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# Relative motions of hotspots in the Pacific, Atlantic and Indian Oceans since late Cretaceous time

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*Combinations of global plate reconstructions reveal average velocities for the last 50 to 65 million years of 10 to 20 mm yr$^{-1}$ between the Hawaiian hotspot and those beneath Iceland, Tristan da Cunha, Réunion, St. Paul's Island, and Kerguelen. Therefore hotspots do not define a fixed reference frame. Uncertainties in these reconstructions are less than the errors incurred by assuming fixed hotspots and less than the differences among various proposed frames of reference of fixed hotspots[1-3].*

WHEN Morgan[4,5] elaborated Wilson's[6] idea that linear volcanic chains and aseismic ridges emanate from localized hotspots, by suggesting that the hotspots are fixed with respect to one another, he offered a hypothesis for defining a fixed frame of reference for plate motions. Although hotspot tracks are now commonly used to constrain histories of plate motion, results of various tests of the fixed hotspot hypothesis differ significantly. By finding agreement between most calculated directions of present-day plate motions and the measured orientations of linear volcanic chains and aseismic ridges, Minster *et al.*[7,8] found no relative motion among the hotspots for the past 5-10 Myr. Others[9-11] reported relative motions of hotspots of 10 to 20 mm yr$^{-1}$ (or more) for longer durations. Morgan[1,2] questioned these studies, and, like Duncan[3], he deduced relative movement of less than 5 mm yr$^{-1}$ of hotspots in the Atlantic and Indian Oceans. Morgan associated some chains in the Atlantic with different hotspots from those used by Burke *et al.*[9], and he interpreted the calculated relative positions of hotspots and aseismic ridges differently from Molnar and Francheteau[10].

Because rapid motion of plates over hotspots occurs in the Pacific and not in the Atlantic Ocean, the most definitive test of fixed hotspots must also use the motion of the Pacific plate. In particular, the bend in the Hawaiian-Emperor seamount chain, whose age is 43.1 ± 1.4 Myr (ref. 34), presumably marks a major change in the direction of motion of the Pacific plate. A convincing test of fixed hotspots should thus match the history of plate motions both before and after the formation of the bend, and in particular the position and the age of the bend. Previous attempts to test fixed hotspots could not use the Pacific plate for times older than about 35-40 Myr (ref. 11), because of the obvious existence of a plate boundary somewhere between the North Pacific and East Antarctica (Fig. 1*a*). We believe that we have found the missing plate boundary in what is now the Antarctic plate[12], so that we can now quantify the displacement at the missing plate boundary and use this to test fixed hotspots since about 68 Myr.

If the motion of one plate over its hotspots is known, and if these hotspots are assumed to be fixed with respect to those under a second plate, reconstructions of the past positions of the two plates can be used to compare the predicted positions of a hotspot under the second plate with its known trace. Because the validity of this test depends on accurately knowing the motion of the first plate with respect to its hotspots, we have carried out two tests. First, using the positions of the African plate with respect to hotspots beneath it[1-3], we compared the calculated history of motion of the Pacific plate over the Hawaiian hotspot with the ages and trends of the Hawaiian-Emperor Chain. Second, using those measured ages and trends to define the history of motion of the Pacific plate over the Hawaiian hotspot, we calculated the histories of motions of the plates beneath the Atlantic and Indian Oceans with respect to their hotspots. We present calculated positions of hotspots for the times of the old edge of anomaly 5 (10.59 Myr), the centres of anomalies 6 (19.90 Myr), 13 (35.58 Myr), 18 (42.01 Myr), 21 (49.54 Myr), and 25 (58.94 Myr), and the reversed polarity interval between anomalies 30 and 31 (68.47 Myr), using the DNAG geomagnetic reversal timescale[13,14] and recently determined reconstructions for the South Pacific[12], the Indian[15], the South Atlantic[16], and the North Atlantic Oceans (ref. 17; K. D. Klitgord, H. Schouten and P.M., unpublished results). For each reconstruction, uncertainties expressed as partial uncertainty rotations for each pair of adjacent plates[18] have been combined to yield uncertainty ellipses, which we consider to be 95% confidence regions, for the combined rotations[19].

Implicitly we assume that there are no additional plate boundaries at which there was motion of parts of the plates in question. Specifically, we neglect deformation between East and West Antarctica, despite some evidence suggesting a small amount (≤200 km) of Cenozoic displacement between them[12,20]. Thus, we ignore the remote possibility of a small amount of displacement of East and West Antarctica being describable by a large rotation about a pole close to Antarctica.

## Motion between Hawaii and Tristan da Cunha

Morgan[1,2] and Duncan[3] concluded that the hotspots in the Atlantic and Indian Oceans move only very slowly with respect to one another. If so, a good test of fixed hotspots could be made by using the history of one plate with respect to its hotspots to calculate the history of motion of the Pacific plate over the Hawaiian hotspot. For Morgan's[1,2] or Duncan's[3] parameters, the calculated motion of the Pacific plate, with respect to a Hawaiian hotspot fixed to the hotspots beneath Africa, changed from southeasterly before 42 Myr to east-southeasterly after that time (Fig. 1). Thus the calculated motions changed in the correct sense and at approximately the same time as the Hawaiian bend, giving us confidence that the modification to the history of the South Pacific[12] is sensible.

None of the three sets of parameters[1-3] allow the African hotspots and the Hawaiian hotspot to be fixed with respect to one another (Fig. 1*b*). For Morgan's earlier set[1], the calculated bend lies about 300 ± 100 km from the Hawaiian-Emperor bend, but for both his later set[2] and Duncan's[3], it lies about 800 ± 100 km from the bend. Therefore, both Duncan's[3] and Morgan's more recent (presumably preferred) parameters[2] imply that the average rate of movement between the Hawaiian and Tristan hotspots for the past 42 Myr was 20 ± 2 mm yr$^{-1}$. These conclusions do not depend upon our revision of the early Tertiary history of the South Pacific. Morgan's older parameters[1] yield

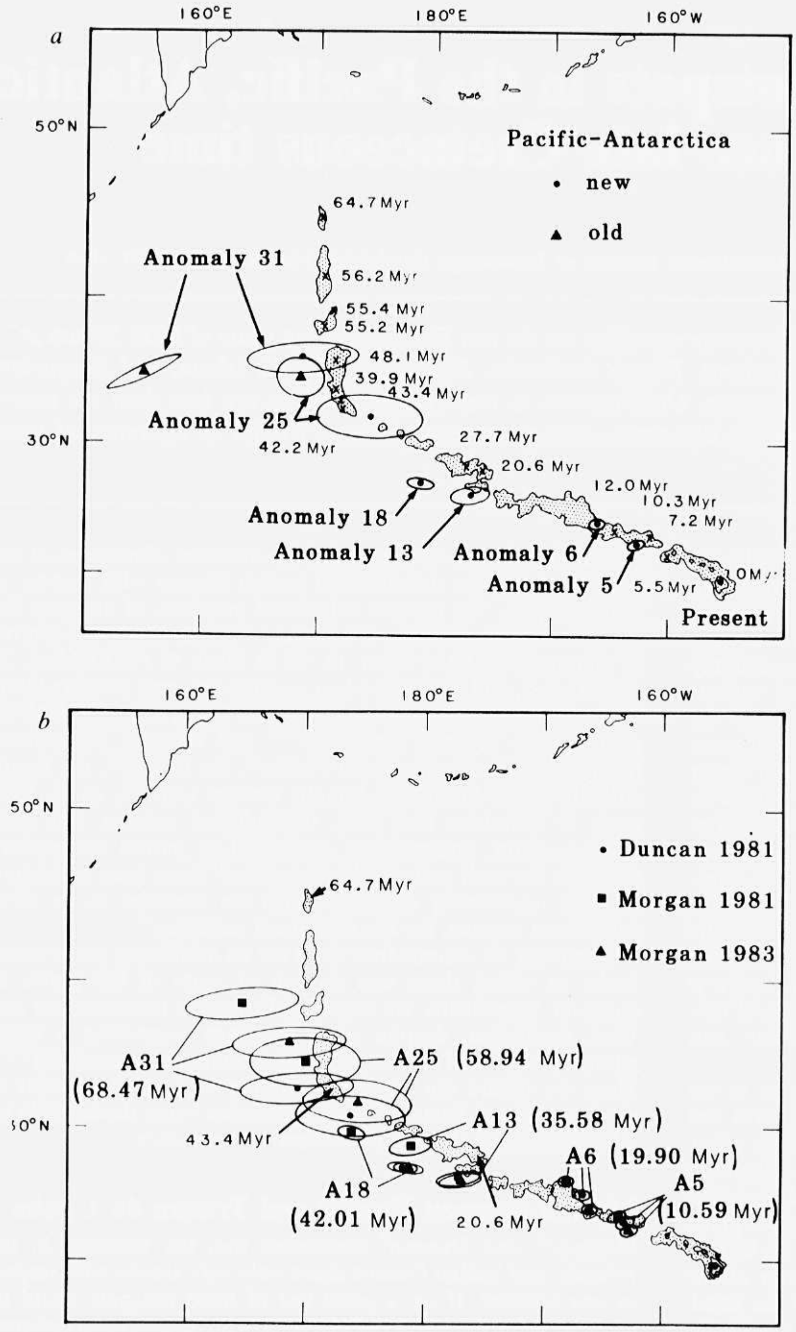


**Fig. 1** Maps of Hawaiian-Emperor chain and calculated positions of the Hawaiian hotspot, assuming that it is fixed with respect to the Tristan da Cunha hotspot. *a*, Morgan's[2] parameters for the motion of Africa over Tristan da Cunha are used, and calculated positions based on the old history of the south-west Pacific and a new, revised version of it[12] are compared. With the old model there is little difference in the directions of relative movement before and after the time of anomaly 18, but with the new one there is. ×, indicate selected ages of islands and seamounts[34]. *b*, Calculated positions using Morgan's[1,2] and Duncan's[3] parameters for the motion of Africa over Tristan da Cunha are compared. Note the significant differences among them for various times before and after the age of the bend. The sequence of rotations is hotspots to Africa[1-3], to Antarctica[15] and to the Pacific[12].

a lower average rate: $7 \pm 2$ mm yr$^{-1}$. All three sets of parameters also call for relative motion between these two hotspots since before the formation of the bend.

The difference in Morgan's[1,2] two sets of parameters for fixed hotspots in the Atlantic corresponds to a 500-km difference in the calculated position of the Pacific plate with respect to the Hawaiian hotspot at the time of anomaly 18 (Fig. 1*b*). This difference is both independent of and larger than the uncertainties contributed by the reconstructions in the Pacific–Antarctic–African plate circuit. Clearly the motion of the African plate over its hotspots is not known well enough for it to be used to determine relative velocities among hotspots.

## Motion between Hawaii and other hotspots

Because the most thoroughly dated and acknowledged hotspot trace is the Hawaiian-Emperor volcanic chain[34], the best test of fixed hotspots can be made by assuming that we know the motion of the Pacific plate over the Hawaiian hotspot. To describe that motion, we have used poles at 68 °N, 75° W (ref. 21) for the Hawaiian Chain (0 to 43 Myr) and at 17° N, 107° W (ref. 24) for the Emperor Chain (43–69 Myr). Rotation angles were derived using Clague and Dalrymple's compiled ages of seamounts and their distances from Kilauea along the Hawaiian-Emperor chain, assuming that the age of the bend is 43.1 Myr (ref. 34) and that its location is 34° from Kilauea[22]. We allowed for a 95% confidence region of radius 200 km in the positions of the Pacific plate over the hotspot. This spans the width of the chain and at 92 mm yr$^{-1}$ (ref. 34) allows for errors of 2.2 Myr in the ages either of the rocks or of the geomagnetic timescale (Fig. 2). These uncertainties are represented in the combined reconstructions as two partial uncertainty rotations[18]: a rotation of 1.94° or 1.87° about the poles, noted above, describing the creation of the Hawaiian or the Emperor chain, respectively, and a rotation of 1.8° about an axis lying 90° from the hotspot in the direction parallel to the chain.

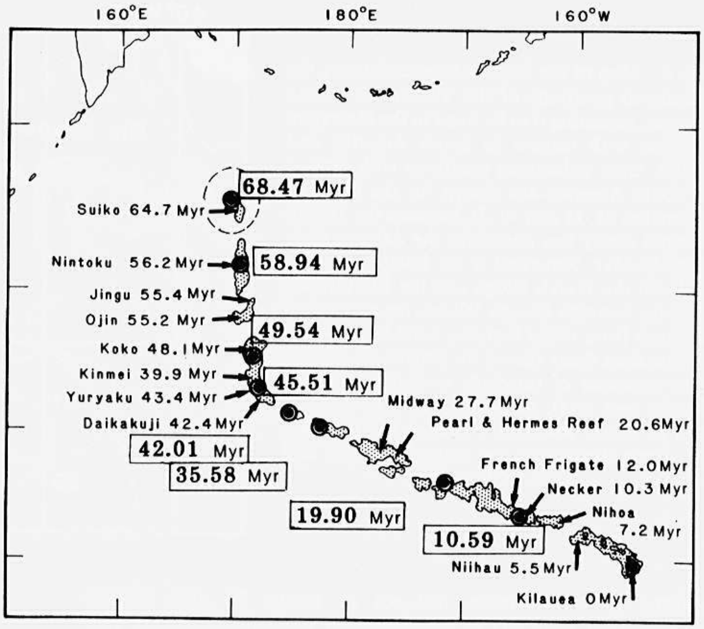


**Fig. 2** Map of the Hawaiian-Emperor chain with ages of well dated seamounts and islands[34] indicated by arrows and large dots showing the positions of the Hawaiian hotspot at the times of the magnetic anomalies used in calculations of the positions of other hotspots. The dashed circle around the anomaly 31 position shows the 200-km uncertainty assigned to the position of the hotspot and incorporated in subsequent calculations.

**Iceland.** Volcanism associated with this hotspot presumably is responsible for the southeasterly trending Iceland–Faeroes Ridge and for the British Tertiary volcanic province of igneous rocks with ages of 50 to 60 Myr (ref. 23) (Fig. 3). The Iceland hotspot apparently also underlay Greenland in early Tertiary time; volcanic rock with ages between 55 and 60 Myr (ref. 24) crops out along the coast north of Skaergaard[25], where intrusive rock with a Rb/Sr age of $49 \pm 2$ Myr (ref. 26) is present.

The calculated positions of the centre of Iceland lie progressively south-east of the island at progressively older times and define a trace that diverges from the Iceland–Faeroes Ridge and lies south of it (Fig. 3). Relative movement of the Hawaiian and Iceland hotspots is only barely resolvable. The uncertainty ellipses for the calculated positions of the hotspot overlap the southern edge of the ridge, and if the hotspot had underlain that edge of the ridge, it could have been fixed with respect to the Hawaiian hotspot. In contrast, for about 50 Myr (anomaly 21), the calculated minimum distance of the hotspot from the axis of the ridge is $450 \pm 300$ km, implying a minimum average rate with respect to the Hawaiian hotspot of at least $9 \pm 6$ mm $yr^{-1}$. The calculated positions of the hotspot for about 50 and 59 Myr (anomalies 21 and 25) lie $700 \pm 300$ km and $600 \pm 500$ km west of the westernmost volcanic centres in northwestern Scotland and northeastern Ireland. These imply minimum average velocities of $14 \pm 6$ mm $yr^{-1}$ and $10 \pm 8$ mm $yr^{-1}$ of the Iceland and Hawaiian hotspots. Finally if, following Morgan[1,2], we used the present location of Surtsey, just south of Iceland, instead of the centre of the island, the calculated distances and rates would be about 200 km and 3–4 mm $yr^{-1}$ larger.

The calculated positions of the Iceland hotspot beneath Greenland define a southwesterly trend, instead of the northwesterly trend implied by the outcrops of early Tertiary volcanic rock on the coast of Greenland. The distance from the most southwestern volcanic rock, near Skaergaard, to the calculated positions of the hotspot at about 50 and 59 Myr (anomalies 21 and 25) are $700 \pm 200$ km and $900 \pm 700$ km, respectively (Fig. 3). Thus, they imply average velocities between Hawaii and Iceland of at least $14 \pm 4$ mm $yr^{-1}$ and $15 \pm 12$ mm $yr^{-1}$. Again, were the hotspot to underlie Surtsey, the calculated distances and rates would be larger. Moreover, if the distances were measured to the middle of the volcanic area in Greenland, the calculated distances and rates would be another 200 km and 3–4 mm $yr^{-1}$ higher. Thus an average rate of 20 mm $yr^{-1}$ between the Hawaiian and Iceland hotspots is possible.

**Tristan da Cunha.** The calculated positions of this hotspot define an east–southeasterly trend that diverges markedly from that of the Walvis Ridge (Fig. 4). For 68 Myr (anomalies 30–31), the calculated position of the hotspot lies $1,000 \pm 300$ km from the nearest part of the Walvis Ridge. Therefore it implies a minimum average rate between the Hawaiian and Tristan hotspots of $14 \pm 4$ mm $yr^{-1}$. The distance from DSDP site 359, where basalt with an age of 50 to 55 Myr is interpreted to have erupted from a seamount[27], to a point midway between the calculated

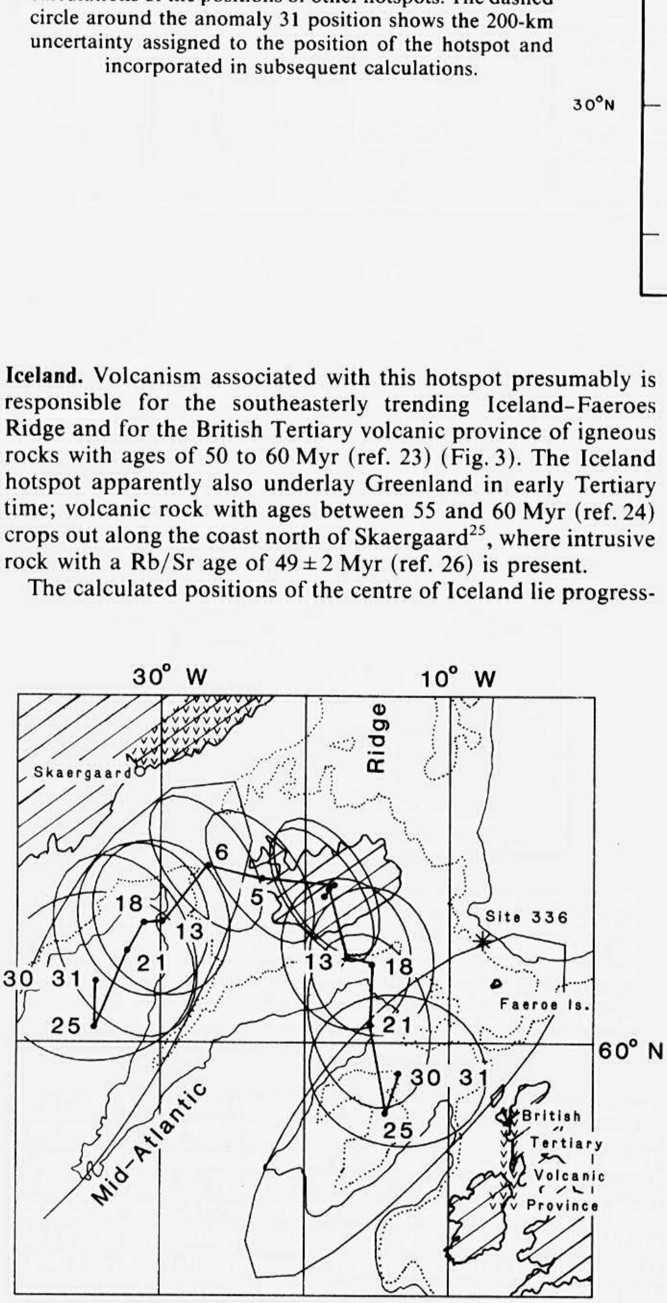


**Fig. 3** Map of the North Atlantic showing the calculated positions of the Iceland hotspot, assuming it to be fixed to the Hawaiian hotspot, with respect to Greenland and Europe. The area covered by early Tertiary volcanic rock in Greenland and in the British Isles is shown with Vs. K–Ar ages from basalts at site 336 are 40–43 Myr (ref. 33). The sequence of rotations is hotspots to the Pacific (see text), to Antarctica[12], to Africa[15], to North America[17], to Europe, and to Greenland (K. D. Klitgord, H. Schouten and P. Molnar, unpublished results).

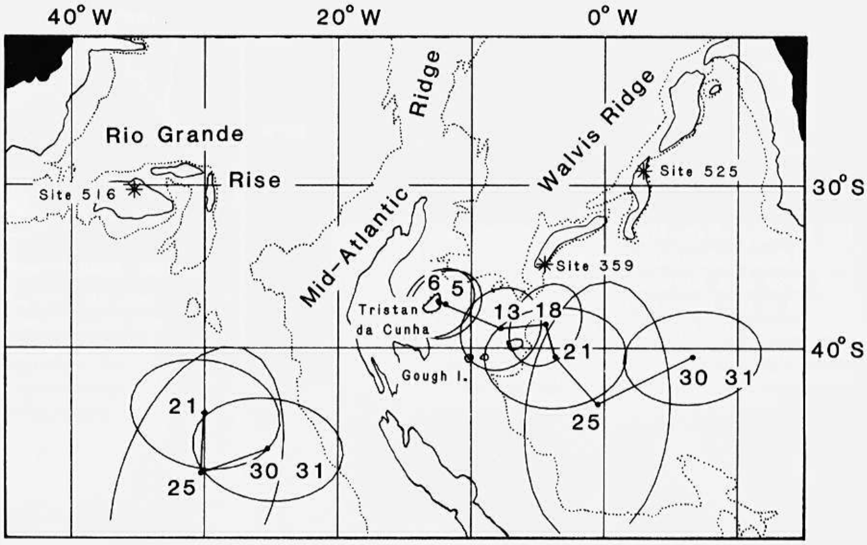


**Fig. 4** Map of the South Atlantic showing the calculated positions of the Tristan da Cunha hotspot, assuming it to be fixed to the Hawaiian hotspot, with respect to South America and Africa. Only calculated positions with respect to South America are shown for the times of anomalies 21, 25 and 30–31, because the Tristan hotspot surely has underlain the African plate since 50 Myr. Note that if the hotspot responsible for the Walvis Ridge and the Rio Grande Rise lay beneath Gough Island, the calculated distance from those features would be 400 km farther than those shown for Tristan da Cunha. The sequence of rotations is hotspots to the Pacific (see text), to Antarctica[12], to Africa[15] and to South America[16], except for anomaly 25, where Antarctica was rotated to India and then to Africa[15].

positions of the Tristan hotspot at about 50 and 59 Myr (anomalies 21 and 25) is 800 ± 500 km corresponding to 16 ± 10 mm yr$^{-1}$. Tuffs, with a K–Ar age of 40.1 ± 1 Myr, overlie older sediment at this site[28]. (All K–Ar ages that we quote have not been corrected for new decay constants.) The calculated distance to the Tristan hotspot at 42 Myr (anomaly 18) is 500 ± 300 km. If deposition of these tuffs marked the location of the hotspot, the average velocity would have been 12 ± 8 mm yr$^{-1}$. The calculated position of the hotspot at 68 Ma lies 1,300 ± 300 km from DSDP site 525, where late Maastrichtian sediment (66–75 Myr) overlies basalt[29]. If the hotspot lay beneath this site at about 68 Myr, the average rate would have been 19 ± 4 mm yr$^{-1}$. Finally, if the hotspot lay beneath Gough Island instead of Tristan da Cunha, the calculated distances and average rates would be a few hundred km and several mm yr$^{-1}$ greater.

The calculated positions of the Tristan hotspot with respect to South America for 59 and 68 Myr, lie 1,300 ± 700 km and 1,300 ± 300 km south of the south-east end of the Rio Grande Rise (Fig. 4). If the Tristan hotspot had underlain the South American plate at those times, minimum average velocities of the Tristan and Hawaiian hotspots would have been at least 22 ± 12 mm yr$^{-1}$ or 19 ± 4 mm yr$^{-1}$.

**Réunion.** Calculated positions of Réunion before 42 Myr (anomaly 18) lie beneath the African plate, but for older times they define a northerly trend a few hundred km east of the Chagos–Laccadive chain (Fig. 5). At 59 Myr, the calculated position is about 500 km east of that chain, but the uncertainty ellipse overlaps part of the chain. The calculated positions for 59 and 68 Myr lie south and east of the Deccan traps, which were erupted at 64 ± 1 Myr (ref. 30) and are thought to result from the Réunion hotspot beneath India[1]. The distance from the interpolated position of Réunion at 64 Myr to the southern edge of the Deccan traps is 600 ± 300 km, corresponding to a minimum relative velocity between the Hawaiian and Réunion hotspots of 10 ± 5 mm yr$^{-1}$. The distance to the centre of the vast area covered by volcanic rock is 1,000 ± 300 km, corresponding to an average velocity of 15 ± 5 mm yr$^{-1}$.

**Kerguelen and St Paul's Island.** The formation of the Ninety East Ridge has been ascribed to hotspots beneath either Kerguelen or St Paul's Island (or both)[31], but no volcanic chain or ridge has been found between the southern end of the Ninety East Ridge and St Paul's Island (Fig. 5). Calculated positions of both possible hotspots for 50, 59 and 68 Myr (anomalies 21, 25 and 30–31) define north-northeasterly trends about 1,000–1,500 km east of the Ninety East Ridge. The calculated distances from the Kerguelen and St Paul's hotspots at 59 Myr to DSDP site 214 on the Ninety East Ridge, which yielded K–Ar ages of 52.9 and 53.9 Myr on basalts and biostratigraphic ages on overlying sediment of 56–58 Myr (foraminifera) and 57–61 Myr (nannofossils)[32] are 1,500 ± 300 km and 1,600 ± 400 km, respectively. These distances correspond to average rates with respect to Hawaii of 25 ± 5 mm yr$^{-1}$ and 27 ± 7 mm yr$^{-1}$. Similarly calculated distances for 68 Myr and DSDP site 216, with K–Ar ages of 62.9, 64.9 and 64.4 Myr and biostratigraphic ages of <67 Ma (foraminifera) and 65–67 Myr (nannofossils)[32] are 1,500 ± 300 km for Kerguelen and 2,100 ± 400 km for St Paul's, corresponding to average rates of 22 ± 4 mm yr$^{-1}$ and 31 ± 6 mm yr$^{-1}$. Morgan[1], who did not consider a hotspot under St Paul's Island, referred to Kerguelen as "the least fixed" of the hotspots that he studied in the Atlantic and Indian Oceans. We agree.

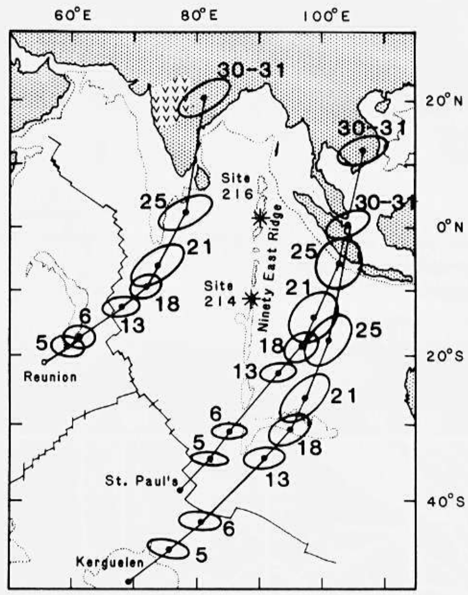


**Fig. 5** Map of the Indian Ocean showing the calculated positions of the Réunion, St Paul's, and Kerguelen hotspots with respect to the Indian plate, assuming them to be fixed to the Hawaiian hotspot. The part of India covered by the Deccan traps, with ages of 64 ± 1 Myr (ref. 30), is shown with Vs. The sequence of rotations is hotspots to the Pacific (see text), to Antarctica[12] and to India[15].

## Conclusions

Using Morgan's[1,2] or Duncan's[3] motions of Africa over its underlying hotspots, calculated motions of the Pacific plate over the Hawaiian hotspot show a change in direction at approximately the age of the bend in the Hawaiian-Emperor chain, but the calculated positions of the Hawaiian hotspot for that time are 300 to 800 km from the bend. More importantly, the different parameters[1-3] yield very different positions of the bend, implying that the positions of the African plate with respect to the Tristan da Cunha hotspot are not known well enough to be used in a test of fixed hotspots.

Using the history of motion of the Pacific plate over the Hawaiian hotspot defined by the ages of volcanic rocks along the Hawaiian-Emperor chain[34], the calculated relative positions of hotspots (presumed to be fixed) beneath Iceland, Tristan da Cunha, Rèunion, Kerguelen and St Paul's Island lie from several hundred to more than a thousand km from the traces left by them. These calculations call for relative velocities between these hotspots and Hawaii of at least 10 mm $yr^{-1}$ and as much as 20 mm $yr^{-1}$ in some cases. Thus the hotspot traces do not define a fixed reference frame, and uncertainties in plate reconstructions are much smaller than the errors made in reconstructions based on the assumption of fixed hotspots.

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