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THE MANTLE-PLUME MODEL, ITS FEASIBILITY AND CONSEQUENCES

BY

P. W. C. VAN CALSTEREN*

ABSTRACT

High heat-flow foci on the Earth have been named 'hot-spots' and are commonly correlated with 'mantle-plumes' in the deep. A mantle plume may be described as a portion of mantle material with a higher heat content than its surroundings. The intrusion of a mantle-plume is inferred to be similar to the intrusion of a salt diapir and the process of diapirism is discussed. The theoretical mechanistic and thermal effects of hot diapirs and the tectonic and metamorphic implications are discussed. Two sets of diapirs, i.e. a first order diapir equal to a mantle-plume and, originating from it, second order diapirs causing hot spots, are invoked to give a reasonable explanation for the Palaeozoic evolution of the continental lithosphere of Western Galicia (NW Spain); the heat-flow pattern in the Rio Grande rift is also elegantly explained in a similar way. The sources of heat that might cause a mantle-plume are discussed but no one can be singled out as the most plausible. Mantle-plumes may be held responsible for the creation of a zone of weakness that is essential to initiate seafloor spreading, but certainly not every mantle-plume will play that role. The behavioural parameters of a mantle-plume are briefly explored and it is inferred that the heat content might be the most important one.

INTRODUCTION

In a quickly growing number of places on the Earth, thermal regimes have been recognized that are characterized by high heat-flow values causing hydrothermal activity and volcanism not related to subduction or sea-floor spreading. The classical example is Hawaii, but Burke & Wilson (1976) identified 122 hot spots of which 53 are situated in ocean basins and 69 on continents.

According to Wilson (1963) hot spots are caused by mantle-plumes; a mantle-plume may be described as a substantial portion of mantle material with a higher heat content than the surrounding mantle. As a consequence of its higher temperature a mantle-plume has a lower density and tends to rise buoyantly.

DIAPIRISM

The structures which are supposed to have originated as mantle-plumes resemble the well-known salt diapirs. The process of diapirism has been demonstrated on a laboratory scale (see for a bibliography Braunstein & O'Brien, 1968). Specially relevant to mantle-plume reasonings is a recent paper by Whitehead & Luther (1975) reporting theoretical calculations and laboratory experiments using Newtonian fluids such as oils of different densities and viscosities (rocks in high PT, low strain rate environment are supposed to behave also as Newtonian fluids). They have shown that wherever a thin layer of a Newtonian fluid exists below another Newtonian fluid with a higher density, the low density layer will develop narrow channels through which it flows upwards. In

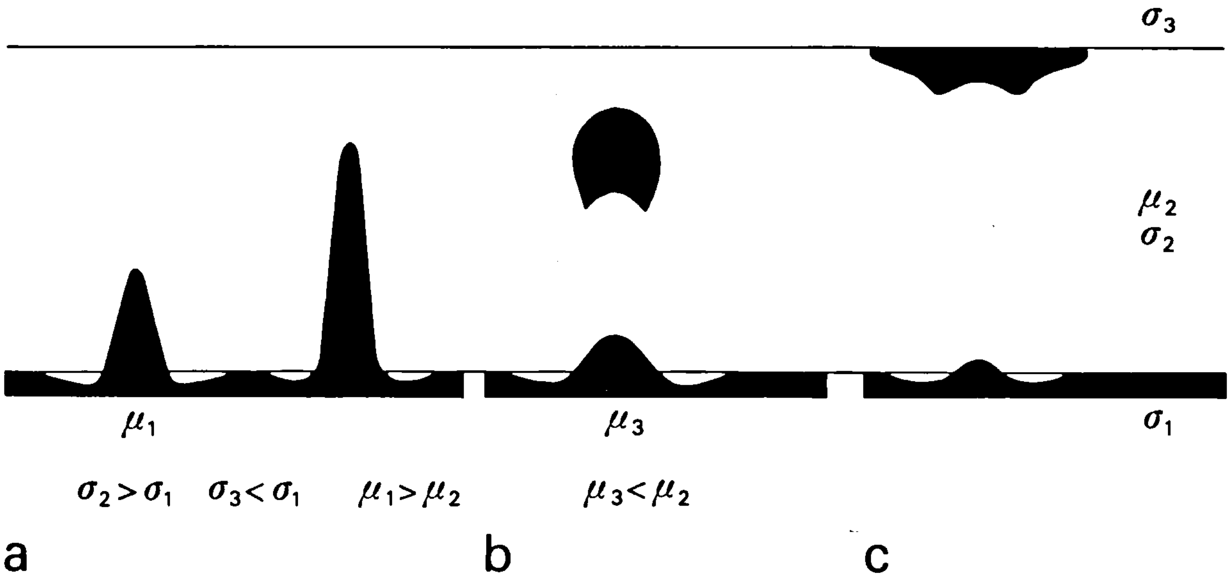

Fig. 1a. Shape of a diapir with higher viscosity than the high density source layer, 1b. shape of a diapir with a viscosity lower than the high density layer, 1c. lateral extension of a diapiric hat at the end of its buoyancy.

*) Dr. Peter W. C. van Calsteren, The Open University, Earth Sci. Dept., Walton Hall, Milton Keynes, England MK 6 2AQ.

the case of a plastic material a small pressure gradient – equivalent to a little depth variation – is necessary to reach the same effect. The narrow flow channels are the diapirs, and their shape is related to the viscosity contrast between the low- and high density fluids. When the low density fluid has a lower viscosity than the surroundings, the flow channel will be thin and will eventually be necked off whereby the top of the diapir will assume the shape of a jelly-fish and around it rim-synclines will develop (Fig. 1b). In the opposite case, with the high density surrounding fluid having the lower viscosity, the diameter of the diapir will decrease during rising (Fig. 1a). Diapirism will proceed until the density inversion ceases and at that level lateral extension will take place, that will continue until the low density source layer is exhausted (Fig. 1c).

TECTONICS

Bhattacharji & Koide (1978) discussed the mechanistic effects of intrusions on their surroundings. They used several types of ellipsoids with different aspect ratios for their model calculations. Prolate ellipsoids can be regarded as approximating the shape of a mantle-plume. From their calculations it can be concluded that a magmabody with a large height/width ratio intruding with an overpressure of 1 kb will cause graben or cauldron formation immediately above it. This effect is similar to the action of a wedge that is driven into its overburden; the pressure applied by the sides of the wedge pushes the surroundings in a direction normal to the wedge planes resulting in tension above the apex (Fig. 2). Similarly the total movement of an ellipsoid or diapir pushes up the roof and produces doming. The amount of doming depends on the height/width ratio: a large ratio will produce only a small dome in which case the wedging effect predominates. This is to be expected when the viscosity of the intrusion is higher than the viscosity of the wall-rock (see above). On the other hand the intrusion of a relatively low viscosity diapir will involve a considerable amount of doming.

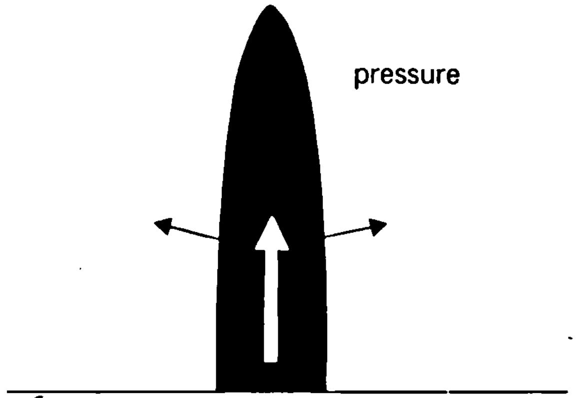

Fig. 2. Tectonic effects of an intruding ellipsoid with a large height/width ratio.

HEAT

The average heat-flow in continental shield areas is 1 HFU while in rift valleys such as the Rio Grande rift in New Mexico the heat-flow values are characteristically in excess of 2.5 HFU. In this Rio Grande rift zone several hot-spots occur with heat-flows ranging from 6.0–16.0 HFU. The latter value corresponds to a geothermal gradient of over 200 °C km^{-1}. (Reiter et al., 1978). According to these authors local heat anomalies are most probably caused by magma bodies with radii of 15–35 km situated at lower crustal depths between 15 and 30 km in an area with already elevated heat-flow. A possible explanation for this rather complicated heat-flow pattern is the postulation of two sets of diapirs of different magnitude (Fig. 3). The large *first order* diapir is a mantle-plume which caused a regional thermal dome. The smaller *second order* diapirs originated at the top of the mantle-plume and intruded into higher levels giving rise to the local very steep geothermal gradients of the hot-spots.

In a workshop at a NATO Advanced Study Institute in Norway 1977, Henri Pollack reported and discussed preliminary results of theoretical calculations made by him and his co-workers on the heat-flow systematics of mantle-plumes. Starting point of the calculations is a heat source with a temperature 300 °C in excess of the ambient rocks at the base of the lithosphere. Heat of this source will never reach the surface by conduction if the lithosphere moves with respect to the heat source with a speed of 10 cm y^{-1} (Fig. 4a). If the lithosphere is stationary with respect to the heat source and only conduction takes place it will be 100–200 My later before the near-surface heat-flow increases (Fig. 4b), and consequently, elevated heat-flows remain present 100–200 My after extinction of the heat source at depth. In the case of convective heat transfer, when the heat source eats its way through the lithosphere, the time involved is an order of magnitude lower (Fig. 4c). Pollack emphasized that the calculations at that time were not refined enough to include – for example – the magnitude of the heat source, which is

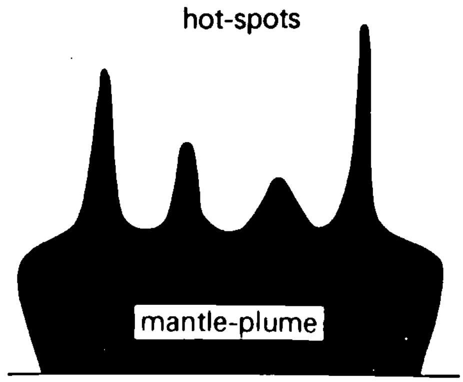

Fig. 3. Large diapir labelled 'mantle-plume' and at the top of it development of second order diapirs labelled 'hot-spots'.

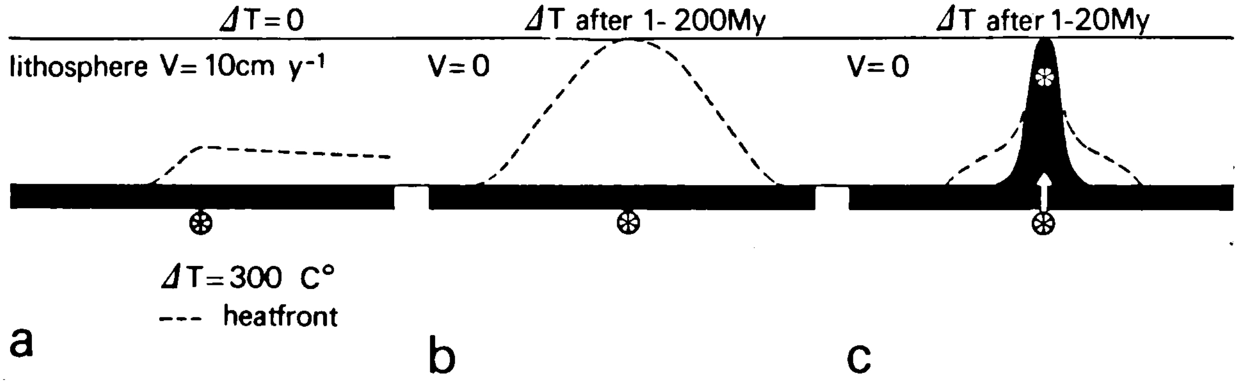

Fig. 4a. No surface heat effect if the lithosphere moves fast over a heat source, 4b. heat effect at the top of the lithosphere 1-200 My after its generation, 4c. heat effect 1-20 My after its generation if the heat source is able to rise.

expected to play an important role. According to the calculations discussed, second order diapirs might reach the upper crust within 20 My after the generation of a mantle-plume thereby causing a hot-spot. If such a second order diapir is arrested in the lower crust its heat will develop a (high-grade) contact aureole in the surrounding rocks. In the case of a non-moving plate, regional high heat-flow may occur 100 My later, causing ultrametamorphism of the lower crust and the generation of granite batholiths that might last some 100 My. This pattern is g r o s s o m o d o similar to the sequence of events advocated for the Palaeozoic evolution of the continental lithosphere of western Galicia under influence of a mantle-plume (van Calsteren, 1977; Den Tex, this volume). No significant heat-flow is to be expected around hot-spots in fast moving plates such as the Pacific plate around Hawaii.

SPACING

In the experimental work of Whitehead & Luther (1975) with silicon oils a regular hexagonal pattern of diapirs is developed. The distance between individual diapirs depends a.o. on the density contrast and the viscosity ratio, but is mainly determined by the thickness of the source layer. In geological cases regular patterns seem to be rare. A good example has been given by Talbot (1971) in a paper on mantled gneiss domes in the Fungwi Reserve, Rhodesia. No systematic partitioning of recent mantle-plumes is apparent from world-maps, and the Cenozoic double track mantle-plume chain as discussed by Sonnenfeld (1978) seems highly speculative. Lack of visible regularities may be explained by the anisotropy in the mantle as is inferred from P-wave velocities (Raitt et al., 1972) and from regional variations in velocity distributions. Moreover, the present picture may be obscured because it is time integrated over at least 200 My (see above).

CAUSES

In most diagrams a zone is shown at the base of a mantle-plume where the shading simply peters out and no hint is given to what might cause the mantle-plume. Earlier in this paper the importance of an elevated temperature for a mantle-plume is pointed out; higher temperature means lower density and a density inversion implies diapirism. So we can focus our attention to a heat source. Convection currents, hot fluids and anomalous composition have been proposed as such sources but none of these provides a satisfactory explanation. Convection currents should be rather effective in eliminating local steep temperature gradients; moreover, plumes are not confined to zones where rising convection currents can be inferred (see below). Even if this holds it would only shift the problem to a deeper level. Heat transfer from the lower mantle or from the core by fluid phases is advocated by Bailey (1978) and it seems to be a feasible mechanism for the generation of mantle-plumes but the actual heat source again stays hidden in the deep. Concentration of heat-generating radioactive elements is rather unlikely because no mineral phases are known to be stable at deep-mantle PT conditions that can incorporate significant amounts of these elements in their lattice. In summary: the origin of the heat that is necessary to generate a mantle-plume is yet unknown.

PLATE-TECTONIC RELEVANCE OF MANTLE-PLUMES

Mantle-plumes are situated in various plate-tectonic settings. The Mid-Atlantic Ridge for instance passes over the Iceland mantle-plume. It has been argued by Wilson (1963) that mantle-plumes below a continental lithosphere cause the break-up of that lithosphere by lateral extension of diapiric heads as they lose their buoyancy. The break-up should take place along pre-existing lines of weakness in the crust or along the connecting lines between various mantle-plumes. In the case of the opening of the Atlantic Ocean, the array Iceland-Azores-Ascencion-Tristan da Cunha could be held responsible. Burke & Dewey (1973) proposed that mantle-plumes deliver the energy forces needed to break up the continents in the first stage of plate motion. This concept overcomes the need of the classical 'conveyor belt' motion of mantle convection for which little evidence seems to exist. Later plate motions may arise either from plates sliding off the ridge (Hales, 1969) or from pulling of the plates by the downgoing slab (Jacoby, 1970), or both.

Sea-floor spreading and ocean-floor creation is however certainly not always the result of mantle-plume action. For instance the Upper Rhine graben is most likely the consequence of the intrusion of a mantle-plume situated below the Kaiserstuhl. But the related lateral extension along the graben is limited to some 5 km (Illies, 1974) and the quantity of mafic intrusives is insignificantly small if compared with spreading ridges. The Hawaii mantle-plume has had no other impact on the Pacific plate than the creation of a trail of volcanos albeit that this volcano-production lasted at least 80 My. A third example is given by Wilshire & Pike (1975). They speculate that kimberlitic intrusions are caused by mantle-plumes and they advocate a similar origin for nepheline basanite, alkali basalt eruptions and Alpine peridotites. In their views the depth where a mantle-plume stops rising determines what will happen, i.e. termination near the base of the lithosphere leads to kimberlitic intrusions, and prolonged rising into the upper crust will result in Alpine-type peridotites, while major basalt production is confined to intermediate rising.

A satisfactory explanation for not reaching the spreading stage by the Hawaii mantle-plume may be that the Pacific plate moves with a considerable speed over the mantle-plume preventing the temperature from rising high enough to create a zone of weakness.

The magnitude of a mantle-plume is also an important parameter and it seems obvious that all three factors – magnitude, depth of origin, and speed difference – play an important role in the determination of what influences a mantle-plume will have on the ambient lithosphere. Not to forget of course the nature of that lithosphere and what may be the most important: the heat content of the mantle-plume.

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