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Plumes and Concentric Plume Traces of the Eurasian Plate

THERE are many more lines of volcanoes which increase in age from one end to the other than can be due to chance. One explanation which has been proposed is that volcanoes form overheated columns or plumes rising from deep in the mantle at fixed locations[1]. The lines of volcanoes are thus plume traces marking the loci of movements of lithospheric plates. This case can be strengthened if several lines of volcanoes on the same plate can be shown to approximate to small circles about a common pole[2,3]. Such confirmation is particularly desirable for short lines on continents, because volcanic uplifts on continents are large and continents commonly move slowly[4] or not at all[5]. For example, the uplifts generated on one stationary plate are about 220 by 80 km (ref. 6) and a movement of 1 cm yr^{-1} would take 22 m.y. to double the length of the average major axis. Clearly it would be impossible to define a pole position precisely from one such line.

Table 1 Five Plume Traces Generated on the Eurasian Plate During the Past 25 m.y.

Plume trace	Ends	Lat.	Long.	Approximate age	Length (km)	Ref. No.
Massif	Cantal	44.5° N	3° E	Miocene	180	9
Central	Puy de Dôme	46° N	3° E	Recent	180	9
Rhine	Kaiserstuhl	48° N	7.7° E	18 m.y.	200	9, 10, 11
graben	Eifel	50.2° N	7° E	Recent		9, 10, 11
Hekla	North Rockall Bank	60° N	15° W	50 m.y.	600	10
	Hekla	64° N	20° W	Active	600	10
Myvatn	Faeroes	62° N	7° W	55 m.y.	500	10
	Myvatn	65.7° N	17.2° W	Active	500	10
Azores	Santa Maria	37° N	25° W	20 m.y.	350	14, 15
	Fayal	38.6° N	28.8° W	Active	350	14, 15
Pole position from normals to these five plume traces: 18° N 48° W						
McKenzie's instantaneous pole from seismic results: 9° N 46° W						7
Pitman and Talwani's pole for the last 19 m.y. obtained by rotating magnetic anomalies: 31° N 35° W						8

Because the African plate has been at rest over its plumes during this period, poles describing the motion of the Eurasian plate with respect to the African (from refs. 7, 8) are not significantly different from the average pole describing the motion of the Eurasian plate over its plumes.

Here we describe five plume traces on the Eurasian plate which are all less than 25 m.y. old and seemingly concentric (Fig. 1, Table 1). The restriction of the analysis to the parts of the traces formed during Neogene time permits the application of an independent test of their validity. Elsewhere we have argued that the African plate has been stationary for the past 25 m.y. (ref. 5). Because the African plate and the plumes beneath Eurasia are both fixed relative to the mantle, the poles of rotation of the Eurasian plate should be the same in both cases.

Table 1 shows that the poles computed from seismic[7] and magnetic anomaly data[8] to describe the motion of the Eurasian plate with respect to the African plate are roughly coincident with the pole derived from a study of the five plume traces.

The first trace lies in the Massif Central and has a somewhat complex volcanic history. Recent volcanism seems to mark the Puy de Dôme area as the present position of the plume. From it a line of large central volcanoes extends south to the Cantal which is taken to mark the other end of the trace. There the oldest volcanics are of Middle Miocene age (about 15 m.y. old), although the youngest are only Villafranchian (>1 m.y. old)[9].

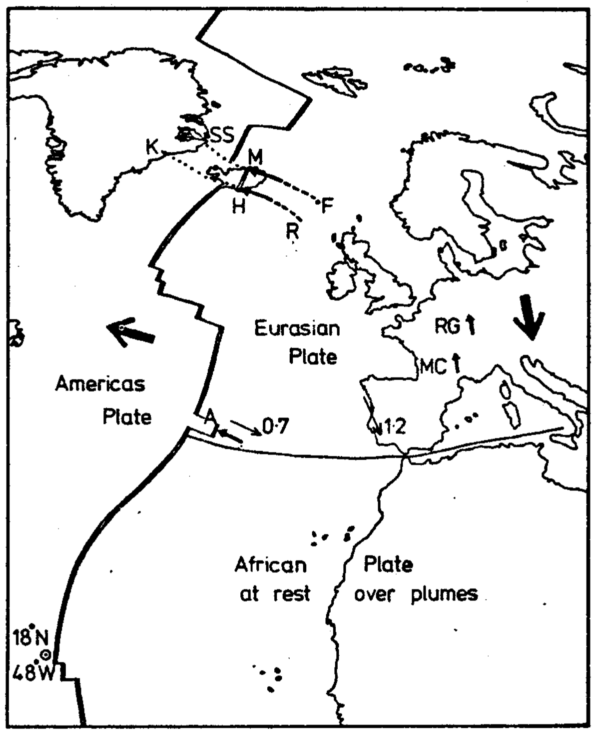

Fig. 1 Concentric plume traces on the Eurasian plate for the last 25 m.y. A, Azores; MC, Massif Central; RG, Rhinegraben; M, Myvatn; H, Hekla. Arrowheads are the positions of active and inactive volcanoes at the young ends of the traces. Dot in a circle at 18° N 48° W is the approximate position of the average rotation pole describing the five plume traces on the Eurasian plate. Dashed lines are possible extensions more than 25 m.y. old of two traces. Dotted lines from Scoresbysund (SS) and Kangerdluqssuaq (K) in Greenland indicate the traces of the Myvatn and Hekla plumes on the Americas plate generated during the last 50 m.y. Broad arrows show the sense of motion of the Americas and Eurasian plates with respect to Africa since the African plate came to rest. Small numbered arrows show the sense and velocity of motion in cm yr^{-1} of the Eurasian plate with respect to the African plate over the last 9 m.y. (from ref. 8, Fig. 2). Because the African plate is at rest with respect to the world plume population this motion is the same as that of the Eurasian plate over its plumes and these arrows are concentric with the Eurasian plume tracks.

Duncan *et al.*[10] regarded the Central European volcanic province as an east–west plume trace. We agree that the Eifel and Vogelsberg mark the young end of a second trace but hold that it extends north from the rocks 16 to 18 m.y. old of the Kaiserstuhl[9,11] and the Swabian tuff pipes at the southern end of the Rhinegraben, volcanics that they did not mention. Because of their age (20–35 m.y.) the North Bohemian volcanics[10] formed largely before Africa came to rest 25 m.y. ago need not be concentric with those under discussion.

Because these two plumes lie within the Eurasian plate they each produced a trace in one direction only. We suggest that three more plumes lie on the boundary with the Americas plate, so that each has produced two traces in opposite directions. Two of these plumes lie beneath Hekla and Myvatn volcanoes in Iceland and the fifth plume is in the Azores (Fig. 2).

Although, at present, a zone of fairly continuous ridge activity lies between the two Icelandic plumes, their separate character is well displayed by the excess of lava erupted at the ends of their traces.

About 50 m.y. ago, when the Myvatn plume was near the Faeroes on the Eurasian plate and the Hekla plume was near the northern end of Rockall Bank, the two plumes and their traces were clearly distinct. Since that time the products of the plumes have overlapped to form a broad ridge on both sides of Iceland within which short-lived changes in plume trace direction may yet be mapped. It is possible that a stretch of plume trace concentric with the North Bohemian trace and about 25–35 m.y. old may be found within this broad ridge.

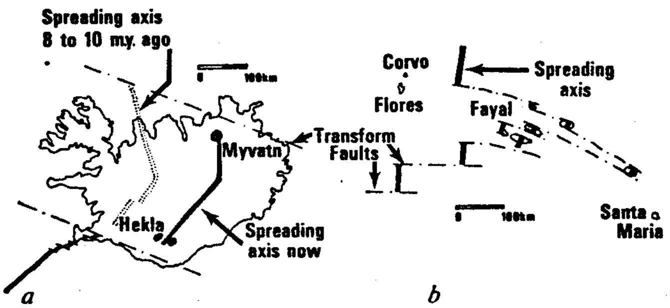

Fig. 2 During the past 25 m.y. since the African plate came to rest over its plumes the mid-Atlantic Ridge in both the North and the South Atlantic has been migrating westward away from what had been axial plumes. In Iceland (*a* based on ref. 13) a ridge jump about 8 m.y. ago put the Icelandic rift back on to the Hekla and Myvatn plumes. This motion accounts for the prominent ridge re-entrant near Iceland. We suggest that a similar re-entrant at the Azores (*b* based on ref. 15) originated in the same way. The obscurity of the Azores plume track on the Americas plate close to the Azores perhaps results from the ridge jump.

On the Americas plate when continental rupture took place Scoresbysund and Kangerdluqssuaq on the Greenland coast lay over the two plumes now in Iceland and were jóined by a curving rift marked by dykes injected during breakup[12]. The shape of the coast and the parallel strike of dykes reveal the form of the original rift in spite of large scale sedimentation on the continental shelf. This rift boundary can be rotated to overlie the well known bent rift of Iceland. If this is done on the Americas plate (which, of course, has a separate pole of rotation) the present positions of the two plumes coincide with the 50 m.y. old sites. It is not possible to match neighbouring parts of the Greenland coast to the north and south with the Mid-Atlantic Ridge because of the ridge jumps which have taken place. The latest shift of spreading in Iceland took place 7 or 8 m.y. ago when the spreading rift jumped from a position in western Iceland to its present more easterly position[13]. This illustrates that the westward movement of the spreading crest of the Mid-Atlantic Ridge which we noted in the South Atlantic[5] has also affected the North Atlantic, except in the immediate vicinity of the powerful plumes where the crest has jumped to the east in an effort to remain over the top of the plumes (Fig. 2).

The fifth trace lies in the Azores and extends north-north-west from Santa Maria on the African-Eurasian plate boundary which is 20 m.y. old[14] to the active islands of Gracioso, San Jorge and Fayal[15] (Fig. 2). Pitman and Talwani (ref. 8, Fig. 2) using magnetic anomaly data have computed the velocity of the Eurasian plate towards the African plate near the Azores at 0.7 cm yr^{-1} parallel to the direction of the plume trace.

The interpretation and map by Machado *et al.*[15] show that the crest of the Mid-Atlantic Ridge has moved westward from the Azores except in the immediate vicinity of the plume just as it has in Iceland. This movement has served to hide the true nature of the western trace of the Azores plume and explains why it is not easily recognized farther west. It lies within the Azores extending from the vicinity of Fayal to Flores.

Farther east we have identified only one other possible plume trace on the Eurasian plate. This may be partly a result of inadequate information but may also be related to an inability of most plumes to leave their mark on continental lithosphere moving over them at more than about 2 cm yr^{-1}. A line of Cainozoic volcanics 800 km long extending ENE through Petrovsk, south-east of Lake Baikal[16], lies on a small circle 110° from our rotation pole. If this line is a plume trace, we would expect the volcanoes at its eastern end to prove youngest.

Eastern China is probably not part of the Eurasian plate and its pattern of Neogene plume volcanism and uplift[5] resembles that of Africa which is stationary with respect to plumes.

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Palaeogeography of South West England and Hercynian Continental Collision

THE application of plate tectonics has revitalized the study and interpretation of ancient orogenic belts. Recently Nicolas[1] has suggested that the Hercynian orogenic belt was Andean[2], and developed on the margin of a continental mass bordered to the south by the Tethyan sea. He considered that there was "no evidence for a large eugeosyncline, but rather small subsiding basins or troughs with a shallower type of sedimentation". This interpretation has been challenged by Burrett[3], who maintained that the Hercynian orogeny coincided with the closing of a mid-European ocean between northern and southern European continental masses.

The sedimentary facies sequences in the Upper Palaeozoic of south west England (the Culm geosyncline) support the suggestion that the later stages of the Hercynian orogeny involved collision between two continental masses. The facies