

articles

Formation of discrete islands in linear island chains

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Mantle convection studies indicate that large-scale shear beneath plates acts together with the buoyant uplift of the lower density plume material to produce a succession of discrete plumes and consequently island chains such as Hawaii. The spacing of the Hawaiian Islands requires that its low viscosity shear zone is less than 80 km thick.

PLUMES in the Earth's mantle have long been thought to explain the formation of island chains such as Hawaii. It is unclear, however, what mechanism operates within the mantle to produce the discrete islands in these chains. Mantle convection studies indicate that a large-scale shear flow exists beneath the plates and we suggest that this shear and the buoyant uplift of the lower density plume material act together to produce a succession (in time) of discrete plumes. We describe here a simple laboratory experiment designed to test this idea and give a theoretical explanation of the results. We also present a crude calculation of a mantle with a low-viscosity shear zone and conclude that the observed spacing of the Hawaiian Islands requires that such a zone be thin—less than about 80 km thick. A similar conclusion has been reached by many geophysicists for various reasons.

Plume dynamics

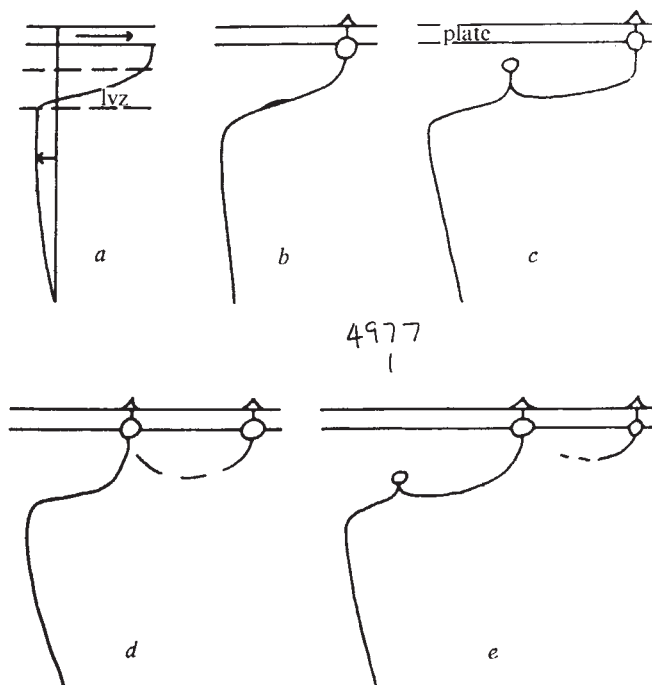
In 1963 Wilson¹ suggested that island chains such as Hawaii were formed as plates passed over a fixed region of mantle where large amounts of magma were being produced. Some years after this suggestion, Morgan² proposed that certain volcanic regions, principally island chains, were the result of plumes of hot rock rising from the core mantle boundary. The fact that these chains aligned themselves with plate motions inferred from seafloor spreading data strengthened the idea. McKenzie³ suggested that the upper mantle–lower mantle interface is a more likely source for this material; but also support the idea that such plumes exist within the earth's mantle. Gilluly⁴ has discussed the evolution of magmas associated with the Hawaiian Islands. Each island begins with tholeiitic lava, but changes to alkaline basalt before dying out. This sequence suggests a downward migration of the source with time. His conclusion was that, even though the suggestions of Wilson and Morgan could account for the formation of a chain of islands, it was hard to see why the source of magma should behave in this rise–descend–rise sequence.

Our approach has been to consider a simple problem in plume dynamics and to concentrate on the fluid dynamical aspects of plume behaviour. It has been assumed that there is a source of low density, low-viscosity fluid at some depth in a host fluid of high and possibly variable viscosity which is in a state of shear. In the absence of shear it has been found experimentally that the less viscous fluid pushes out into the host fluid, and its nose is

subjected to a gradually increasing normal stress. At first the fluid forms into a spherical pocket at the source and grows without rising. Eventually the radius becomes large enough so that the sphere rises buoyantly more rapidly than the rate of growth of this radius. The spherical pocket begins to rise when this stage is reached, and as it does so, it trails behind a narrow feeder pipe⁵.

If the host fluid is in a state of shear, it is reasonable to expect that the feeder pipe will deviate from the vertical and assume progressively greater tilt as time increases. As this tilt increases, the buoyancy force causing the fluid to flow along the pipe decreases so that the velocity within the pipe decreases also. If we assume a constant flow rate in the pipe, the radius must increase to conserve mass. It seems inevitable that at sufficiently large angles of tilt, it would be easier for the fluid to form a new nose (possibly aided by the swelling of the pipe) which would then rise vertically, than to move up the small incline of the existing pipe. After some time, this new nose could be expected to form a new spherical pocket trailed by a new vertical feeder pipe which would itself assume progressively greater tilt as time increases. The repetition of such a procedure might lead to the formation of a succession of new blobs. This is illustrated in Fig. 1.

Fig. 1 Schematic diagram showing a possible mode of formation of island chains as the result of the interaction between a low-viscosity pipe, which is rising due to buoyancy, and a horizontal shear flow. *a*, Possible shear flow for mantle with a low viscosity zone (lvz); *b*, formation of a new nose; *c*, a new pipe, and *d*, a new Island; *e*, process repeats.



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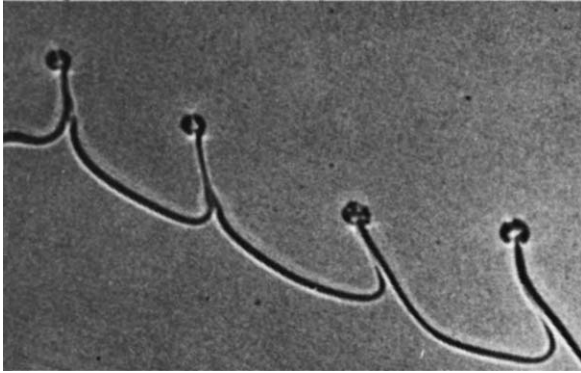


Fig. 2 New pipes formed as a result of an unstable wavelike disturbance on a pipe inclined at about 25° to the horizontal.

By understanding the relationship between the spacing of these blobs and such parameters as the mass flux of the low viscosity fluid, the viscosities of the two fluids, the variation of viscosity with depth in the host fluid, the rate of shear in the host fluid and the density difference between the two fluids, we can apply this concept to real island chains.

Preliminary experiments

Experimentally, a silicon oil of viscosity 10 centistokes (cst) and density 0.934 g cm^{-3} was fed through a pipe into the base of a tank containing oil of viscosity 1,000 cst and density 0.971 g cm^{-3} and allowed to flow until the spherical pocket of fluid had reached the upper surface. A mature plume was thus formed. When this state had been reached, the tank was tilted (causing a minimum of disturbance to the fluids) so that the feeder pipe was inclined. Figure 2 shows the behaviour of a pipe which was tilted to an angle of about 25° to the horizontal. Before tilting, flow in the pipe was laminar and the radius was independent of height; soon after tilting, however, a wave-like disturbance appeared on the pipe. The amplitude of this disturbance increased with time until the pipe took on the form shown in Fig. 2 about 2 min after tilting. This behaviour was only observed in experiments in which the inclination of the pipe to the horizontal was less than 35° . For greater angles of inclination, the pipe appeared to be stable.

Theoretical calculations

A simple theoretical explanation of this behaviour can be derived as follows. We may approximate the uplift velocity law by the expression for the terminal velocity of rods rising or falling through a viscous fluid. The rise velocity of an element of pipe inclined at angle θ to the horizontal is then⁶:

$$W(\theta) = \ln\left(\frac{l}{c}\right) \frac{gc^2 \Delta\rho}{8\mu} (3 - \cos 2\theta)$$

where $\Delta\rho$ is the density contrast, μ is the viscosity of the host fluid and l and c are the length and radius of the element of pipe. (In fact, $\ln l/c$ does not vary rapidly with large l/c and a value of 10 for this factor is taken as reasonable.)

We have already indicated that the radius, c , of the pipe also depends on the inclination θ . Whitehead and Luther⁵ have given an expression for c when the pipe is vertical and the buoyancy force along the pipe is proportional to $g\Delta\rho$. When the pipe is inclined, the buoyancy force driving flow along the pipe is proportional to $g \sin \theta$ so that their expression can be accordingly modified. From this we find that

$$c^2 \propto (\sin \theta)^{-1/2}$$

and

$$W(\theta) \propto (3 - \cos 2\theta)/(\sin \theta)^{1/2}$$

This function has a minimum at $\theta_c = 35.3^\circ$. When $\pi/2 > \theta > \theta_c$, $dW/d\theta$ is small and positive; however, when $0 < \theta < \theta_c$, $dW/d\theta$ is

negative and $dW/d\theta \rightarrow -\infty$ as $\theta \rightarrow 0$. Thus, when the inclination of the pipe is less than this critical value, θ_c , small wave-like disturbances will be amplified because the curvature they produce gives rise to a large differential uplift. When $\theta > \theta_c$, however, these disturbances will not grow.

The above considerations have dealt with pipes subject to buoyant uplift but no horizontal shear flow. To study the case in which both factors are present, we have developed a numerical scheme which allows us to trace the evolution of a pipe subject to a specified shear flow, $U(z)$, and uplift $W(\theta)$. From such calculations, in which we specify both velocity functions, we can determine the time necessary for a new nose to be initiated. It is, of course, the inverse problem that we would like to solve for real island chains: given the time between successive islands, can we determine the velocity and hence the viscosity structure of the underlying mantle. We will present more details of these studies elsewhere.

We will consider at present a simple analytical model which allows us to determine the time taken for new nose to form as a function of the other parameters of the problem. To obtain such an analytical relationship, we consider a viscosity of the form

$$\mu = 10^{23} (1 + z^2/L^2)/(1 + h^2/L^2) \text{ poise.}$$

Here z is the vertical displacement from the viscosity minimum, h is the height of the surface (at which we assume the viscosity is prescribed to be 10^{23} poise) and L is the length scale for the variation of μ . (Cgs units are used in all calculations.) Such a viscosity structure leads to a horizontal shear flow of the form

$$U(z) = U_T \tan^{-1}(z/L)/\tan^{-1}(h/L)$$

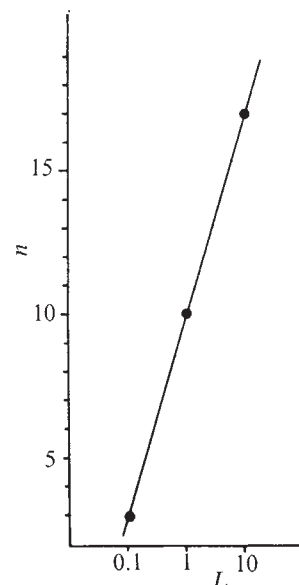
where U_T is the velocity at the surface $z = h$. The full expression for the uplift velocity in this case is found to be

$$W = 10^{-23} \ln\left(\frac{l}{c}\right) \frac{(1 + h^2/L^2)}{(1 + z^2/L^2)} (g\Delta\rho Q \bar{\mu}/8\pi)^{1/2} \frac{(3 - \cos 2\theta)}{(\sin \theta)^{1/2}}$$

where Q is the mass flux of fluid of viscosity $\bar{\mu}$ up the pipe.

We calculate the time required for a new nose to form by a simple two-step procedure. Starting with a vertical pipe, we subject it to shear flow only for time ηt_c , where t_c is the required time. Then we subject the tilted pipe to buoyant uplift only for the remaining time $(1 - \eta) t_c$. t_c is minimised when $\eta = 1/3$. For this second step, we calculate the vertical rise of the pipe at $z = 0$ and at one other value of $z (> 0)$ and require that the difference be

Fig. 3 Variation of L with $\bar{\mu} = 7.4 \times 10^n$ when t_c is taken as 1 Myr.



equal to z . This gives an estimate of the time required to attain a horizontal gradient on the pipe as a function of z . This function has a minimum when $z^2 \simeq 0.85 L^2$. After algebraic manipulation, we find that the minimum value of t_c is given by

$$\ln(l/c) h^2 10^{-23} (gQ\Delta\rho\bar{\mu} U_T t_c^3/8\pi L^7 \tan^{-1} h/L)^{1/2} = 2$$

where we have assumed that $(h/L)^2 \gg 1$. If we consider the Hawaiian chain and estimate $h \simeq 100$ km, $Q \simeq 10^6$ cm³ s⁻¹, $\Delta\rho \simeq 0.25$ g cm⁻³, and $U_T = 3 \times 10^{-7}$ cm s⁻¹ (10 cm yr⁻¹), we find that

$$t_c^3 \bar{\mu}/L^7 = 2 \times 10^{16}$$

If the islands in this chain are approximately 1 Myr apart, we may use this expression to relate the remaining unknowns: L and $\bar{\mu}$. We find that $L \simeq 2,800 \bar{\mu}^{1/7}$ so that L is very insensitive to the value of $\bar{\mu}$ chosen. This is fortunate as there is considerable uncertainty in the value of this parameter. Figure 3 shows that values of L in the range 0.1–10 km are indicated for reasonable values of $\bar{\mu}$. This corresponds to a range of mantle viscosity contrasts of 10^6 – 10^2 and of 90%-shear zone widths of ~ 1 –80 km. Computer calculations using the parameter values given above indicate that the above expressions overestimate t_c by a factor of about 2. Thus the values of L given above are also discrepant but only by a factor of $2^{3/7}$ or about 1.35.

Conclusions

We cannot defend in detail the numbers we have chosen in the above calculation. However, because L is raised to the seventh power in the expression for t_c , the values of L which we predict are insensitive to the other parameters of the problem. We propose, therefore, that the existence of a narrow shear zone in the mantle is necessary for the formation of new islands on the timescale observed at the surface of the earth. This, however, is not a new suggestion; many geophysicists^{7–12} have proposed the existence of such a low viscosity shear zone for a variety of different reasons. Thus, the predictions of our model fit well into an existing conceptual framework which strongly indicates that this mechanism may well be responsible for the formation of discrete islands in island chains.

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Transmission of hormonal stimulation by cell-to-cell communication

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Rat ovarian granulosa cells and mouse myocardial cells respond to cell-specific hormones by cyclic AMP-dependent mechanisms. In coculture, these heterologous cells communicate by means of gap junctions. Exposure of the cocultures to a hormone specific for one cell type causes the heterologous cells to respond through a cell contact-dependent mechanism. These studies suggest that this cross-stimulation results from the intercellular communication of a mediator that is common to both cell types. The communicated mediator may be cyclic AMP.

IN multicellular organisms, cells communicate by various mechanisms, including the formation of low-resistance junctions. Since the discovery of low-resistance connections between neurones¹, this form of cell-to-cell communication has been documented widely in both excitable and nonexcitable cells. These junctions have been correlated with the capacity for intercellular transfer of fluorescent dyes^{2–4}, labelled cations⁵, nucleotides⁶, amino acids⁷ and other metabolites⁸. These and other studies indicate that molecules with a molecular weight of less than approximately 1,200 can pass from cell to cell⁹. Low-resistance pathways (ionic coupling) and nucleotide transfer (metabolic coupling) have also been associated with the presence of a specific cell structure, the gap junction¹⁰. It is generally accepted that gap junctions can provide a structural pathway for the transfer of small molecules from cell to cell¹¹.

Cell communication in the form of ionic coupling allows synchronous electrical activity in the heart, smooth muscle and

some neurones¹². However, in nonexcitable tissues, the function of ionic coupling is unclear because there is no obvious requirement for electrical synchrony. It has been proposed that intercellular channels could allow the cell-to-cell transfer of small molecules that might regulate and synchronise activities such as metabolism, growth and differentiation in multicellular systems^{12–16}.

The studies described in this report were designed to investigate the potential role of communication in hormonally responsive systems. For example, when a hormone stimulates a cell within a target tissue, coordination could be achieved by the gap junctional transfer of low-molecular weight mediators of the response to other cells within the population. This presumptive mechanism is particularly attractive in the case of hormones with effects mediated by cyclic nucleotides. In this regard, there is experimental evidence that cyclic AMP can be transferred between cells because it has been shown that exogenously applied cyclic AMP diffuses through cardiac ventricular muscle, presumably through a gap junctional pathway¹⁷.

To examine this hypothetical mechanism we used a system composed of cultured rat ovarian granulosa cells and mouse myocardial cells, two cell types that communicate through gap junctions and respond to specific, but different hormones by cyclic AMP-dependent mechanisms. If these heterologous cells were able to communicate in culture, it should be possible to determine whether stimulation of one cell type influences the activity of the other. A positive result would suggest that a signal induced by the hormone can be transferred from the stimulated cell to the heterologous cell which is unresponsive to that hormone when cultured alone. We report here evidence that cross stimulation does occur in communicating cocultures of granulosa and myocardial cells.