axis started simultaneously.

Plumes were generated by introducing less dense fluid through a hole in the base of the tank. In order to minimize side wall effects the source was placed 12 cm from the axis of the tank. The plume fluid was a mixture of glycerol (90%) and water (10%) having a density 0.026g/cm^3 and a viscosity 24% of that of the glycerol. Dye was added to this mixture in order to clearly mark the plume material. The plume was fed at the desired flow rate using a valve and a constant gravitational pressure head from a reservoir container.

Plume trajectories were recorded by photographing from the side of the tank and calibrating the magnification caused by the cylindrical geometry of the tank. Of most interest, however, was the track of the plume at the lid. That is, we wished to know the path of the plume intersection with the lid, relative to

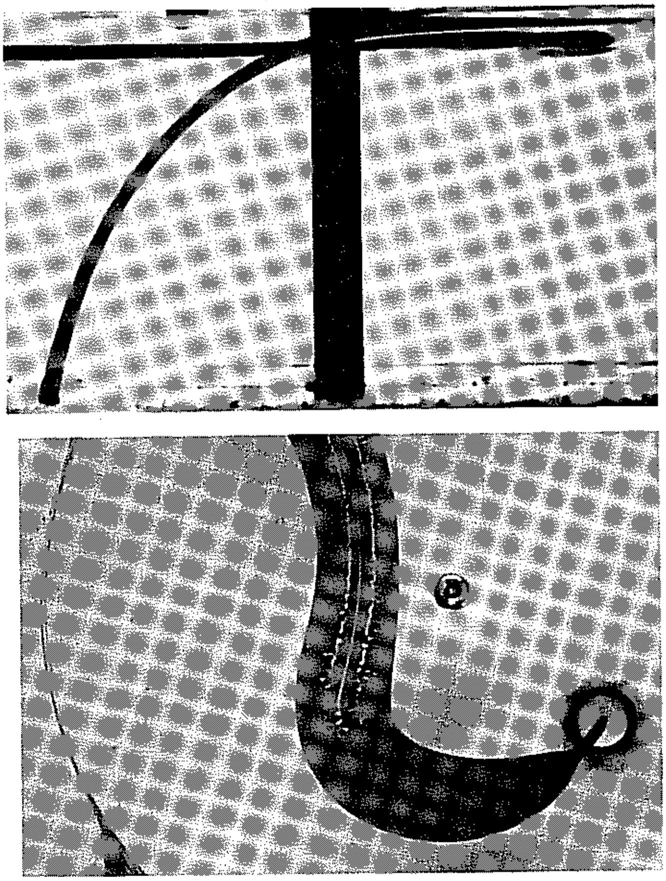

Fig. 2. Photographs of the plume in Run B (Table 1). a) Side view showing the parabolic steady-state shape of the plume immediately before the change in rotation; b) plan view taken after the change in lid rotation, showing the bend in the track at the lid (see Figure 3). In (a) the lid directly above the source is a small distance above the obvious dark horizontal band, which is the plume material carried around to the far side of the tank. In (b) the centre line of the track is seen as a thin line break in the dyed plume fluid. This line originates a small distance above the source and results from recirculation and entrainment of outer fluid into the rising, tilted conduit [Richards & Griffiths, 1988]. After the plume spreads beneath the lid three-dimensional convection occurs as a result of gravitational instability of a film of outer fluid squeezed against the lid. A characteristic pattern consisting of two main lines parallel to the centre line, with many normal short lines and small blobs, can be seen.

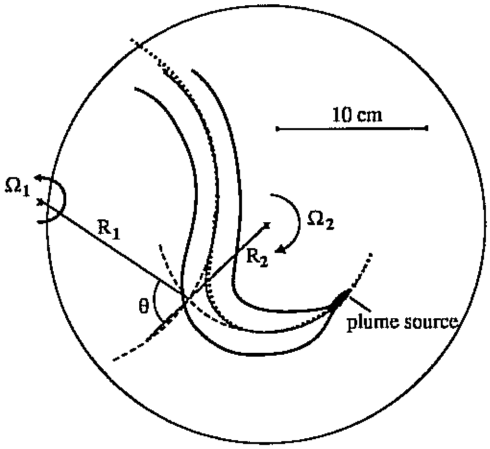

Fig. 3. A tracing of a plume track from the photograph in Figure 2 including the centre line for the plume track (solid) and circular arcs centred on the axes of rotation (broken curves; the apparent position of the primary axis is translated from the centre of the tank by rotation about the secondary axis). The theoretical track is superimposed (dotted). The arcs describe the fully adjusted components of the observed plume track and overlay the computed path. Computed and observed paths are also in close agreement in the bend.

TABLE 1. Results for three plume experiments having $h=9.2$ cm, $R_1=12.0$ cm and $\Omega_1=5.2\times10^{-3}$ rad/s.

	RUN A	RUN B	RUN C
2a (cm)	0.23	0.33(±0.03)	0.63
x_1 (cm)	12.6	8	3.6
R_2 (cm)	9.9	7.2	9.9
x_2 (cm)	22	4.8	5.8
θ	92°	77°	95°
V_2/V_1	1.6	0.60	1.6
$\delta r_1/x_1$	0.59	0.50	0.69
$\delta r_2/x_2$	0.86	0.83	0.66
$\delta r_2/\delta r_1$	2.6	1.0	1.5

the lid. This path was readily seen, as it was the centre-line of the swath of plume fluid which spreads immediately beneath the lid. The plan view of the plume and its track was photographed by a camera positioned vertically above the source.

Results

Before the change in lid velocity the plume met the lid at a distance x_1 downstream of the source. The buoyant material then continued to spread horizontally against the lid and formed a long band which tended to increase in width with distance along the track (Figure 2). The width of this band of plume material was greater for larger source volume fluxes. In each case the centre line of the plume was clearly seen as a thin stripe of entrained surrounding fluid. This centre line formed at the lid a circular arc of radius $R_1=12.0$ cm (Figure 3).

After the change in lid velocity the plume adjusted to a new steady shape for which the horizontal deflection was a distance x_2. The plume track then formed another circular arc of radius R_2 (Figures 2 and 3). When extrapolated the two arcs intersect at an angle θ, which we chose to be close to 90°. The intersection of arcs is the location of the source at the moment the lid motion was changed. Adjustment of the plume from one steady shape to the other is what most concerns us here. If there was no plume deflection, the two arcs would precisely mark the plume track, and their intersection would mark the change in plate motion. However, when there is a non-zero deflection, the adjustment requires a finite time and leads to a curved path at the lid leading from one steady state track to the other. The adjustment path is most simply described by two distances: the arc lengths (δr_1 and δr_2) from the intersection of the circular paths to the points where the plume track meets those arcs.

The experimental parameters and measured quantities for three different plumes are listed in Table 1. The case with the smallest plume radius shows the largest deflection. In all cases, the adjustment distances δr_1 and δr_2 are proportional to, and slighlty less than, the total horizontal deflection of the plume from source to lid. For the two smallest plumes the values of $\delta r_2/x_2$ (≈0.8) are systematically larger than those of $\delta r_1/x_1$ (≈0.6). This may be due to the restricted time available for the plumes to reach their steady state deflections before the axis of rotation was changed. The latter explanation is particularly relevant to the smallest plume and would explain the relatively large values of x_2/x_1 and $\delta r_2/\delta r_1$ (both of which should otherwise be proportional to V_2/V_1) in Run A. However, the important result is clear: the adjustment distances, or radius of curvature, of a bend in a plume track are comparable to the horizontal deflection of the sheared plume.

Discussion

In Richards & Griffiths [1988] we hypothesised that the adjustment of plumes and the shape of their tracks is predicted quantitatively by the superposition of an advection velocity (integrated over time) and a Stokes rise velocity for each element of the plume. We have confirmed this by computing the surface tracks predicted by this hypothesis for the laboratory conditions and cylindrical geometry described above. A computed track is superimposed on Figure3. The computation requires an estimate of the conduit Stokes velocity, for which two values found. One value was obtained in the usual way from measurements of the plume density contrast, radius and the ambient viscosity [equation 1 of Richards & Griffiths, 1988], and the other was found from the observed deflection

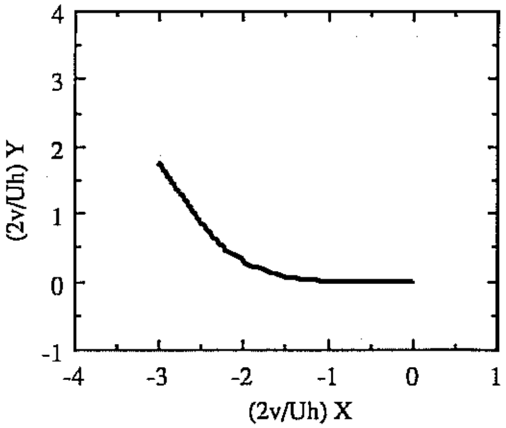

Fig. 4. A theoretical plume track relative to a moving plate which undergoes an instantaneous change in direction through 60° with no change in speed. The plume rises through a layer of constant shear. Spatial coordinates are non-dimensionalised so that unit distance is the maximum horizontal deflection. This becomes the radius of curvature for the bend.

of the plume, which was proportional to the lid speed, the distance from the source to the lid, and the inverse of the Stokes velocity [equation 7 of Richards & Griffiths, 1988]. The two were consistent, differing by only about 10%. Differences between the observed and computed plume track at the lid are only small and comparable to the uncertainty in determining the centre line of the track from the photographs. Hence the match is satisfactory and gives additional confidence for extrapolation of the description to other geometries.

A similar computation (Figure 4) for the bend between between two otherwise rectilinear paths with an included angle of approximately 120° (chosen to emulate the Hawaiian-Emperor bend) again shows that the adjustment distance is approximately equal to the steady state plume deflection. For this computation we have again assumed a linear velocity profile through the mantle shear zone and have presented the result in dimensionless terms by normalising the coordinates by the steady state plume deflection d, which is given by

$$d = Uh/2v$$

[equation 7 of Richards & Griffiths, 1988], where U is the plate speed, h is the depth of the shear layer and v is the conduit Stokes velocity.

Maps showing the bend in the Hawaiian chain are common [e.g. Jackson et al., 1972; Clague & Dalrymple, 1987]. The bend has a maximum radius of curvature of less than about 200km [see, e.g., Jackson et al., 1972]. This adjustment occurred over a time of approximately 3Ma, although the adjustment time may have been influenced by the time taken for the change in plate motion. The mantle wind may also have had a complicated depth-dependence, with different flow directions at different depths. However, the adjustment path of the surface hotspot track gives a robust upper limit to the lateral plume deflection in the direction of plate motion, and our results indicate that the plume must have been deflected by less than 200km before the change in plate motion.

Given this constraint on the horizontal deflection of the plume we now discuss the stability of the plume conduit to breakup by diapirism in the manner first suggested by Whitehead & Luther [1975]. An angle of tilt greater than about 60° from the vertical is necessary for this type of instability. Thus, if the shear generated by motion of the Pacific plate was spread through depths greater than about 100km, the plume could not have been sufficiently inclined and the plume is likely to have been stable. Diapiric instability due to tilting could occur only in a shallow, low viscosity layer [as discussed by Whitehead, 1982] in which the plume conduit trajectory would respond to changing plate motion more rapidly than the deeper mantle. However, instability might not occur even in this case unless the diameter of the plume is much less than the depth of the shear zone (i.e., of order 10km or less). Broader plumes could be stable because the diameter would be comparable to the horizontal deflection and because diapirism would be inhibited by the top and bottom of the shear layer.

We are not able to draw conclusions about the shear profile in the mantle. However, if we assume the effective depth of the upper mantle shear layer is large (say 400-650 km), then a small plume deflection implies a Stokes velocity for the conduit greater than the plate speed. The Stokes velocity in turn depends on the density contrast and diameter (i.e., buoyancy cross-section) of the plume. Hence the sharpness of the Hawaiian-Emperor bend could also be used, in conjunction with estimates of the buoyancy flux, to place constraints on the diameter and viscosity of the underlying plume as well as the viscosity of the uppermost suboceanic mantle. However, such constraints depend upon the model shear profile and mantle viscosity structure used, and are not discussed in this paper.

Concluding Remarks

The sharpness of the bend in the Hawaiian-Emperor island chain at 43Ma before the present implies that the Hawaiian hotspot was not displaced far in the horizontal direction relative to the source of the underlying plume despite the motion of the Pacific plate. The small deflection of the plume in turn implies that the plume was likely to have been stable to the type of diapiric instability which can result from plume inclination, regardless of the vertical profiles of mantle viscosity and horizontal motion. The experimental results presented here show that the theory developed in Richards & Griffiths [1988] is adequate to describe plume adjustment to changes in mantle shear due to plate motion.

The resistance of a continuous plume to deflection in a shear flow is determined by its buoyancy cross-section, which is greater for a larger heat flux and a larger plume viscosity (using results from viscous pipe flow). Hence plumes carrying a smaller heat flux than the Hawaiian plume will be more readily bent over by shear beneath moving plates, will have larger along-track adjustment distances when the plate motion changes, and may also break up into a train of discrete diapirs. More attention to the response of traces of weaker hotspots to changes in plate motion (particularly on the Pacific plate at 43Ma ago) is warranted.

Acknowledgements. We thank Derek Corrigan for construction of the laboratory apparatus. M.A.R. received support from an A.N.U. Visiting Fellowship and NSF grant #EAR-8718500.

References

Clague, D.A., and G.B. Dalrymple, The Hawaiian-Emperor volcanic chain, U.S. Geological Survey Professional Paper 1350, 49pp, 1987.

Davies,G.F., Ocean bathymetry and mantle convection I. Large scale flow and hotspots, J. Geophys. Res., 93, 10467-10480, 1988.

Jackson, E.D., E.A. Silver, and G.B. Dalrymple, Hawaiian-Emperor Chain and its relation to Cenozoic circumpacific tectonics, Geol. Soc. Am. Bull., 83, 601-618, 1972.

Molnar, P., and J. Stock, Relative motions of hotspots in the Pacific, Atlantic and Indian Oceans since late cretacious time, Nature, 327, 587-591, 1987.

Morgan, W.J., Plate motions and deep mantle convection, Geol. Soc. Am. Mem., 132, 7-22, 1972.

Richards, M.A., and R.W. Griffiths, Deflection of plumes by mantle shear flow. Experimental results and a simple theory, Geophys. J., 94, 367-376, 1988.

Skilbeck, J.N., and J.A. Whitehead, Formation of discrete islands in linear chains, Nature, 272, 499-501, 1978.

Whitehead, J.A., Instabilities of fluid conduits in a flowing earth - Are plates lubricated by the asthenosphere?, Geophys. J. R. astron. Soc., 70, 415-433, 1982.

Whitehead, J.A., and D.S. Luther, Dynamics of laboratory diapir and plume models, J. Geophys. Res., 80, 705-717, 1975.

R.W. Griffiths, Research School of Earth Sciences, Australian National University, Canberra, Australia, ACT 2600.

M.A. Richards, Department of Geological Sciences, University of Oregon, Eugene, Oregon 97403.

(Received November 22, 1988;
accepted February 13, 1989.)