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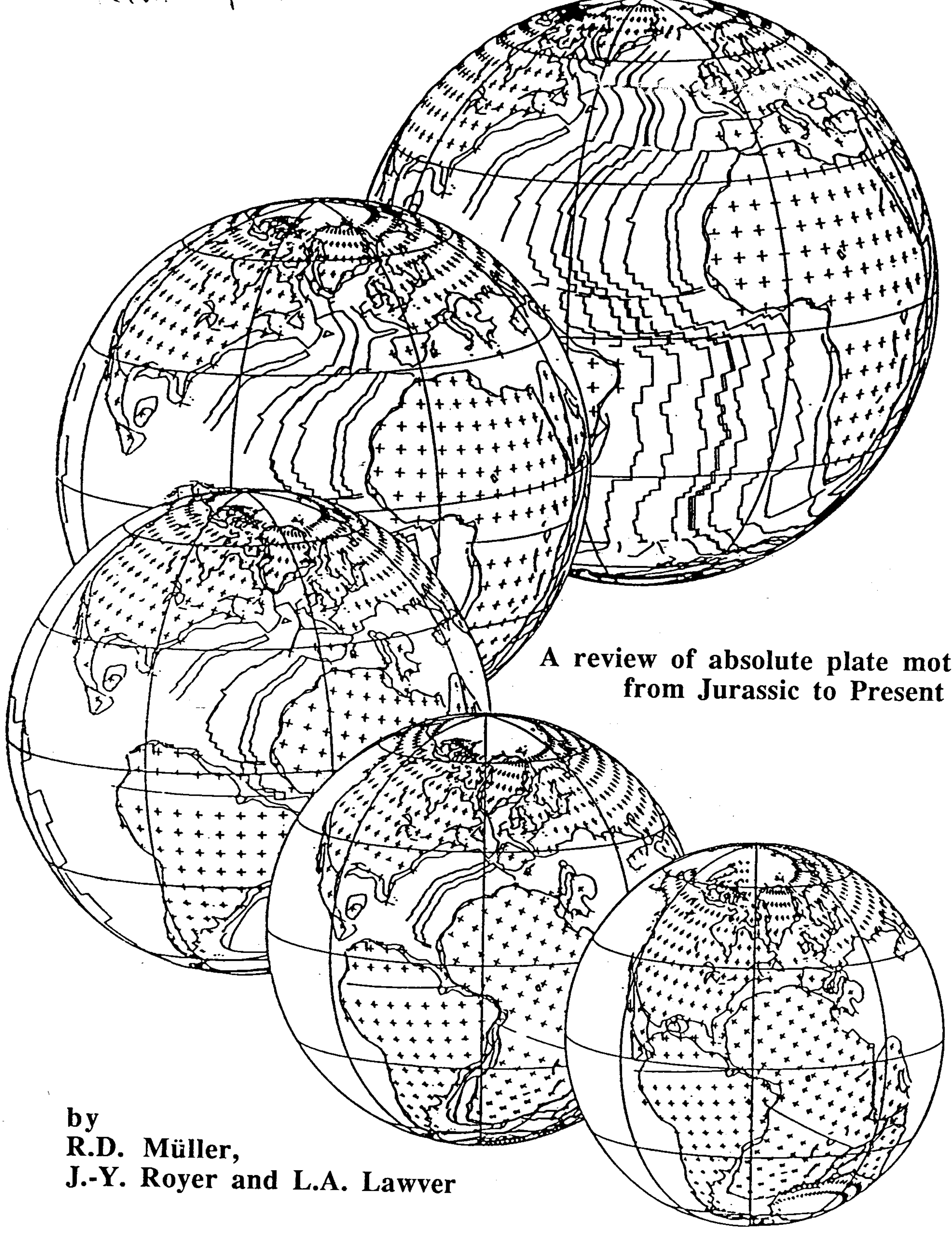

A review of absolute plate motion models from Jurassic to Present Day

by
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Introduction

Knowledge of the relative motion between the major tectonic plates over the last 180 million years has increased substantially during the past twenty years. Even so models for "absolute" plate motions relative to a "fixed" mesosphere are still controversial. Several concepts which have been put forward to reconstruct "absolute" plate motions include: paleomagnetic data, hotspot traces and the "no net torque" model. Paleomagnetic data is used to determine paleopoles, i.e. the paleo-meridian orientation and the paleolatitude of a plate. However, the earth's dipole field is radially symmetric, so no paleo-longitudinal information can be deduced from paleomagnetic data. Restoration of plates along hotspot tracks, i.e. seamount chains with linear age progression, has been used with the assumption that the motion of the underlying hotspots relative to each other is negligible ("fixed hotspot hypothesis"). Molnar and Stock (1987) showed, though, that the Hawaiian hotspot moved with average velocities of 10 - 20 mm/yr relative to the Iceland hotspot and hotspots beneath the African and Indian plates during the Tertiary. A third model to determine absolute plate motions, the "no net torque" model, was developed by Solomon and Sleep (1974). It is based on the fact that the lithosphere can not exert a net torque on the asthenosphere. If the boundaries and relative velocities of the plates through time are known, the forces acting on the plates can be calculated. This concept does not provide a unique solution for absolute plate velocities, since the forces caused by coupling between the lithosphere and asthenosphere, whose nature and lateral variation are not known, can not be calculated accurately.

Numerous paleomagnetic datasets and models for the "absolute" motions of the North American, African and Eurasian plates during the Mesozoic and Cenozoic have been published (Paleomagnetic data: Harrison and Lindh, 1982; May and Butler, 1986; Besse and Courtillot, 1988; Irving and Irving, 1982; Ziegler et al., 1983; models based on hotspot tracks: Duncan, 1981; Morgan, 1981, 1983; Fleitout et al., 1989) have been published. Our interest in this paper is to review the published apparent polar wander (APW) paths for North America, Africa and Eurasia, evaluate their consistency with each other, and compare them with synthetic APW paths from absolute motion models based on hotspot tracks. Secondly we will compare Pacific and African/Indian plate motions relative to the hotspots and investigate the continuity of the plate circuit between the African, Antarctica and the Pacific plates.

Plate reconstructions

We have used detailed models for relative motions between North America/Eurasia (Srivastava and Roest, 1989; Roest and Srivastava, 1989) and North America/Africa (Klitgord and Schouten, 1986) to test the compatibility of the APW paths and absolute motion models for the North American, African and Eurasian plates. We will show that there are various inconsistencies between different APW paths and hotspot models, but a reasonably good correlation is observed for the Cenozoic North American APW path from Harrison and Lindh (1982) with the hotspot models of Morgan (1983) and Fleitout et al. (1989). Stronger deviations between absolute motion models based on hotspot tracks and APW paths from paleomagnetic data are observed for pre-Cenozoic times. By using a new relative plate motion model (Royer et al., 1988, 1989; Mayes et al., 1990) for the plate circuit Africa/Antarctica/Pacific, we also test the continuity of this plate circuit for possible motion between the Pacific and African hotspots.

Gordon and Cox (1980), Suárez and Molnar (1980), Morgan (1981) and Duncan (1981) proposed that there must have been an additional plate boundary between the Pacific and African plates, either in Antarctica or in the South Pacific, if the motion of the hotspots beneath the Pacific, African and Indian plates relative to each other is assumed to be negligible. We found that given the relative motion model between Africa/Antarctica/Pacific, the motion along the ficticious missing plate boundary would have exceeded 1500 km of extension in the time between 74 and 43 Ma. This magnitude of intraplate motion can clearly be ruled out both for Antarctica and for the Pacific on geologic and plate tectonic grounds. Our results convincingly support the conclusion of Molnar and Stock (1987) that the Pacific and African/Indian hotspots were not fixed relative to each other and do not provide an absolute motion framework. It also appears that the motion between the Pacific hotspots as well as among the African/Indian hotspots was very small during the last 75 million years. A series of absolute plate motion poles for the Pacific plate can be found that well satisfies both the geometry and the age progression along the Hawaiian Emperor chain and the Louisville Ridge for this time interval. Similarly Fleitout et al.'s (1989) model for motion of the African plate relative to the hotspots well fits the geometry of the Chagos-Laccadive and the Ninetyeast ridge, hotspot tracks left by the Reunion and Kerguelen hotspots.

Absolute motion models

There are two absolute motion models for Africa (Duncan, 1981; Fleitout et al., 1989) that are based solely on data (i.e. hotspot tracks) from the African plate. Three other models are based on hotspot traces either on plates around the Atlantic and Indian oceans (Morgan, 1981) or the Atlantic Ocean (Morgan, 1983), or on a global compilation of paleomagnetic data (Ziegler et al., 1983). In these three cases, models of the relative motion between the respective plates were used to combine hotspot or paleomagnetic data from different plates to construct a regional or global absolute motion model in African coordinates.

APW paths for North America, Africa and Eurasia are shown on Figs. 1 and 2. The path for North America (Fig. 1a) consists of the Jurassic/Cretaceous APW path by May and Butler (1986) and the Cenozoic path by Harrison and Lindh (1982). The paths for Africa (Fig. 1d) and stable Eurasia (Fig. 2b) are from Besse and Courtillot (1988).

Different techniques have been used to evaluate the paleomagnetic data and to construct APW paths. Harrison and Lindh (1982) constructed an APW curve for North America for the Mesozoic and Cenozoic by determining mean poles using a sliding 30 million year window and applying different weighting factors to the data used. They introduced a technique which weights the information content of individual studies and the age overlap between the individual study and the age window applied. May and Butler (1986) criticized the sliding window technique as smoothing important information in the data, especially for times of abrupt plate motion changes that result in "cusps" in the polar wander curve. With their method they first determine a time sequence of high-quality paleopoles and construct best fit small circles to a sequence of poles, following the idea put forward by Francheteau and Sclater (1969) and Gordon et al. (1984) that APW paths consist of small circle segments that can be generated by paleomagnetic Euler pole (PEP) analysis. May and Butler (1986), though, did not compute reconstruction poles to obtain the absolute motion of North America.

Besse and Courtillot (1988) used a set of re-evaluated and updated paleomagnetic data from Africa to construct an APW path for Africa from 185 Ma to present. They determined a set of Euler poles that restore the paleomeridian orientation and the paleolatitudinal position of Africa. They selected a reference point on the African plate (0°, 10°E) and performed two finite rotations about the reference point, to restore the declination and paleolatitude for each paleomagnetic pole on the APW path. The Eurasian APW path (Fig. 2b) from Besse and Courtillot (1988) is based on a compilation of various paleomagnetic data from the literature. However, no confidence limits are listed for the individual poles, although A_{95}-confidence circles are given by Besse and Courtillot (1988) for the calculated mean poles.

Ziegler et al. (1983) constructed a global apparent polar wander path by calculating mean paleomagnetic poles for a number of continents (they do not indicate which ones or how many) and used a relative motion model between these continents to rotate the poles into superposition. An APW path was constructed by calculating global mean poles in African coordinates (Fig. 2d). In this paper we use a set of Euler poles (Ziegler et al., unpubl.) that corresponds to the Jurassic and Cretaceous global APW path of Ziegler et al. (1983), but which deviates from their Tertiary path.

Four different models for the absolute motion of Africa based on hotspot tracks have been published in the past eight years (Duncan, 1981; Morgan, 1981, 1983; Fleitout et al., 1989). Duncan (1981) used a number of hotspot tracks on oceanic crust, including the St. Helena, Tristan de Cunha, Bouvet and Prince Edward Island hotspot paths, to reconstruct the absolute motion for Africa during the last 100 Ma (Fig. 3b). He determined the motion of Africa relative to the hotspots in 20 m.y. intervals by use of a visual best-fitting technique. Morgan (1981) used a relative motion model for plates around the Atlantic and Indian oceans (Fig. 3b), while Morgan (1983) used only plates around the Atlantic Ocean (Fig. 4b) to iteratively determine the absolute motion of all the plates considered. He visually fits a number of hotspot paths to computed synthetic hotspot tracks. After determination of the motion of one plate (Africa) relative to the hotspots, he computed the absolute motions of other plates for the last 200 million years, where relative motions were known. It has to be stressed, though, that the geometry and ages of hotspot tracks older than the Late Cretaceous are not well known, so that models for the Jurassic and Early Cretaceous have to be judged with care. Fleitout et al. (1989) determined the location of the hotspot tracks in the South Atlantic by using short-wavelength tectonic features of the seafloor on geoid and bathymetry maps. They calculated a new set of rotations for Africa (Fig. 4d) with respect to the hotspots. Their rotation poles are not drastically different from Morgan's (1983) model for Africa.

Methods

Given a relative plate motion model, an absolute motion model or an APW path can be translated into the coordinates of any other plate considered in the model. Morgan (1981, 1983) used this technique and listed absolute motion poles for a number of plates, including poles for the North American plate that we use to compare his model with the APW path of North America. In order to directly compare the APW paths for North America, Africa and Eurasia, to evaluate the different absolute motion models with respect to the APW paths for North America and Africa and to compare the absolute motions between the African and Pacific plates, we used the most recently updated relative motion models to translate data from the coordinate system of one plate to another plate. The relative motion poles for Africa/North America are from Klitgord and Schouten (1986) and Müller et al. (subm. to Marine Geophys. Res.). The Jurassic through Cenozoic motion between these two plates is very well constrained by a dense coverage of magnetic anomaly picks (Klitgord and Schouten, 1986) and by the large number of fracture zones interpreted from Seasat/Geosat data (Müller et al., POMP Prog. Rep.). The relative motion between North America and Eurasia is computed by use of a revised plate tectonic model for the opening of the North Atlantic based on Srivastava and Roest (1989) and Roest and Srivastava (1989). Plate motions between Africa and Antarctica are from Royer et al. (1988, 1989) and relative motions between Antarctica and the Pacific Plate are from Mayes et al. (in press). The two latter models are based on a combination of magnetic anomaly data and fracture zones interpreted from Geosat deflection of the vertical data.

The North American and Eurasian APW paths were translated into African coordinates (Figs. 1-4) to directly compare them with the African APW path. In a common coordinate system poles from all three plates should ideally coincide for a given time. In the same fashion APW paths in African coordinates were rotated into North American coordinates to allow for a direct comparison with the North American APW path. We also plotted flowlines of the African and Pacific plates for various absolute motion models in order to compare absolute motion models for Africa/North America with the motion of the Pacific plate determined from the Hawaiian-Emperor and Louisville hotspots. This allows us to test the continuity of the plate circuit Africa/Antarctica/Pacific, with whether the Pacific and African hotspots moved relative to each other.

The above method allows a qualitative comparison between absolute motion models for different plates and serves as a simple check for consistency between different models. A more quantitative approach to this problem is problematic for various reasons. Frequently different models are based on different time scales. For a truly quantitative comparison of absolute motion models, all paleomagnetic data absolute motion poles would have to be normalized to the same time scale. Since some of the papers do not even specify which time scale was used, a truly quantitative comparison may be impossible. Models that include a large number of plates whose hot spot tracks or paleomagnetic data were used to construct a regional or global absolute motion model have to rely on the quality of a specific relative motion model (e.g. Morgan, 1981, 1983; Ziegler et al., 1983). The latter models are not only dependant on the quality of the original paleomagnetic data, hotspot tracks or time scale used, but also on the preferred relative motion model. Although we can not consider all these variables in the following analysis, we do present a qualitative comparison between different models.

Apparent polar wander paths

Comparisons of the African, North American and Eurasian APW paths in North American and African coordinates (Figs. 1, 2) reveal distinct differences between these paths. The Neogene North American APW (Fig. 1a) path deviates distinctly from the African (Fig. 1c) and the Eurasian (Fig. 2a) APW path (in North American coordinates), as the former predicts a much slower rate of latitudinal change for both North America and Africa during the last 20 million years (also comp. Fig. 6). A comparison between the African and North American APW paths shows that their geometry is fairly different, including both differences in paleolatitude as well as paleo-meridian orientation. While the African path follows a general counterclockwise apparent polar wander path back in time for the last 185 million years, the North American path corresponds to a clockwise apparent motion of the pole in North American coordinates. Since the errors in the relative motion model between Africa and North America, which we estimate to be in the order of 10-30 km for any reconstruction time, are significantly smaller than the observed inconsistencies between the apparent polar wander of Africa and North America, the latter misfits must be attributed to uncertainties in one or both APW paths. Note that the "cusps" in the North American APW path identified by May and Butler (1986) are not present in any other APW path in North American coordinates. This is mainly due to the course time spacing of the Eurasian and African paleomagnetic data. Also the apparent stillstand in North American APW from 85-130 Ma, as implied by May and Butler's (1986) path, is not visible in the other paths, which do predict significant Early Cretaceous motion of North America. However, the Eurasian and African APW paths from Besse and Courtillot (1988) in North American and African coordinates show a very similar geometry, supporting the assumption that observed misfits between APW paths are not primarily due to errors in the relative motion models.

Absolute motion paths of tectonic plates are thought to ideally match small circle segments, corresponding to uniform plate motion intervals about one pole of rotation interrupted by rapid changes in directions of motion (Francheteau and Sclater, 1969; Gordon et al., 1984). This concept is based on observations of the shape of long, continuous fracture zones and on the curvilinear nature of hotspot tracks (Gordon et al., 1984). If this hypothesis is assumed to hold for all major plates, then an APW path consisting of small circle segments for any one plate should also result in small circle paths for other plates, whose past relative motion to the first plate is well-determined. A good example is posed by the North American Jurassic/Early Cretaceous APW path by May and Butler (1986), whose original path from about 200 Ma to 85 Ma consists of two small circle segments divided by one cusp (Fig. 1a). After concatenation with the relative motion poles corresponding to the opening of the Central Atlantic, i.e. translation of the APW path into the African coordinate system, the Late Jurassic/Early Cretaceous part of the path looses its originally smooth nature (Fig. 1b). This probably does not mean that Africa did not move as smoothly as North America, but rather reveals inconsistencies in the North American paleomagnetic data. A comparison with the Mesozoic North American APW path from Harrison and Lindh (1982) in African coordinates (Fig. 5b) reveals that their path also looses its smooth curvature after translation into African coordinates. This shows that the unsmooth pattern of May and Butler's (1986) path in African coordinates can not be due to the fact that they did not use a moving window technique, implying that errors in single poles could be enhanced. This example demonstrates, how a well constrained relative motion model between different plates can effectively be used to test the consistency of the "apparent smoothness" of an APW path.

Ziegler et al.'s (unpubl.) global absolute plate motion model in African coordinates yields an APW path that displays a rather discontinuous, irregular pattern (Fig. 2d). Although it generally follows the same trend as the African APW path by Besse and Courtillot (1988), there is a considerable mismatch between the Jurassic parts of the two paths. The same model transformed into North American coordinates (Fig. 2c) reveals an even stronger discontinuous, zig-zag like pattern that can not be reconciled with the notion that APW paths should resemble small circle segments. A comparison with the North American APW path from May and Butler (1986) shows a strong disagreement for ages older than Late Cretaceous (Fig. 2c).

The absolute plate motion path of Africa for the last 100 million years by Duncan (1981) based on hotspot tracks is in moderately good agreement with the paleolatitudes of Africa as predicted from Besse and Courtillot's (1988) APW path for Africa (Fig. 3d) as well as with the trend of the North American APW path by Harrison and Lindh (1982) and May and Butler (1986) (Fig. 3c). Duncan's model (1981), however, implies a much more rapid northward motion of North America and Africa between 55 and 80 Ma than implied from paleomagnetic data.

The absolute motion model from Morgan (1981) (Fig. 3a, b) is similar to Duncan's (1981) model for the last 100 million years, although Morgan (1981) implies a more uniform African plate velocity for the Upper Cretaceous/Paleocene. Morgan's (1983) model in North American coordinates (Fig. 4a) yields a path roughly similar in geometry to the North American APW path, although the implied latitudinal motion of North America earlier than 70 Ma is more than 10° less than predicted by the APW path. This portion of Morgan's (1983) path correlates better with the African APW path in terms of paleolatitudes, although the paleo-meridian orientations of these paths are quite different (Fig. 4). The best fit to the Cenozoic portion of the North American APW path is given by Fleitout et al's (1989) model (Fig. 4c).

Paleolatitudes of Africa and North America

In order to further evaluate the consistency between various APW paths and their compatibility with models based on hotspot tracks, we have plotted the predicted paleolatitudes of central North America and Africa from all models discussed here. Fig. 6 shows the paleolatitude of North America and Africa from paleomagnetic data. The plots manifest that there are discrepancies of up to 10° of latitude for the Cenozoic between the Eurasian/African data and the North American data. The most striking disagreement for the paleomagnetic data of Mesozoic age is posed by a strong latitudinal deviation between the North American and the Eurasian/African data for the Middle/Late Jurassic. The deveation between the latitudinal paths computed from Ziegler's (unpubl.) and May and Butler's (1986) APW path is less distinct, although a similar latitudinal divergence for the Middle/Late Jurassic is present. More data from different plates are necessary to pinpoint errors in which datasets are most likely causing this disagreement. In Fig. 7 we have plotted the paleolatitude of both North America and Africa as predicted from hotspot absolute motion models. The latitudinal paths from all four models are relatively consistent. This can be explained by the fact that the database used for all models, i.e. volcanic hotspot chains on the seafloor and relative motion models, do not exhibit as large differences as paleomagnetic datasets. A comparison of Morgan's (1983) absolute motion model with the APW paths from Eurasia, Africa and North America (Fig. 8) shows a clear disagreement for pre-Cenozoic times that may be attributed to wander of the hotspots with respect to the spin axis.

Hotspot tracks

In order to compare the absolute motion models discussed here with observed hotspot tracks on the African and Pacific plates as well as to test the continuity of the plate circuit Africa/Antarctica/Pacific, we plotted synthetic flowlines of the African and Pacific plates for different models (Figs. 9-13). A large number of radiometrically determined ages are available for the Hawaiian-Emperor and the Louisville seamount chains in the Pacific (Fig. 12). For hotspot tracks on Africa the relatively sparse age information was summarized by Duncan (1981). In Fig. 9 we have plotted synthetic flowlines for the African plate starting at the present day locations of the St. Helena, Tristan da Cunha and Comores hotspots. The plots show that the model from Fleitout et al. (1989) (Fig. 9d) gives the best fit to the geometry of the African hotspot tracks on ocean crust. Models based on paleomagnetic data result in zig-zag like flowline patterns (Figs. 9e) mainly reflecting the lacking paleo-longitudinal information inherent in paleomagnetic data. This also exemplifies that even smooth APW paths will usually not result in a smooth flowline pattern for any plate, just because an arbitrary reference point on the plate must be held fixed in order to restore the paleo-meridian orientation and the paleolatitude of any data point. As a result absolute motion paths for large plates computed from paleomagnetic data will always include artificial components and can not be used in a straightforward way to reconstruct "real" paleo-motions of plates that are thought to consist of small circle segments divided by cusps.

Fig. 9 also reveals that the available hotspot tracks on the African plate are rather scanty and do not constrain the motion of Africa relative to the hotspots very well. The Walvis Ridge represents the only well-expressed and continuous volcanic ridge in the eastern South Atlantic. In order to test the validity of Fleitout et al.'s (1989) absolute motion model, we used the plate model for the evolution of the Indian Ocean by Royer et al. (1988, 1989) and Royer and Chang (subm. to JGR) to translate the absolute motion of Africa to Antarctica, Kerguelen, India, the Central Indian Basin and Australia to plot the motion of these plates relative to the Reunion and Kerguelen hotspots. Fig. 10 shows the surprisingly good fit of the synthetic flowlines to both the Chagos-Laccadive and the Ninetyeast Ridge. Two different flowlines were calculated for the Chagos-Laccadive Ridge by (a) modelling the Indian plate and the Central Indian basin as one rigid plate and (b) by including intraplate motion between India and the Central Indian Basin (Royer and Chang, subm. to JGR). The relatively broad geometry of the Chagos-Laccadive Ridge does not allow any discrimination between these two models. DSDP- and ODP-drilling results from the Ninetyeast Ridge (Fig. 10) show a good correlation with the flowline from Fleitout et al.'s (1989) model. It must be noted, though, that a linear age progression along the Ninetyeast Ridge can not be expected since a large ridge jump at chron 26 (61 Ma) and several smaller, subsequent jumps occurred in the vicinity of the Ninetyeast Ridge (Royer and Sandwell, 1989). Their plate model predicts that the ages along the Ninetyeast Ridge should decrease from 84 to 60 Ma between 10°N and 7°S, increase from 60 to 70 Ma between 7°S and about 16°S, and decrease from 60 to 35Ma between 16°S and 32°S. This model agrees well with the ages from DSDP and ODP sites (Fig. 9).

We have translated the model for African motion relative to the hotspots from Fleitout et al. (1989) into coordinates of the Pacific plate by using Royer et al.'s (1988, 1989) rotation parameters for Antarctica/Africa motion and Mayes et al.'s (1990) rotation poles for Pacific/Antarctica motion (Fig. 11a). If all hotspots were fixed relative to each other and if we assume that the plate boundaries between Africa and the Pacific plate are identified correctly, it would be expected that Fleitout et al.'s (1989) flowlines in Pacific plate coordinates match the geometry and ages of the Pacific seamount chains. Although the fit between flowlines and the seamount chain geometry seems to reasonably good at a first glance (except for the Emperor chain), Fig. 11a illustrates that a considerable mismatch is observed between seamount ages and predicted ages from flowlines. For instance the bend between the Hawaii and Emperor chains that is dated as about 43 Ma (Duncan and Clague, 1985) would correspond to an age of 65 M.y. using Fleitout et al.'s (1989) model.

In order to determine the flowline of the Pacific plate over underlying hotspots, we used available data from the Hawaiian-Emperor chain (Duncan and Clague, 1985) and recently published data constraining the geometry and ages of the Louisville seamount chain (Lonsdale, 1988). We used a visual fitting technique to derive absolute motion poles for the Pacific plate in 5 stages (0-5, 5-25, 25-43 43-65) (Fig. 11b, Table 1) that satisfy both the geometry and the age data from the Hawaiian-Emperor and the Louisville chains (Fig. 12) quite well. The poles for the time prior to 65 Ma (Table 1) are from Duncan and Clague (1985). The observed fit serves as good evidence that there was no significant relative motion between the South and North Pacific ocean crust during the last 74 million years. We then evaluated the fit of this model for the Austral-Cook Islands, the Marshall-Gilbert Seamount and the Line Islands (Fig. 13). Here the scatter of radiometric ages (from Duncan and Clague, 1985) is stronger than for the Hawaii-Emperor and Louisville chains, but a reasonably good fit between synthetic flowlines and the island chain geometry is observed. A fit of any flowline to the Marshall-Gilbert Islands can only be achieved if it is assumed that an active hotspot is located at about 19°S, 155°W, as opposed to regarding the MacDonald Seamount (Duncan and Clague, 1985) at about 23°S,140°W as the location of the active hotspot responsible for generation of the Marshall-Gilbert Seamount.

The Pacific absolute motion path was then transformed into African coordinates by using Mayes et al.'s (1990) rotation poles for Pacific/Antarctica motion and Royer et al.'s (1988, 1989) rotation parameters for Antarctica/Africa motion (Fig. 9e), resulting in a flowline pattern very similar to that in Molnar & Stock's (1987) Figure 4, who used different rotation parameters. The predicted path for Africa deviates strongly from the observed African hotspot tracks by up to >2000 km for times earlier than 40 Ma. For the time after 40 Ma only a minor amount of 200 km of African absolute motion is implied. This either means that before 40 Ma another plate boundary existed in the plate circuit Pacific/Antarctica/Africa or that the Pacific and African hotspots moved relative to each other.

Continuity of the plate circuit between the Pacific and African plates

The existance of a possible fossil plate boundary in the South Pacific or within Antarctica was postulated by Gordon and Cox (1980) and Suárez and Molnar (1980) based on paleomagnetic data and plate reconstructions. Gordon and Cox (1980) favor a model in which they follow the fixed hotspot hypothesis and divide the present day Pacific plate into two plates for Early Tertiary times along a plate boundary between the Chatham rise and a North Pacific plate. Suárez and Molnar (1980) speculate that a paleo-plate boundary existed between Marie Byrd Land and East Antarctica before 40 Ma based on paleomagnetic data and following the fixed hotspot hypothesis. Their scenario implies almost 2500 (±1500) km of displacement between East Antarctica and Marie Byrd Land necessary to overlap the 70 m.y. paleomagnetic poles of both plates. This model predicts Early Tertiary left-lateral strike-slip between West and East Antarctica, related to opening of the Weddell Sea. An alternative hypothesis discussed by Suárez and Molnar (1980) involves a pre-40 Ma plate boundary between the North and South Pacific plates with motion along or parallel to the Eltanin Fracture Zone system. Various authors have subsequently followed these ideas by using either a paleo-plate boundary in the South Pacific (Jurdy and Gordon, 1984; Gordon and Jurdy, 1986) or in Antarctica (Jurdy, 1984) in their analyses of plate motions.

The implications of the notion of an extra plate boundary either in the South Pacific or Antarctica can easily be tested. Fig. 14 shows the predicted amount of motion in the South Pacific, if we assume that the North Pacific moved relative to the Hawaiian hotspot and a South Pacific plate was rigidly attached to Antarctica, which moved relative to the African absolute motion frame from Fleitout et al. (1989). The resulting extension of up to >1500 km between 74 and 43 Ma can certainly be ruled out since 1500km of additional ocean floor with the corresponding magnetic anomaly pattern is not observed anywhere in the South Pacific. A missing plate boundary with motion of this magnitude to the north, between the Louisville and Hawaii chains can also be ruled out simply because of the good observed fit of Pacific "absolute" plate motion flowlines to both volcanic chains.

A similar exercise assumes a location of the hypothetical plate boundary in Antarctica somewhere between West Antarctica (Marie Byrd Land) and East Antarctica (Fig. 15) and results in predicted extension of more than 1500 km between the 74 and 43 million years. Extension in Antarctica of greater than 200 km during the Cenozoic can be ruled out based on the known motion of North New Zealand woth respect to South New Zealand. The plate circuit describing the motion between North and South New Zealand consists of two well constrained paths: North New Zealand – Australia – East Antarctica and South New Zealand/Campbell Plateau – Marie Byrd Land. Seafloor spreading in the Tasman Sea ceased at 56 Ma (Cande and Mutter, 1982) making the circuit even shorter. If East and West Antarctica are assumed to have been rigidly attached with no plate boundary during the period 70 Ma to present then virtually no motion is found between North and South New Zealand, which is supported by New Zealand geology (Stock, 1989). Any substantial Cenozoic motion in Antarctica would have a profound effect on the positions of North and South New Zealand with respect to one another. While there is ample evidence for continued tectonic activity in Antarctica (Mt. Erebus, Mt. Melbourne in North Victoria

Land and probable extension in the Terror Rift in the Ross Sea), such activity is of the East African Rift variety and not the Basin and Range (Lawver et al., 1989). A large amount of recent extension in the Ross Sea would severely affect the motion between South and North New Zealand. Since plate reconstructions and New Zealand geology (Stock, 1989) support the concept of no relative motion between North and South New Zealand in the Cenozoic, large amounts of Cenozoic extension in the Ross Sea are highly unlikely. Hence we arrive at a similar conclusion as Molnar and Stock (1987) that the observed misfit of Pacific absolute motions to African hotspot tracks must be attributed to relative motion between the Pacific and African hotspots with magnitudes of at least 10 to 20 mm/yr.

Relative motion of hotspot groups

If we follow this line of arguments it becomes clear that there are two groups of hotspots, the Pacific and the African/Indian hotspot group, that have left a consistent pattern of major volcanic seamount chains on the overlying plates within each hotspot group. Significant motion, though, has occurred between the hotspot groups. In Fig. 16a we have plotted the relative motion between four Pacific hotspots and the African/Indian hotspot group that we held fixed. It appears that depending on the location of any particular hotspot relative to the rotation poles between the two hotspot groups, the direction and velocity of relative hotspot motion differed significantly. Fig. 16b shows the velocity of relative motion between the Hawaii and Louisville hotspots and the African/Indian hotspots for the last 140 million years. It appears that the magnitude of relative motion was about 10-40 mm/y. The absolute motion models for both hotspot groups for times before 100 Ma are subject to a much larger uncertainties, though. Using Duncan and Clague's (1985) motion parameters for the Pacific plate and Fleitout et al's (1989) poles for the African plate the magnitude of relative motion between the South Pacific hotspots and the African/Indian hotspots increased to about 80 mm/y, as shown for the Louisville hotspot in Fig. 16b.

A scenario of two large groups of hotspots moving separately from each other is also supported by observed geoid anomalies, the distribution of hotspot swells and upper mantle velocity anomalies. Fig. 17a shows the global hotspot distribution and the residual geoid obtained from subtracting the subduction geoid from the total GEM8 geoid from Crough and Jurdy (1980). It demonstrates that hotspots are clustered within the two long-wavelength (degree 2) geoid highs that are observed over the Pacific Ocean and over Africa, the eastern South Atlantic and the southwestern Indian Ocean. If the Fourier expansion of the global hotspot distribution is calculated, power spectrum peaks are found at degrees 1,2 and 6 (Cazenave et al., 1989), further confirming this observation. Cazenave et al. (1989) also computed the degree 6 pattern of the spherical harmonic expansion of the topography of hotspot swells and upper mantle velocity anomalies at 400 km. The swell topographies were calculated by determining the spatial extent and height of hotspot swells, fitting Gaussian shapes to the swells and computing their Fourier expansion. The degree 6 pattern of velocity anomalies for the upper mantle (Cazenave et al., 1989) was computed from seismic velocity anomalies from Woodhouse and Dziewonski (1984). Fig. 17b shows that the two major hotspot swells in the Pacific and over Africa correlate well with low upper mantle velocities, suggesting that the hotspot groups are related to large upwelling cells in the upper mantle that also cause the observed geoid highs over both groups (Fig. 17a). Our analysis of hotspot group motion suggests that these two upwelling cells are not stable relative to each other, but move coherently so that major hotspots within one group still leave consistent volcanic traces on overlying lithospheric plates.

Conclusions

Our comparison of apparent polar wander paths for North America, Africa and Eurasia has documented that there are still considerable inconsistencies between paleomagnetic data from the North American and the African/Eurasian plates. Synthetic APW paths from models based on hotspot traces agree only reasonably well with observed APW paths for the Cenozoic. Significant differences can be documented for pre-Cenozoic times that may be due to true polar wander.

The observed discrepancy between the African/Indian plate and the Pacific plate hotspot reference frames can not be reconciled by invoking a fossil plate boundary either in the South Pacific or between West and East Antarctica, since the amount of predicted extension is unreasonably high (1500 km between 74 and 43 Ma). Hence the difference between the two hotspot frameworks must be due to relative motion between the two hotspot groups. A preliminary estimate for relative motion velocities between the two hotspot groups gives a range of 10-40 mm/y during the last 100 million years, up to nearly an order of magnitude higher than inferred motion rates of 5mm/y between hotspots in the Atlantic and Indian oceans (Morgan, 1981, 1983; Duncan 1981).

Acknowledgements

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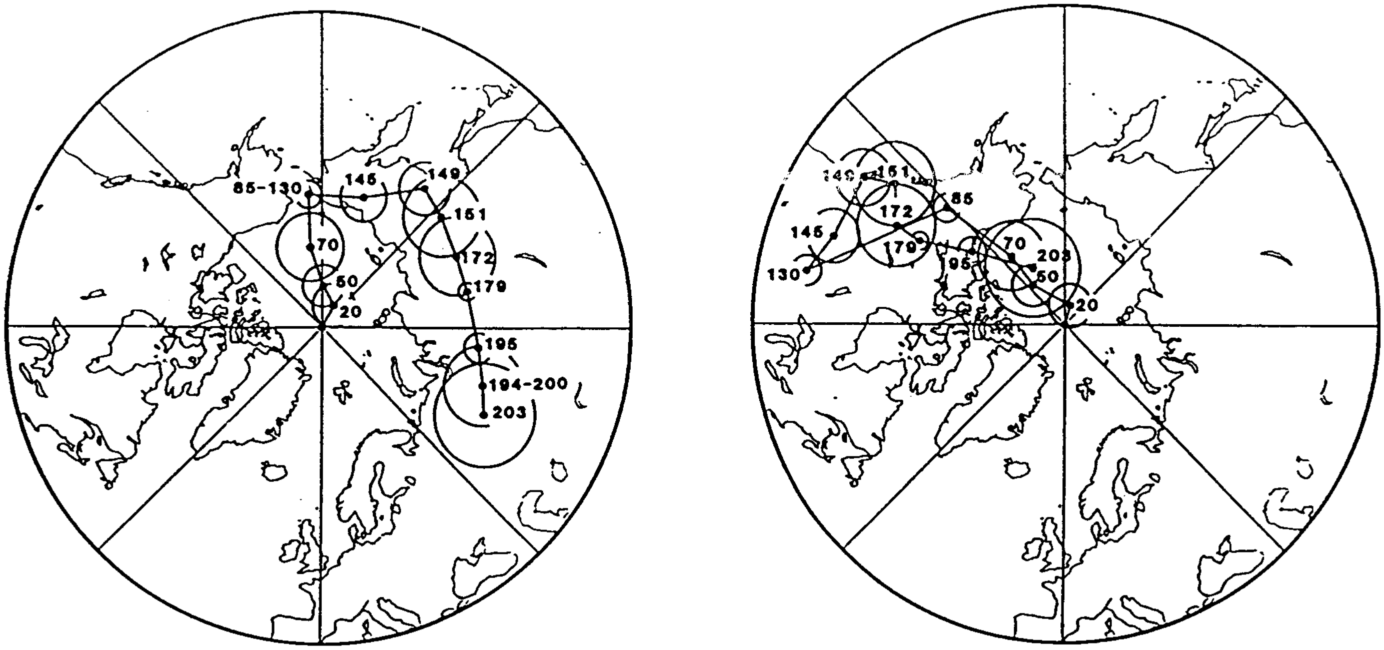
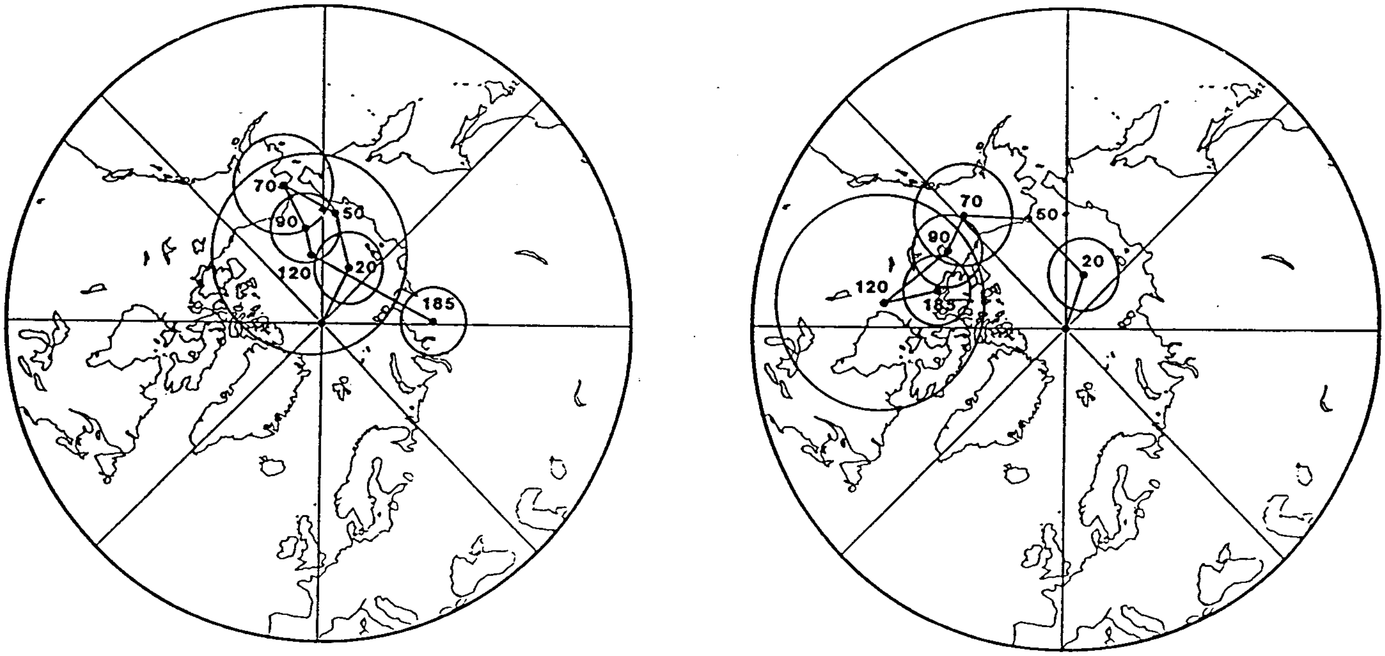


a) North American APWP from
Harrison and Lindh (1982) (20-70 Ma)
and May and Butler (1986) (85-203 Ma)

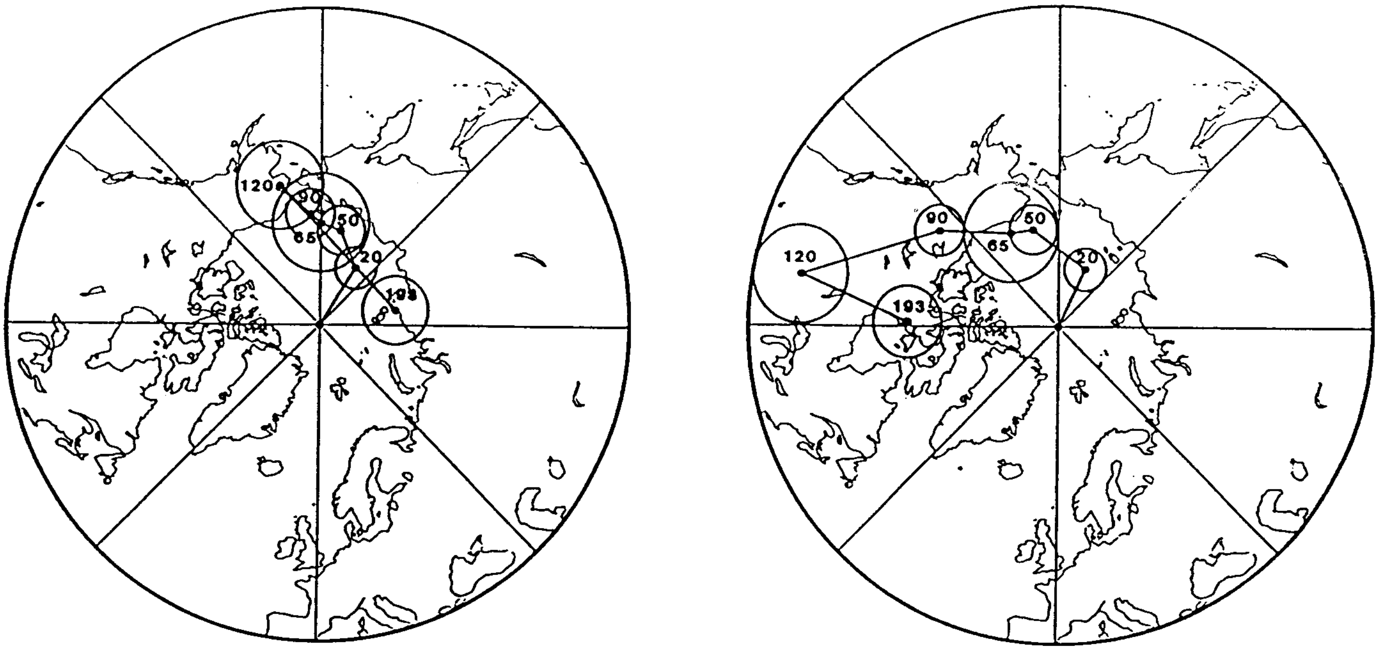
b) North American APWP in African coordinates
from Harrison and Lindh (1982) (20-70 Ma)
and May and Butler (1986) (85-203 Ma)



c) African APWP in North American coordinates
from Besse and Courtillot (1988)

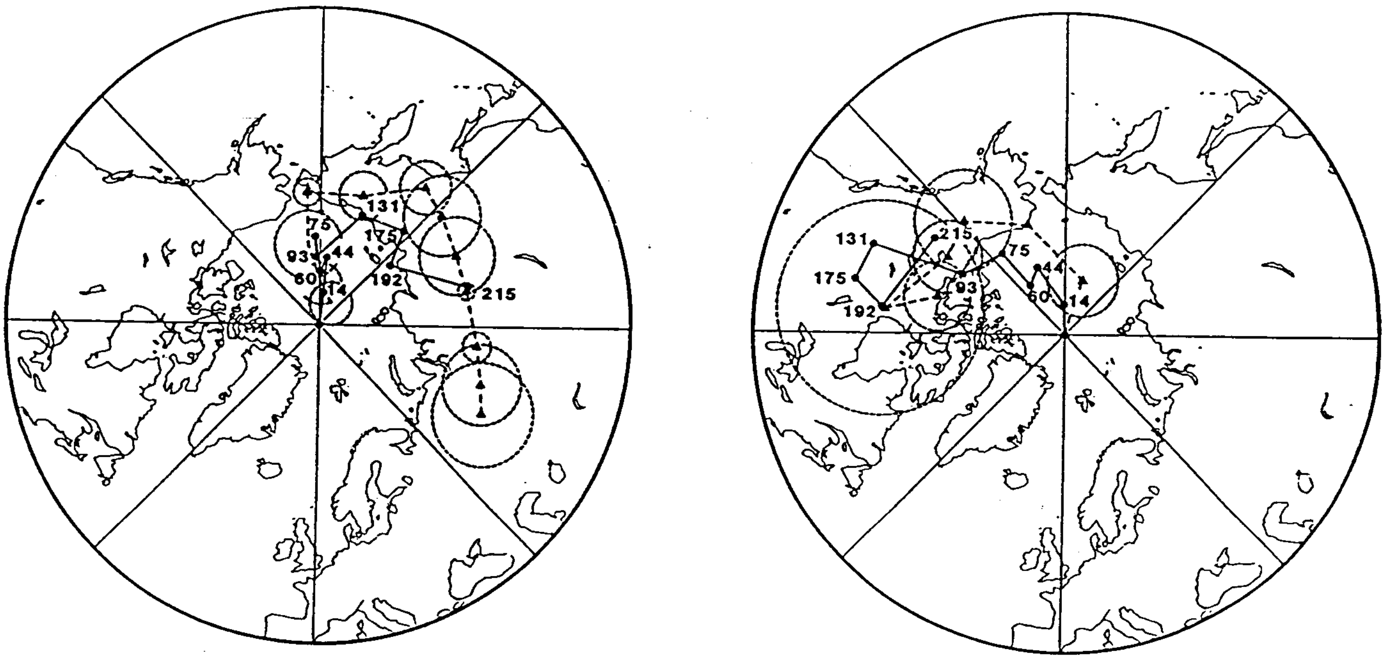
d) African APWP
from Besse and Courtillot (1988)

Fig. 1: North American and African apparent polar wander paths in both North American and African coordinates.



a) Eurasian APWP in North American coordinates from Besse and Courtillot (1988)

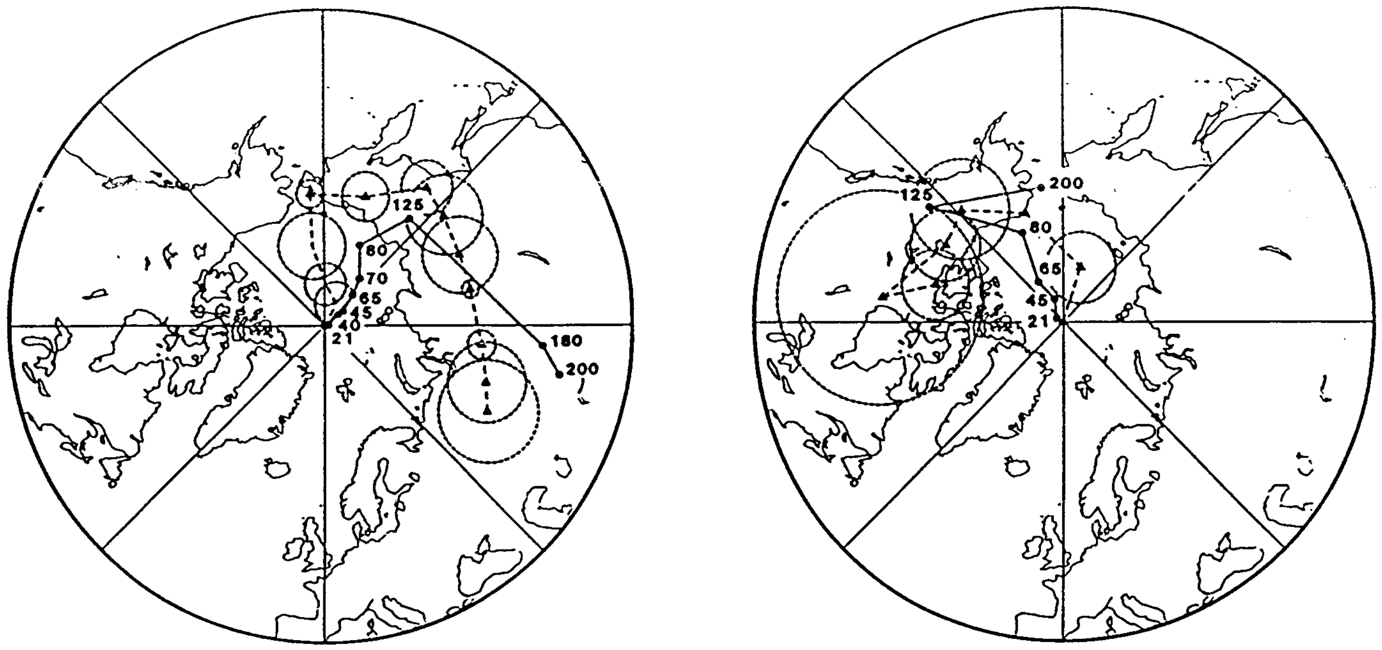
b) Eurasian APWP in African coordinates from Besse and Courtillot (1988)



c) Global APWP in North American coordinates from Ziegler et al. (1983). APWP from May and Butler (1986) dashed.

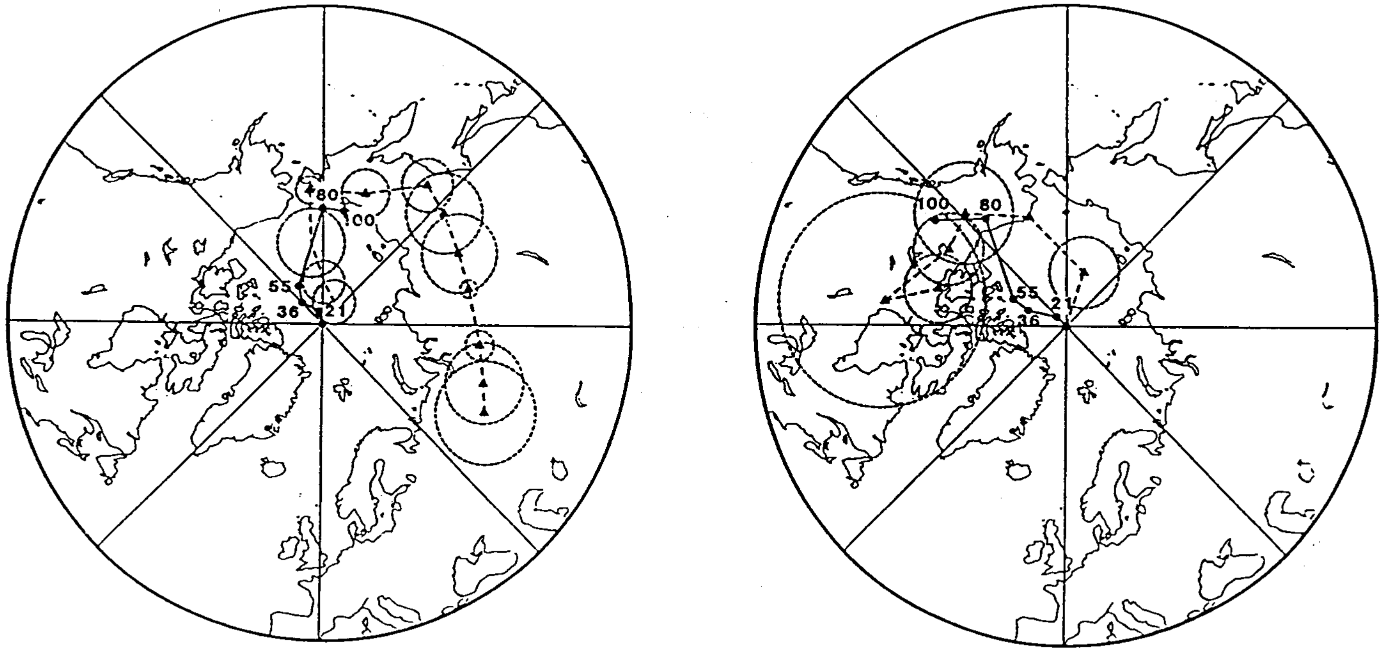
d) Global APWP in African coordinates from Ziegler et al. (1983). APWP for Africa from Besse and Courtillot (1988) dashed.

Fig. 2: Eurasian and global apparent polar wander paths in both North American and African coordinates.



a) Synthetic APWP in North American coordinates
from Morgan (1981)

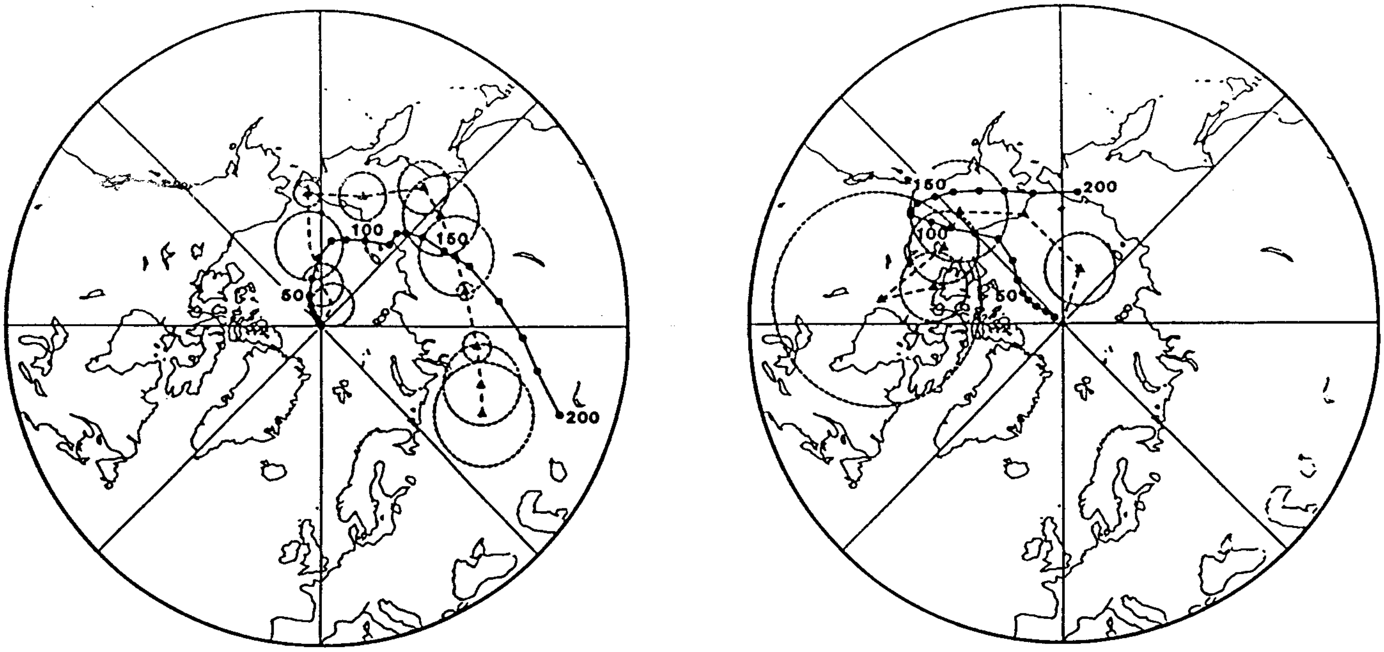
b) Synthetic APWP in African coordinates
from Morgan (1981)



c) Synthetic APWP in North American coordinates
from Duncan (1981)

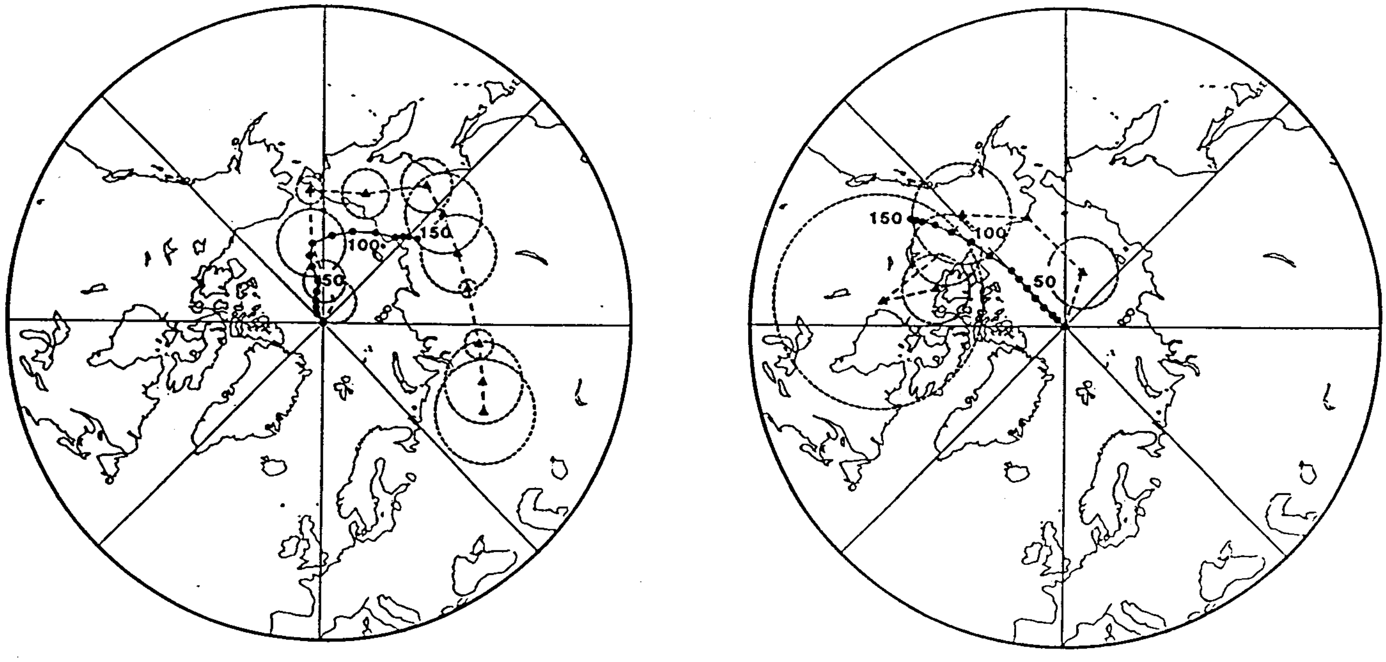
d) Synthetic APWP in African coordinates
from Duncan (1981)

Fig. 3: Synthetic apparent polar wander paths of North America and Africa constructed from the absolute motion models by Morgan (1981) and Duncan (1981). North American (a, c) and African (b,d) APWP's dashed for comparison.



a) Synthetic APWP in North American coordinates from Morgan (1983)

b) Synthetic APWP in African coordinates from Morgan (1983)



c) Synthetic APWP in North American coordinates from Fleitout et al. (1989)

d) Synthetic APWP in African coordinates from Fleitout et al. (1989)

Fig. 4: Synthetic apparent polar wander paths of North America and Africa constructed from the absolute motion models by Morgan (1983) and Fleitout et al. (1989). North American (a, c) and African (b,d) APWP's dashed for comparison.

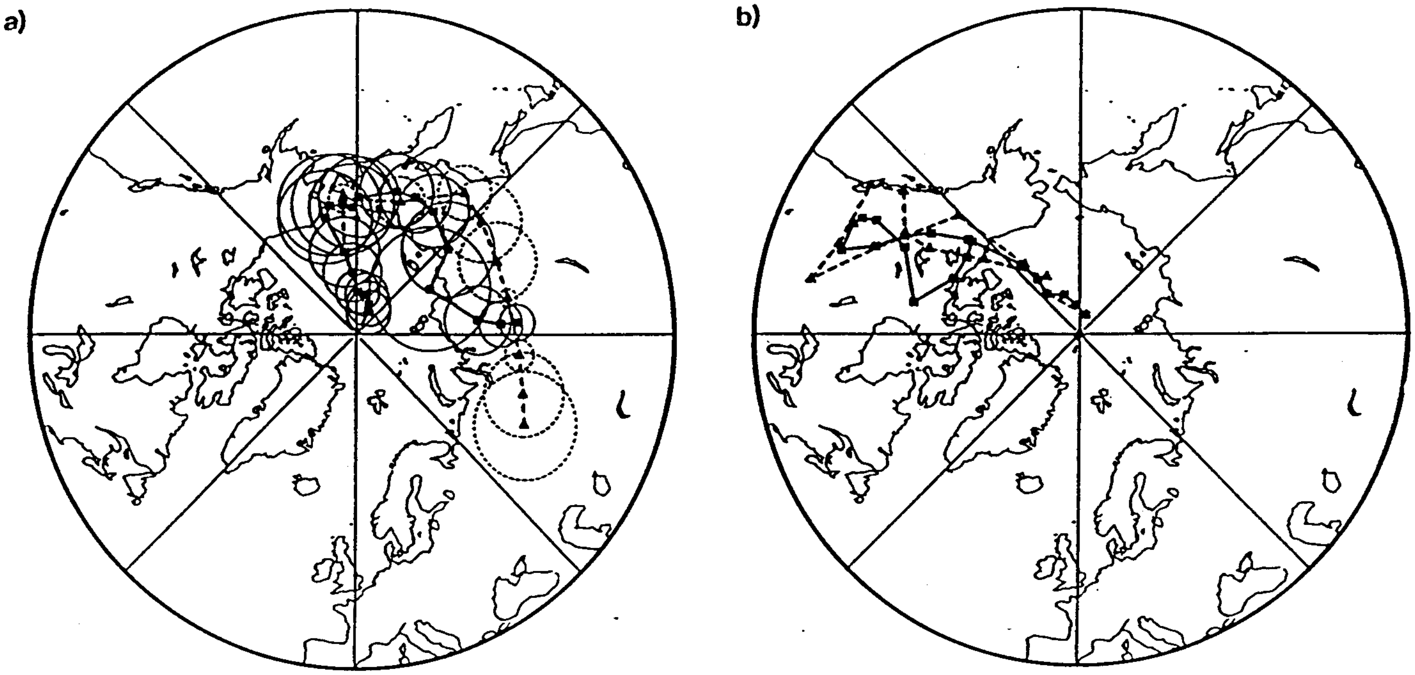
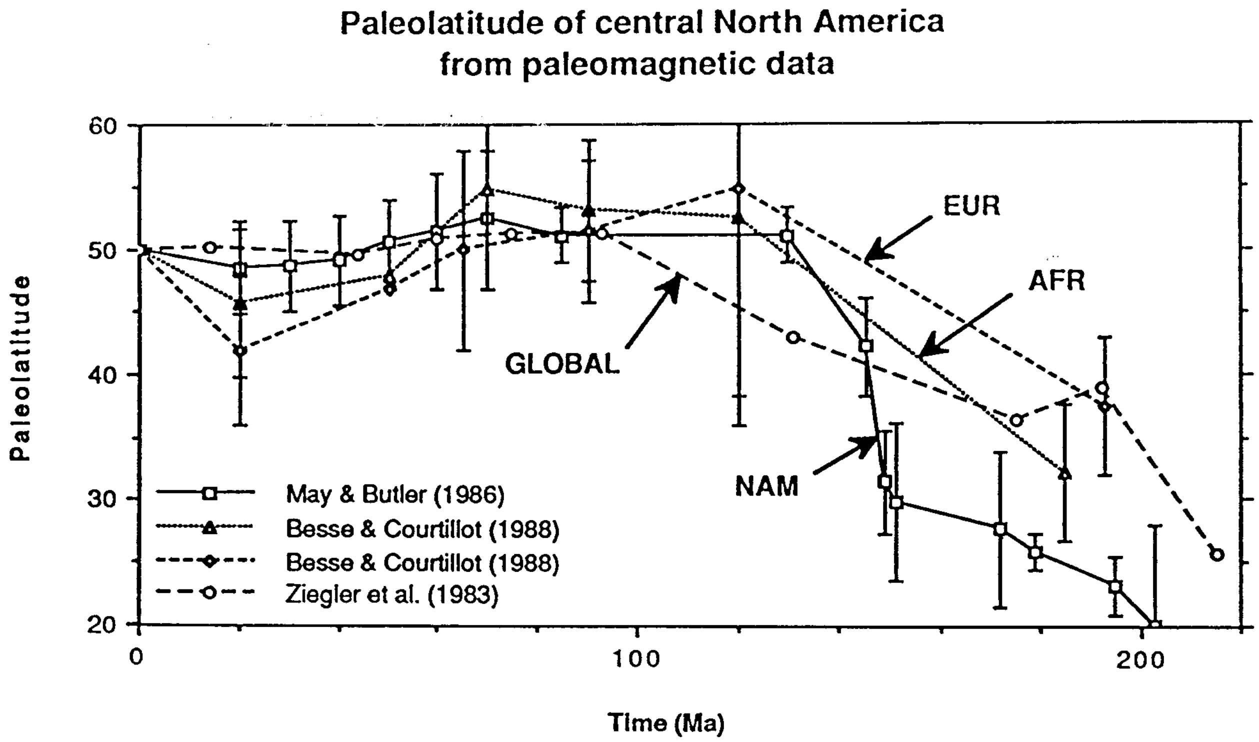


Fig. 5: North American apparent polar wander path in North American and African coordinates from Harrison and Lindh (1982) (squares) in 10 m.y. intervals from 20 to 200 Ma and from May and Butler (1986) for 200 to 85 Ma (triangles). The path from Harrison and Lindh (1982) was constructed using a 30 m.y. sliding window, whereas May and Butler's (1986) path is based on a series of selected high quality paleomagnetic poles. For ages of May and Butler's (1986) APW path see Fig. 1a.


Paleolatitude of central North America from paleomagnetic data

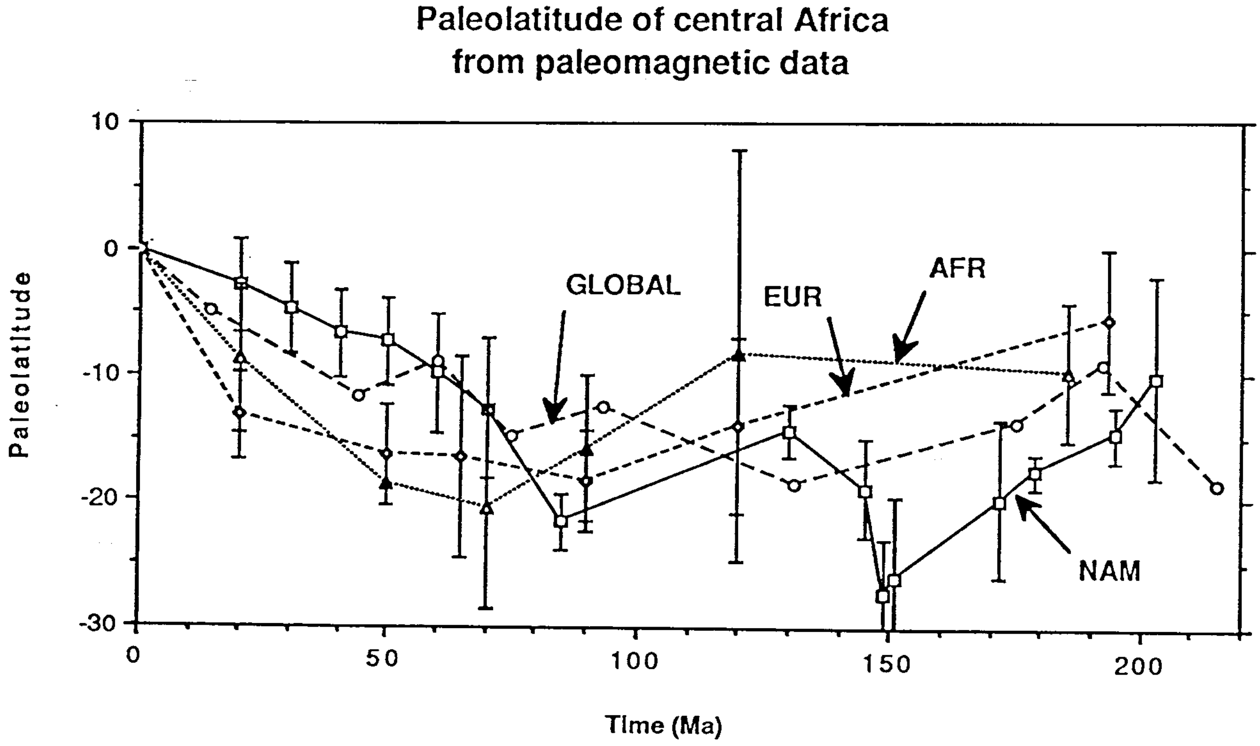
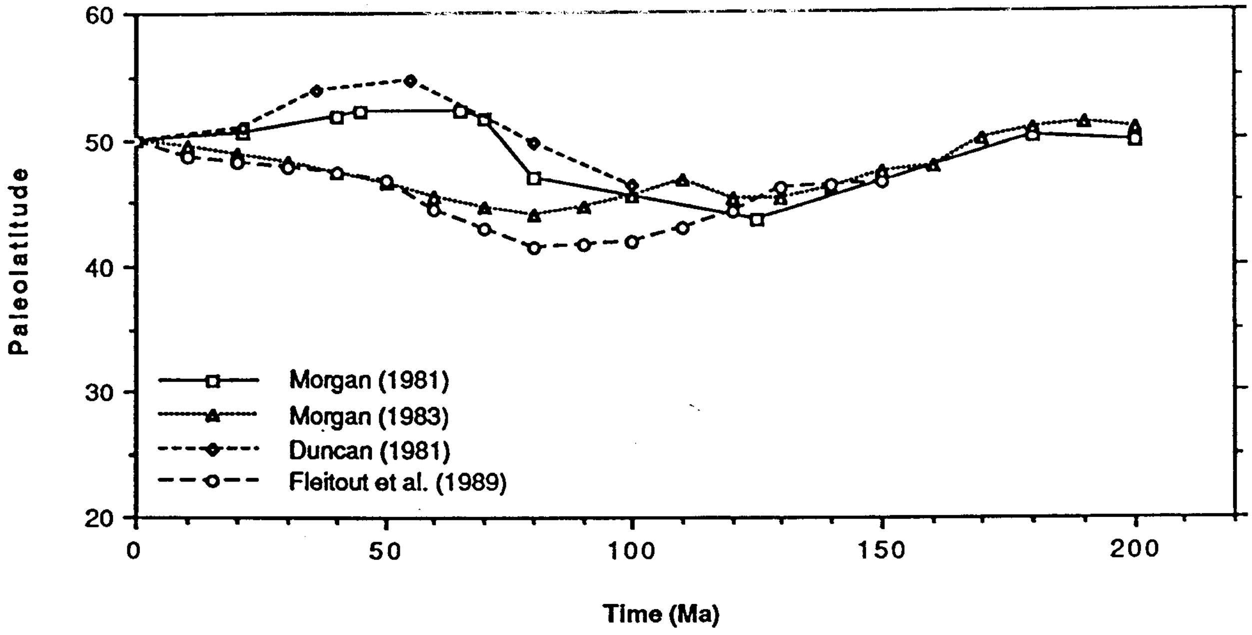
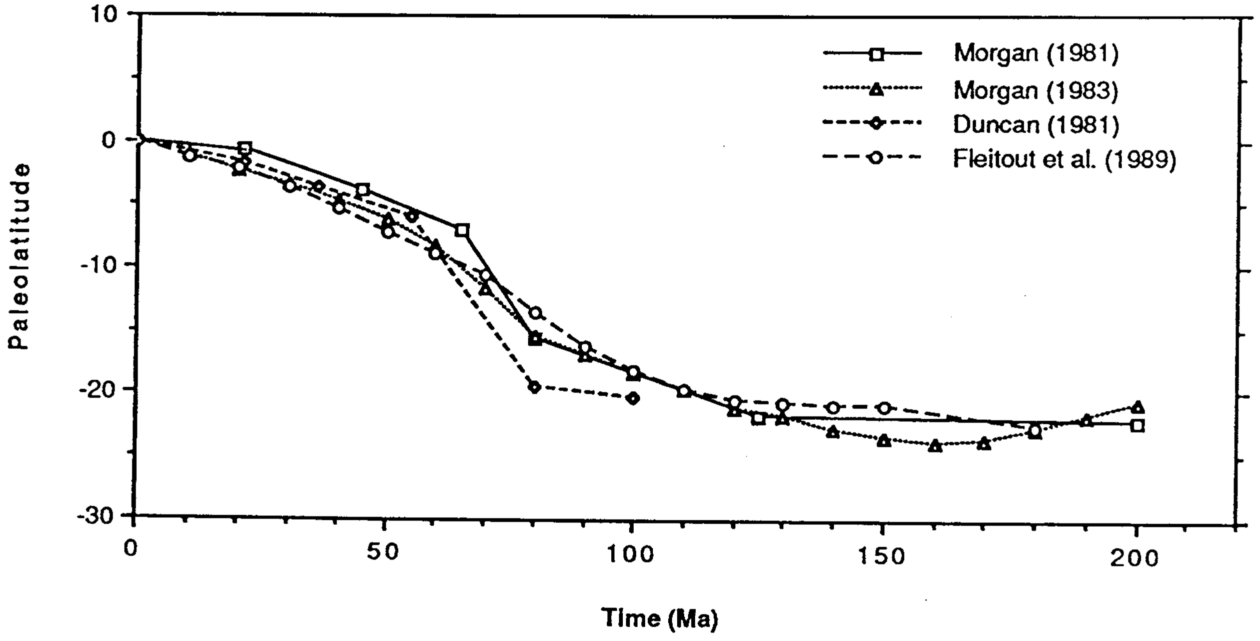

Paleolatitude of central Africa from paleomagnetic data

Fig. 6: Paleolatitude of central North America and Africa from paleomagnetic data

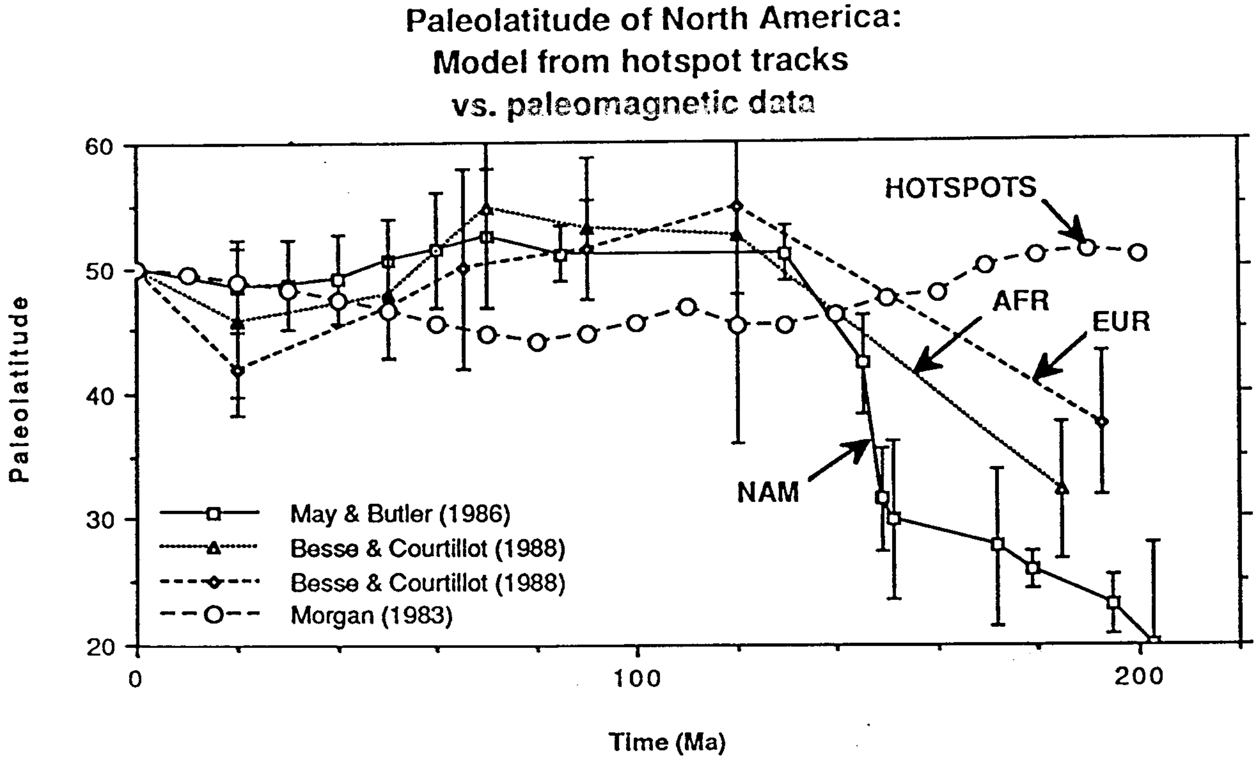


Paleolatitude of central North America from hotspot tracks

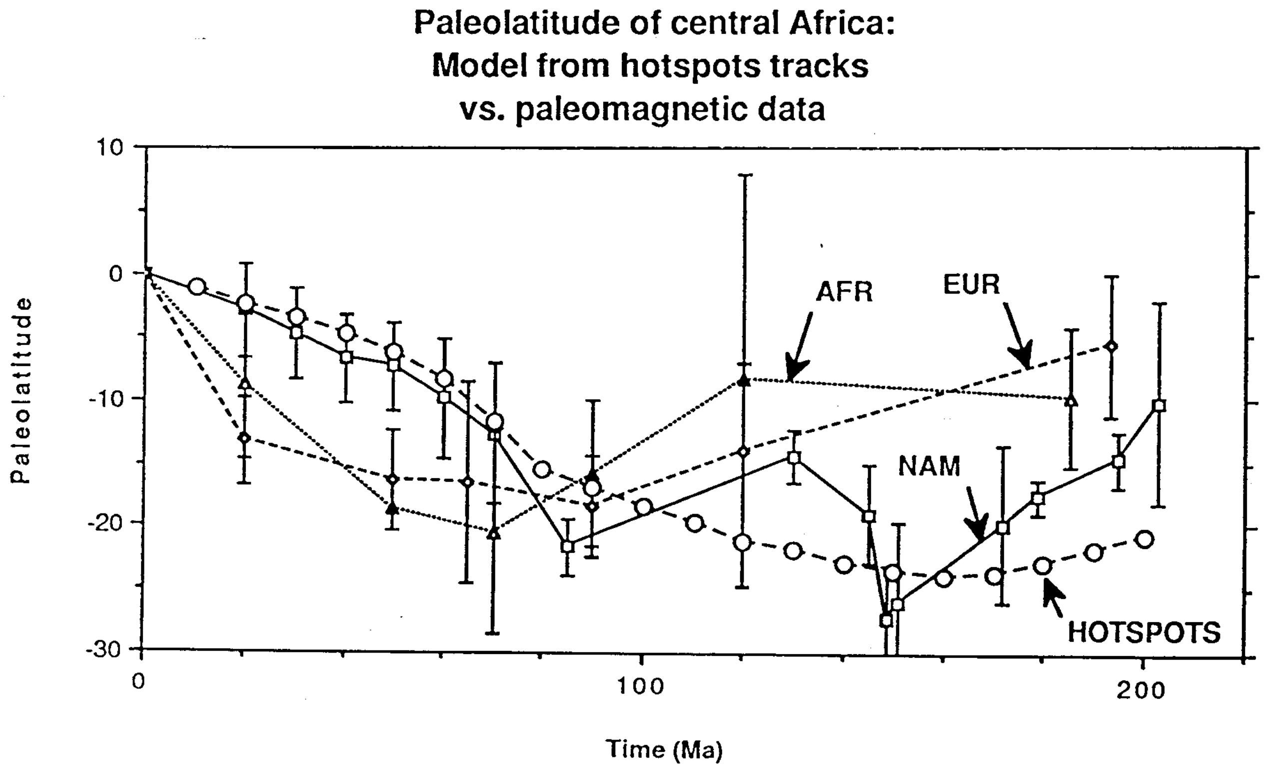


Paleolatitude of central Africa from hotspot tracks

Fig. 7: Paleolatitude of central North America and Africa from hotspot absolute motion models.

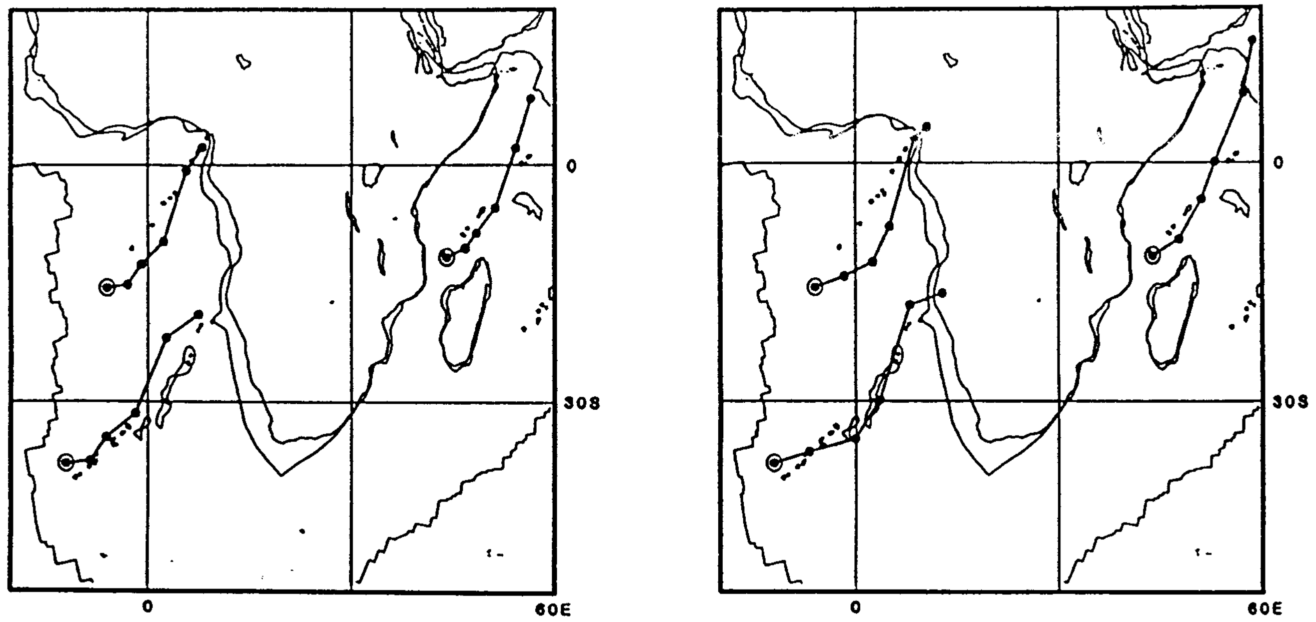


Paleolatitude of North America:
Model from hotspot tracks
vs. paleomagnetic data



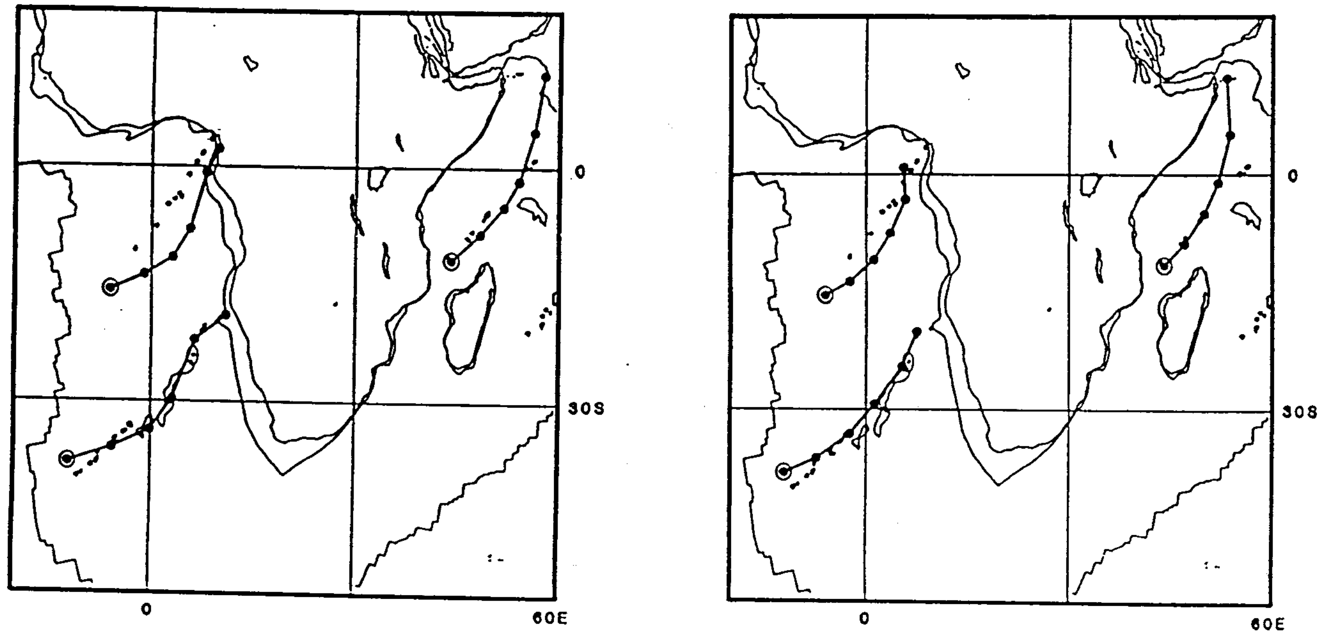
Paleolatitude of central Africa:
Model from hotspots tracks
vs. paleomagnetic data

Fig. 8: Paleolatitude of central North America and Africa: Paleomagnetic data from North America, Africa and Eurasia versus the absolute motion model from Morgan (1983).



a) Duncan (1981)

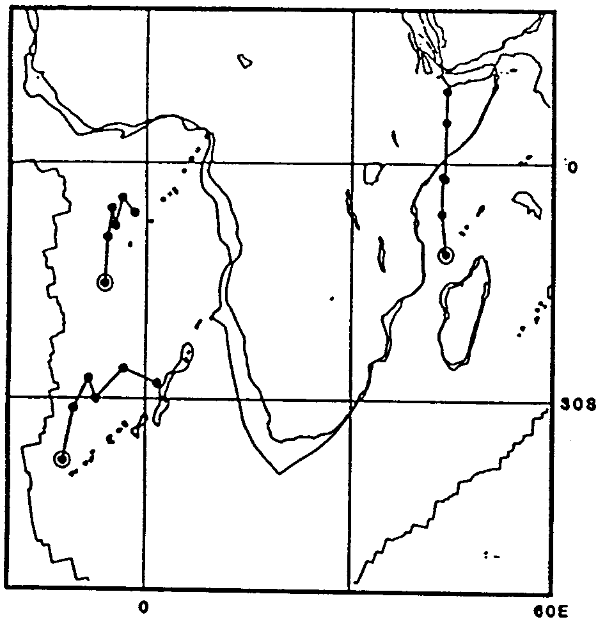
b) Morgan (1981)



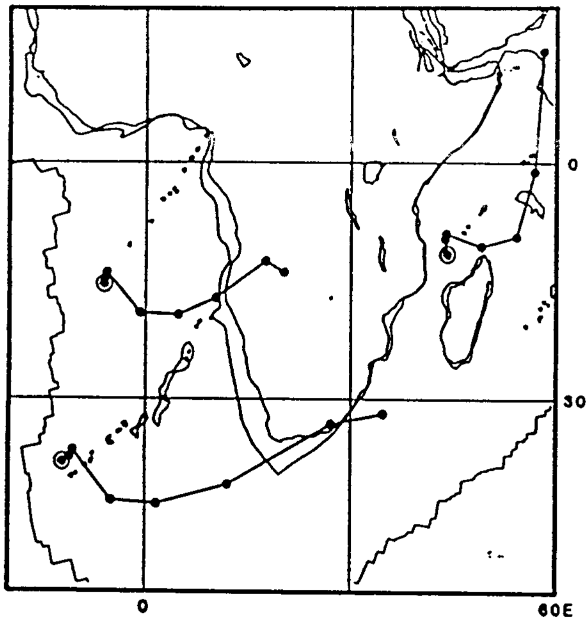
c) Morgan (1983)

d) Fleitout et al. (1989)

Fig. 9: Flowlines of the African plate plotted in 20 m.y. intervals from different absolute motion models. Large open circles are the present day locations of the St. Helena, Tristan da Cunha and Comores hotspots.



e) Ziegler et al. (1983)



f) Motion of Africa calculated by transforming Pacific plate absolute motion into African coordinates using a relative motion model for the plate circuit Africa/Antarctica/Pacific from Royer et al. (in prep.). The Pacific motion from 0-65 Ma is based on matching Pacific flowlines with the Hawaii-Emperor and Louisville seamount chains (See Figs. 8f, 9); pre-65 Ma rotations are from Duncan and Clague (1985).

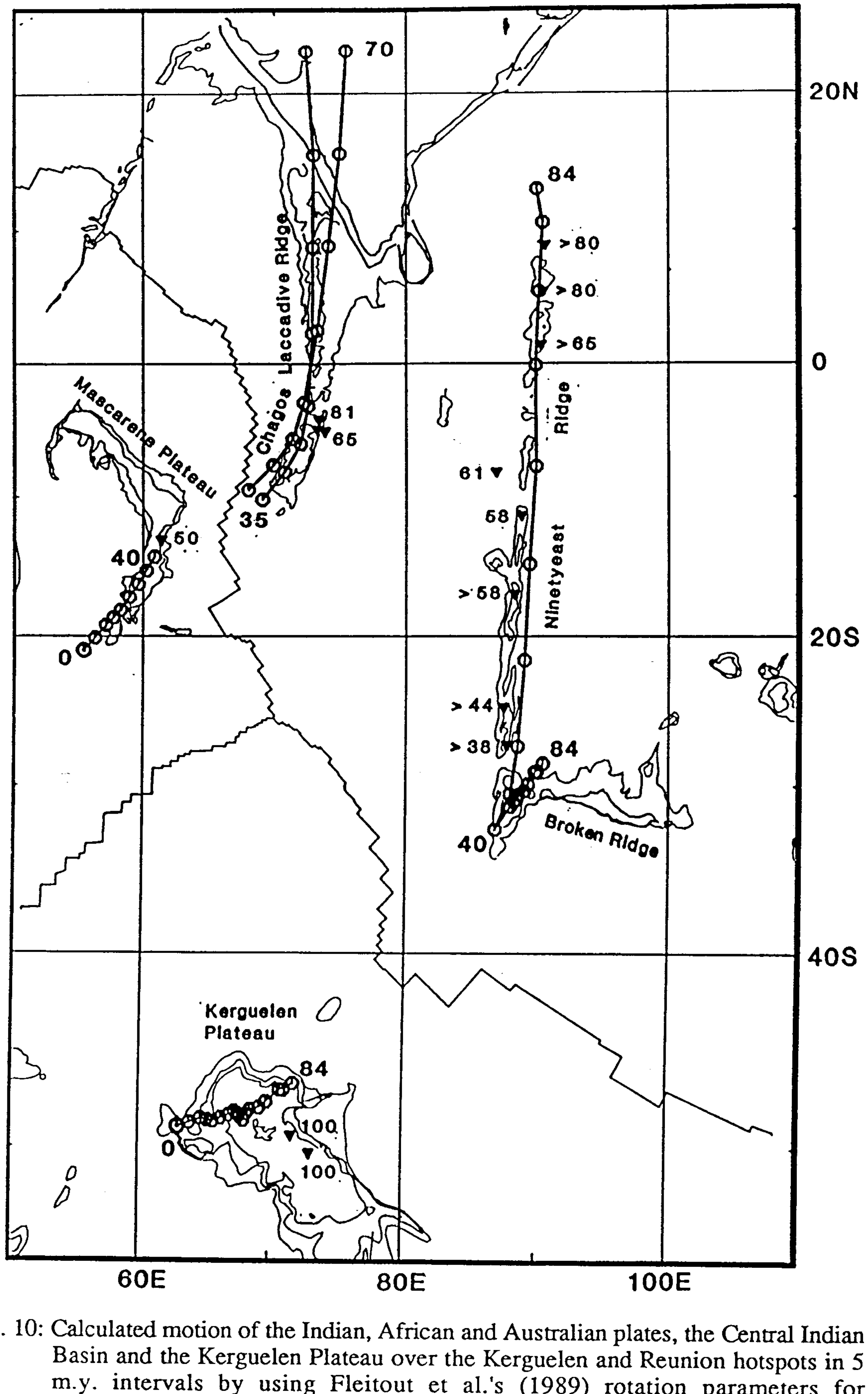
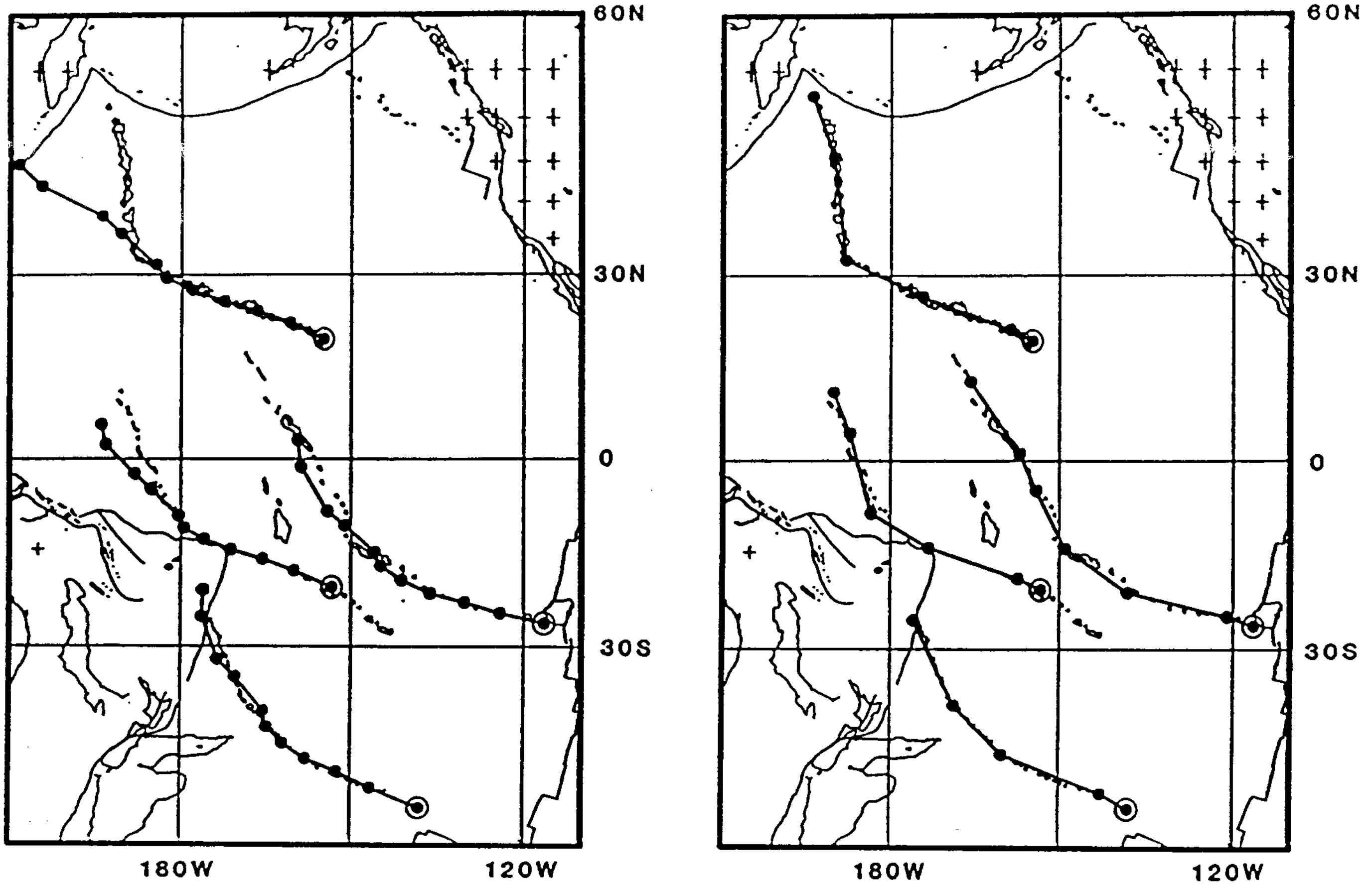


Fig. 10: Calculated motion of the Indian, African and Australian plates, the Central Indian Basin and the Kerguelen Plateau over the Kerguelen and Reunion hotspots in 5 m.y. intervals by using Fleitout et al.'s (1989) rotation parameters for African/hotspot relative motion. Two different flowlines for the Chagos-Laccadive Ridge were computed, a) by modelling the Indian plate and the Central Indian Basin as one rigid plate, and b) by including late Tertiary intraplate deformation in the Central Indian Basin.



a) Fleitout et al. (1989); flowlines are computed in 20 m.y. intervals.

b) Best fit of the geometry and ages of the Hawaii-Emperor and Louisville seamount chains to Pacific plate absolute motion in stages from 0-5, 5-25, 25-43, 43-65 and 65-74 Ma.

Fig. 11: Flowlines of the Pacific plate from different absolute motion models. Large open circles are the locations of present day hotspots.

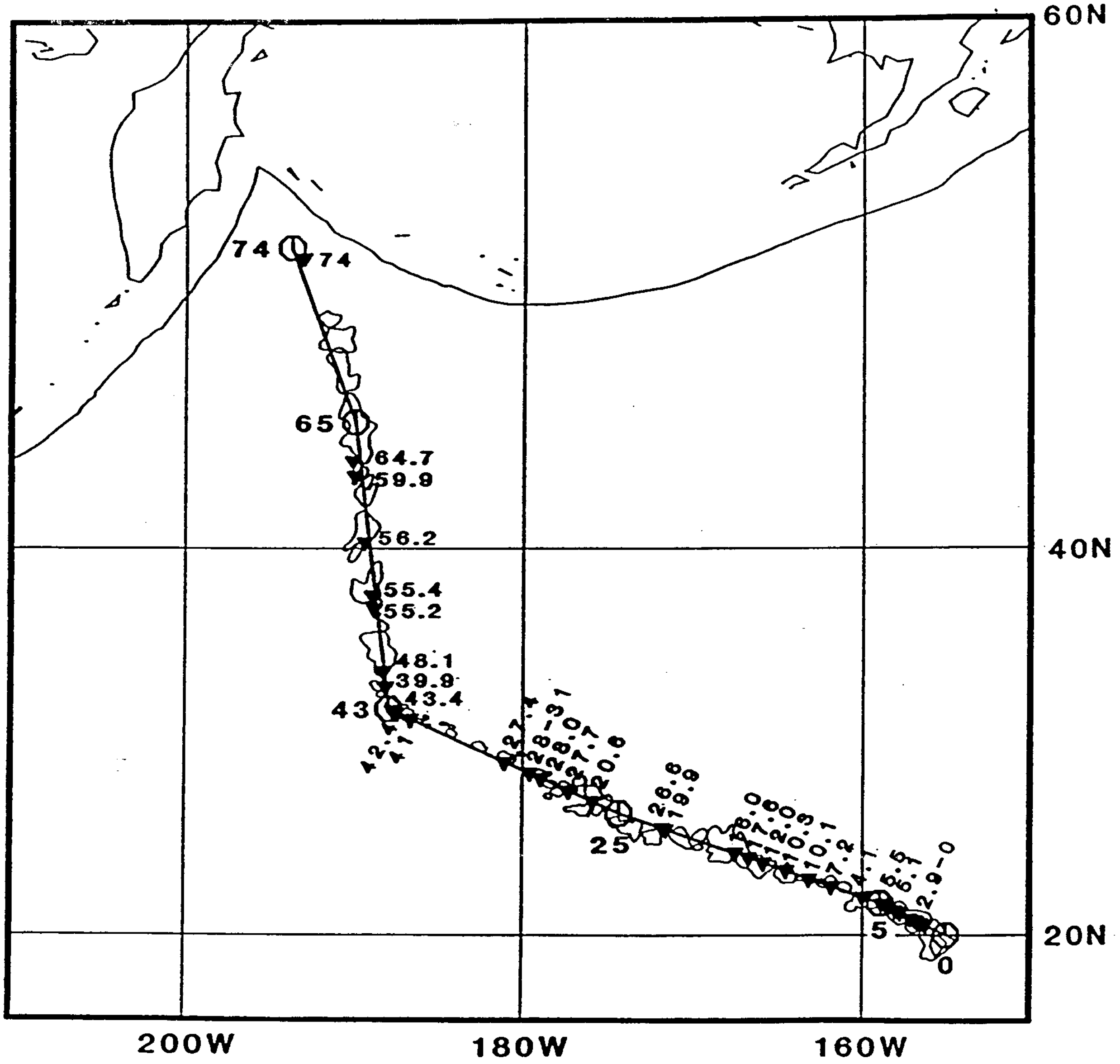


Fig. 12a: Hawaii-Emperor volcanic chain. Triangles indicate radiometric ages from Duncan and Clague (1985). Bold lines represent flowlines of the Pacific plate based on a best fit of Pacific absolute plate motion to the geometry and age progression of both the Hawaii-Emperor and the Louisville chains.

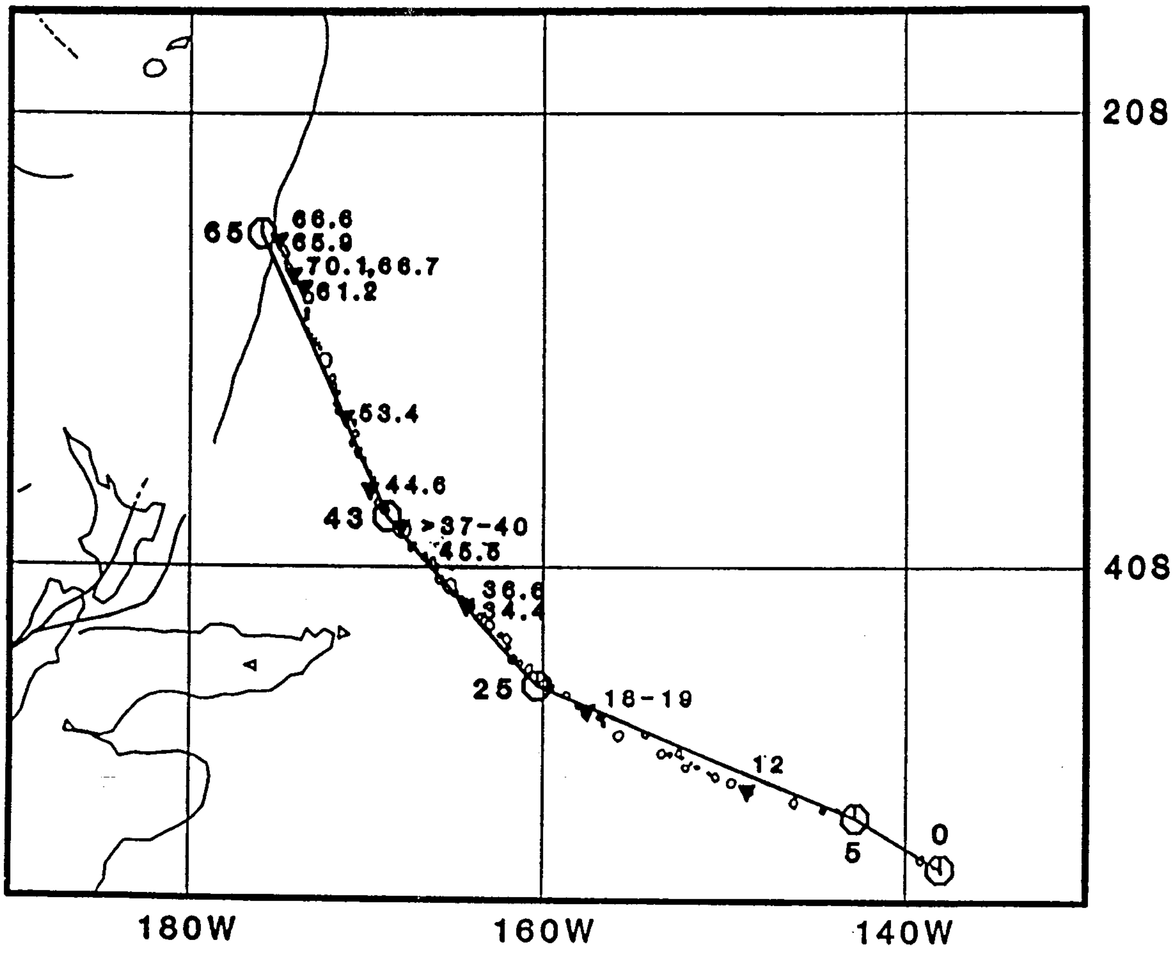


Fig. 12b: Louisville seamount chain. Triangles indicate radiometric ages from Lonsdale (1988). Bold lines represent flowlines of the Pacific plate based on a best fit of Pacific absolute plate motion to the geometry and age progression of both the Hawaii-Emperor and the Louisville chains.

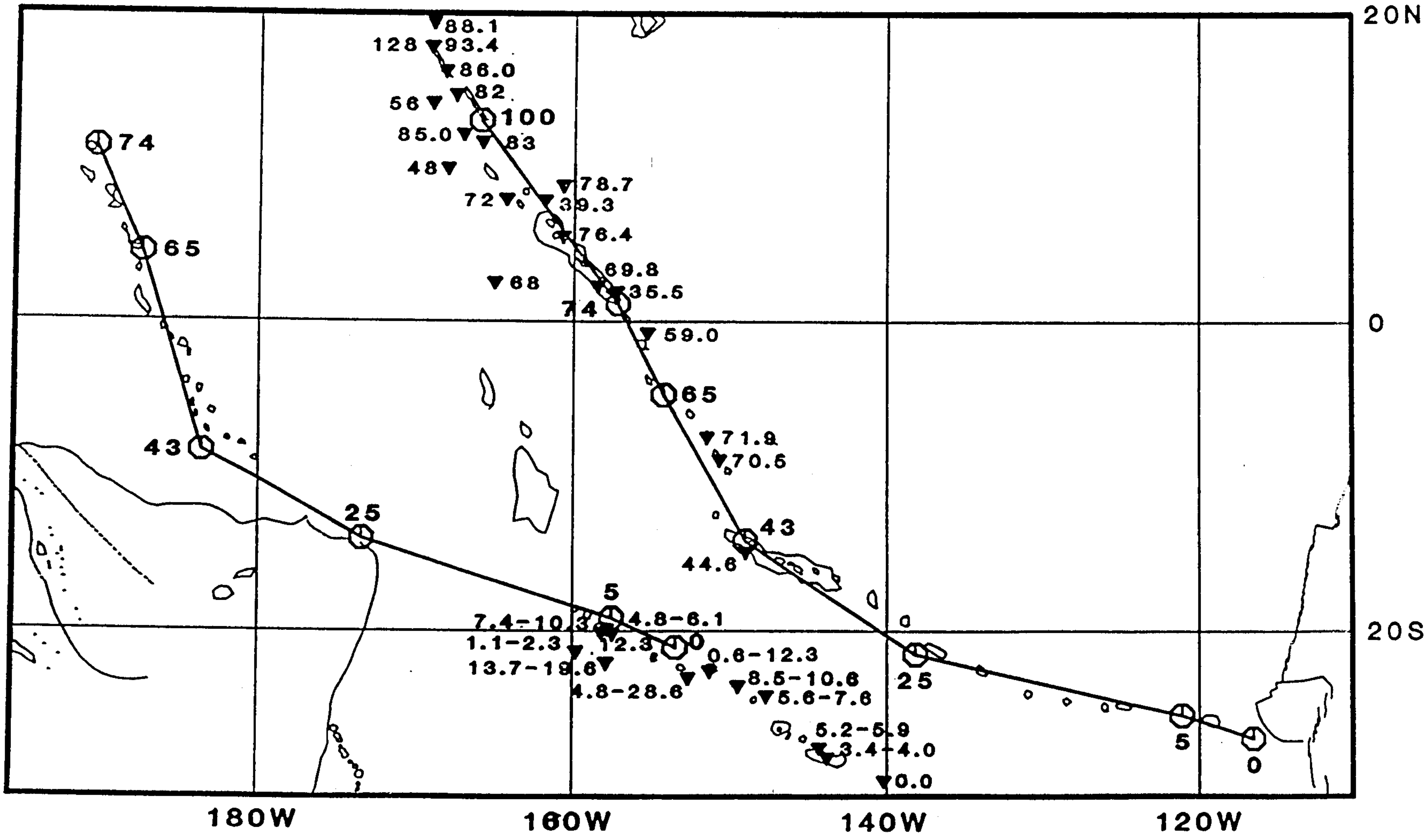


Fig. 13: Austral-Cook Islands, Marshall-Gilbert Seamounts and Line Islands. Triangles indicate radiometric ages from Duncan and Clague (1985). Bold lines represent flowlines of the Pacific plate based on a best fit of Pacific absolute plate motion to the geometry and age progression of the Hawaii-Emperor and Louisville seamount chains.

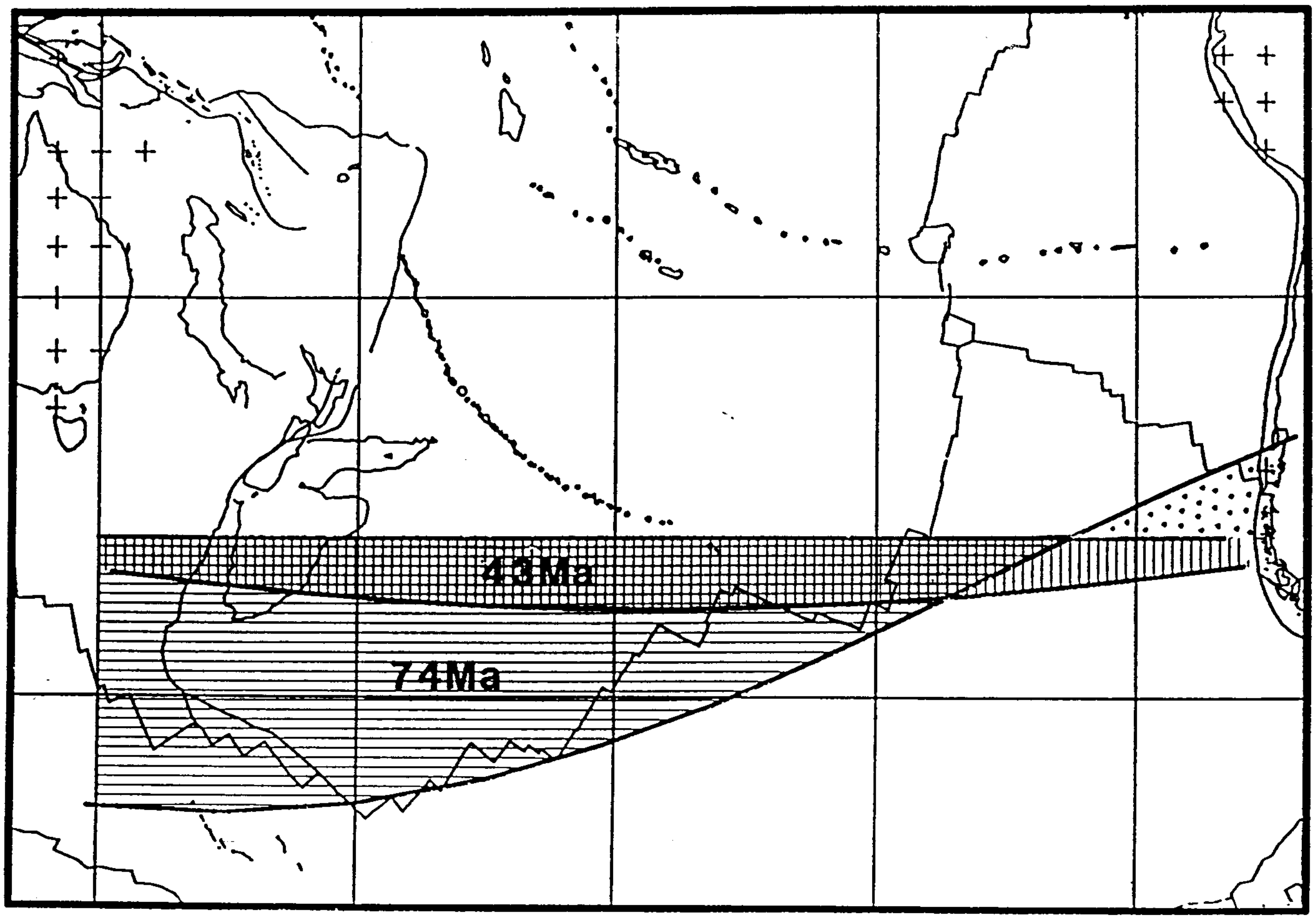


Fig. 14: Implications of a possible Late Cretaceous/Tertiary plate boundary in the plate circuit Africa/Antarctica/ Pacific. If we know the motion of Africa relative to a hotspot reference frame and the motion of the Pacific plate relative to the Hawaii-Emperor and Louisville hotspots the relative motion poles reconstructing Africa to Antarctica and Antarctica to the Pacific plate can be used to calculate the differential motion along a ficticious plate boundary either in Antarctica or in the South Pacific, assuming that the African and Pacific plate hotspots were fixed relative to each other during the last 74 m.y. An E-W oriented line at 50°S is used to demonstrate the differential motion in the South Pacific if all hotspots were fixed. Hatched areas represent extension stippled areas compression. Vertical hatchures correspond to extension from 43Ma to present day, horizontal hatchures delineate extension during the last 74 m.y. Up to 1500 km of extension would result between a Central/South Pacific plate boundary between 74 and 43 Ma.

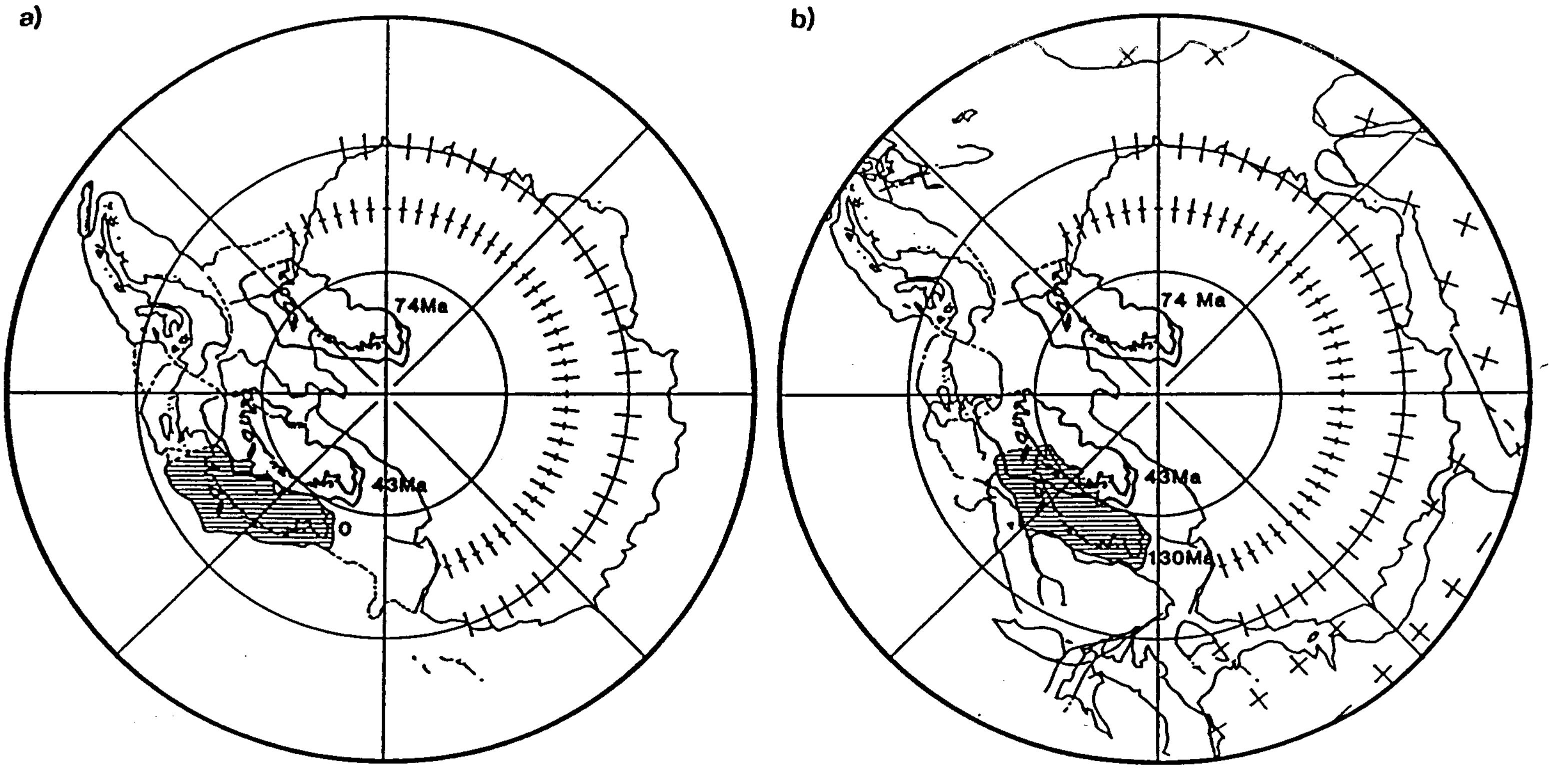


Fig. 15: Here we assume that the "missing" plate boundary in the plate circuit Africa/Antarctica/ Pacific is located between East and West Antarctica. The overlap between Marie Byrd Land and Antarctica at 43 Ma and 74 Ma (Fig. 15a) represents the amount of extension between West and East Antarctica that would be implied following the fixed hotspot hypothesis. The implied extension along the "missing" plate boundary would exceed 1500 km. The largest amount of likely intraplate motion within Antarctica, however, could not have exceeded a few hundred kilometers during the Cretaceous/Paleogene as shown by a reconstruction for 130 Ma (Fig. 15b) that shows Marie Byrd Land in the position for closure of the Ross Sea.. This corresponds to the maximum amount of relative motion that occurred between Marie Byrd Land and Antarctica.

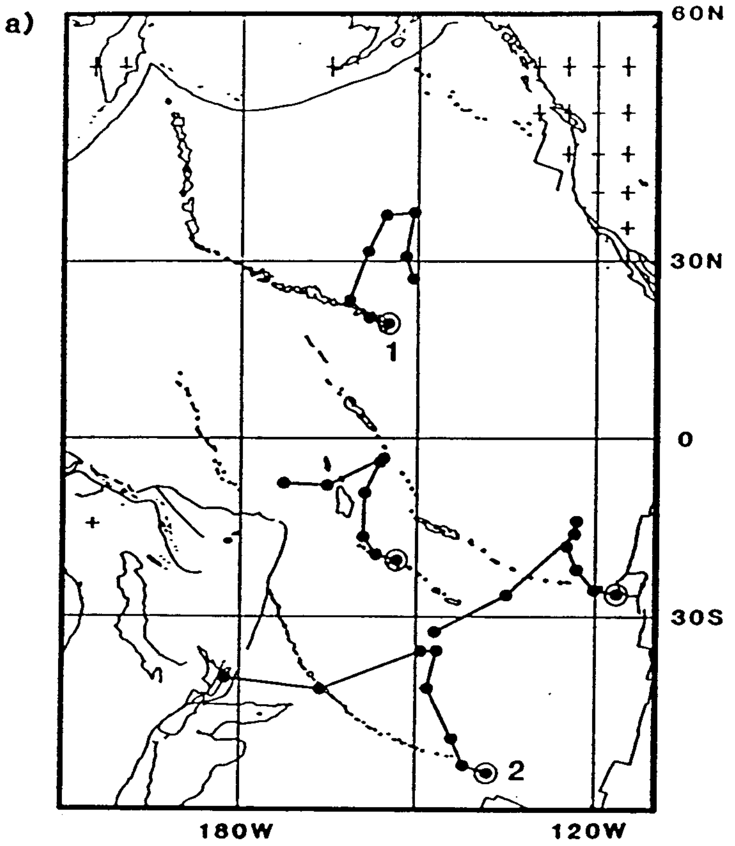
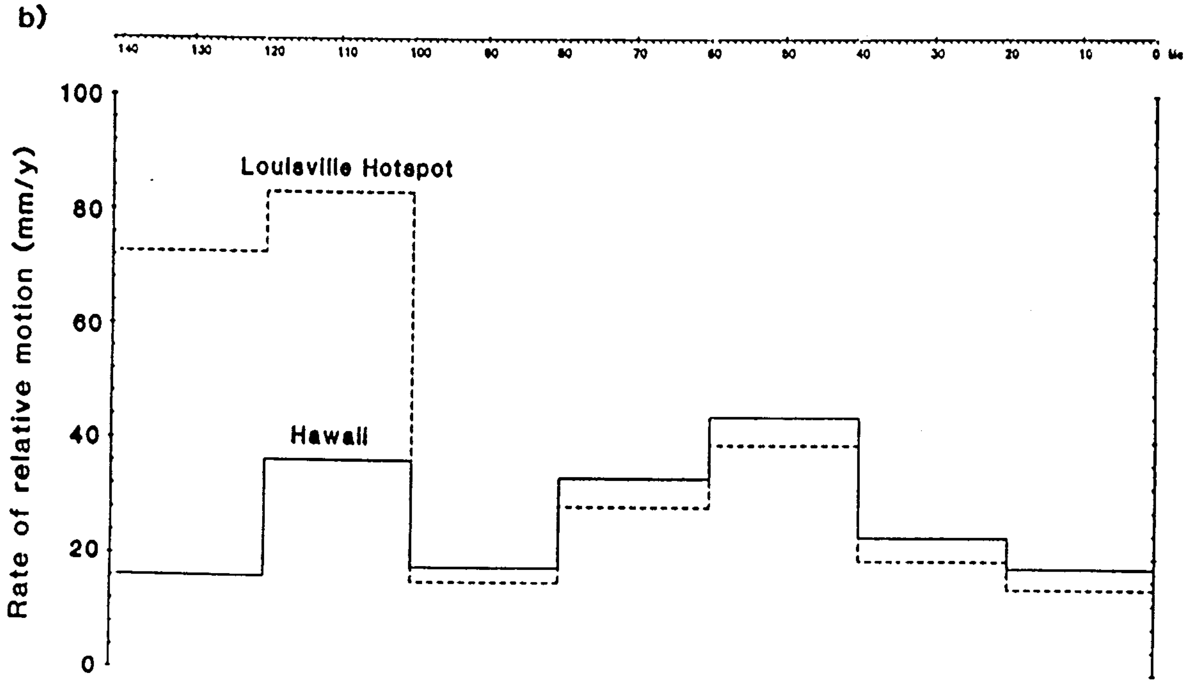


Fig. 16: Relative motion between the Hawaii (1) /Louisville (2) hotspots and African/Indian ocean hotspots. By utilizing the plate circuit African/Indian ocean hotspots/Africa (Fleitout et al., 1989; Morgan, 1983), Antarctica/Africa (Royer et al., in prep.), Antarctica/Marie Byrd Land (Mayes et al., 1990), Marie Byrd Land/Pacific (Mayes et al., 1990) and Pacific/Hawaii and Louisville hotspots (Table 1), we may calculate the relative motion between these two hotspot groups. The motion between the Hawaii/Louisville and African/Indian ocean hotspots in 20 m.y. intervals is shown in Fig. 15(a); the relative motion velocities through time are displayed in Fig. 15(b). The two groups of hotspots appear to be have moved relative to each other up to an order of magnitude faster than hotspots beneath the Pacific or African plates among each other.



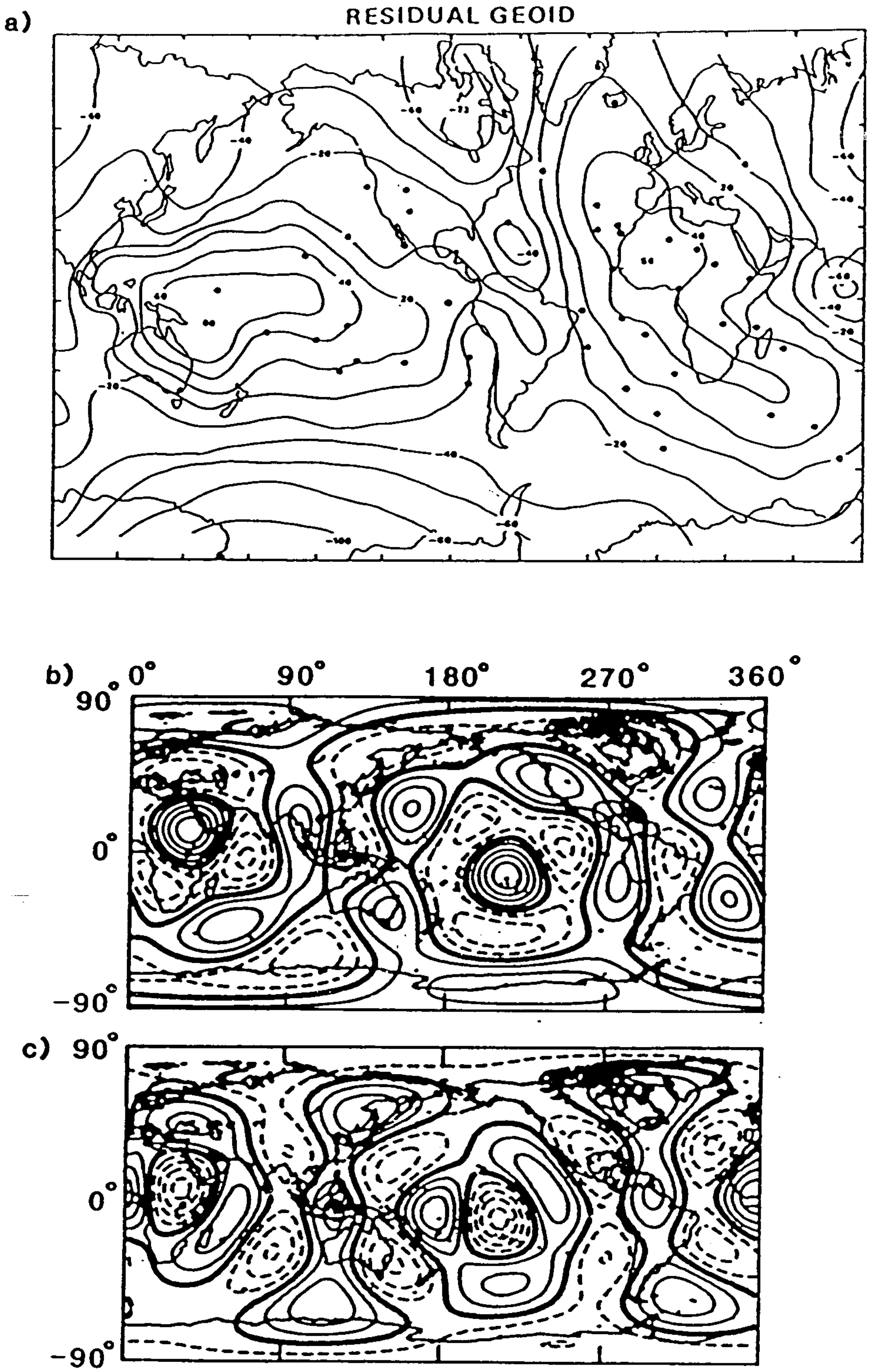


Fig. 17: (a) Residual geoid from subtracting the subduction geoid from the total GEM8 geoid from Crough and Jurdy (1980). Black dots are locations of hotspots.
(b) Degree 6 pattern of spherical harmonic expansion of topography of hotspot swells (contours at 20-m intervals, solid (dashed) contours are positive (negative) anomalies (top); and upper mantle velocity anomalies at 400 km (contours at 0.01 km/s intervals, solid (dashed) lines represent high (low) velocities (from Cazenave et al., 1989).

Table 1: Finite reconstruction poles for the motion of the Pacific plate relative to the Hawaii and Louisville hotspots.

Age (Ma)	Lat.	Lon.	Angle	Reference
0	0.0	0.0	0.0	This paper
5	65.6	-69.6	4.41	This paper
25	70.8	-79.3	20.80	This paper
43	67.0	-62.7	33.41	This paper
65	51.9	-78.4	42.20	This paper
74	47.1	-79.4	48.68	DUNCAN & CLAGUE (1985)
100	44.8	-77.0	63.45	DUNCAN & CLAGUE (1985)
150	54.8	-91.5	81.36	DUNCAN & CLAGUE (1985)