PALAEO

Palaeogeography, Palaeoclimatology, Palaeoecology 161 (2000) 49–69

www.elsevier.nl/locate/palaeo

Hot spot activity and the break-up of Pangea

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Abstract

The Mesozoic and Cenozoic positions of the continents that formed Pangea in the Triassic–Jurassic were derived from paleomagnetic and intraplate volcanic data, paleoclimatic observations, such as reef and fossil flora distribution, and geological observations. Major hot spots helped to determine the longitudinal position of Pangea and to construct a model of plate motion during the Pangean break-up. The position of the northern part of Pangea was constrained using Iceland and Jan Mayen hot spots. The Iceland hot spot was traced from its present day position to Greenland in the Paleocene, to Baffin Bay in the Late Cretaceous, to the Alpha Ridge in the Early Cretaceous, to the Chukchi Borderland in the Middle–Late Jurassic, to Franz Joseph Land in the Early Jurassic, the Yenisei–Khatanga Trough in the Middle Triassic, and finally to West Siberia in the Late Permian–Early Triassic. The hot spot activity is expressed by Eastern and Western Greenland volcanics, the Siberian trap basalts, and perhaps by Alpha Ridge and Chukchi Borderland volcanics. The Chukchi Borderland volcanics are related to the early stage of the opening of the Canadian Basin. The position of the southern part of Pangea was constrained using the Bouvet hot spot. This hot spot was tracked from its present day position to Western Antarctica in the Early Cretaceous–Late Jurassic and to South Africa in the Early Jurassic–Late Triassic. This hot spot activity produced the Ferrar and Karoo volcanics. The model of plate motion obtained agrees with other data on intraplate volcanics, which are also related to hot spots. At the time of the opening of the Central Atlantic, the Cape Verde and Canary Island hot spots were located along the ocean's spreading axis. The long lasting location of hot spot and associated mantle upwelling plumes could help to explain forces driving the Tethys transit plates, opening of the Ligurian Ocean and Eastern Mediterranean. The European hot spots are related to the several Mesozoic phases of rifting. For example, the Rhine Graben hot spot may have been located at the rifting axis in the North Sea. Several authors have already discussed the contribution of hot spots to the opening of the South Atlantic and Indian oceans. Mantle plumes associated with hot spots play an active role in rifting and initial phases of spreading. The lithospheric displacement, caused by upwelling combined with sometimes remote collisional forces on the other side of continental plate, may result in compression and basin inversion.

Keywords: Cenozoic; hot spot tracks; Pangea; plate tectonics; Mesozoic; volcanism

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PII: S0031-0182(00)00117-6

1. Introduction

The objective of this paper is to review the possibility of using the hot spot framework to constrain the position of Pangea and its components during Triassic–Jurassic time and to determine the relations between hot spot activity and supercontinental rifting and break-up. The scope of this work is limited to hot spots located within the broad boundaries of the Pangean supercontinent; the hot spots located within the Panthalassa (Pacific Ocean) are not discussed.

The Mesozoic and Cenozoic positions of the continents that formed Pangea in the Triassic–Jurassic were derived from paleomagnetic and intraplate volcanic data, paleoclimatic observations such as reef and fossil flora distribution, and geological observations. Major hot spots could help to determine the longitudinal position of Pangea and to construct a model of plate motion during the Pangean break-up. Generally, two remote hot spot locations provide enough information to fix the position of the supercontinent prior to the Middle Jurassic break-up. The obtained model of plate motion can be compared with other data on intraplate volcanics, which are also related to hot spots. This approach allows us to check the accuracy of the predicted model as well as to determine the role of hot spots and mantle upwelling in the break-up processes.

2. Methodology

30 major hot spots related to the Pangea break-up have been chosen: 15 locations within the Atlantic realm, six within the Indian Ocean, three in Africa, six in the Mediterranean area and in Europe. This hot spot cluster corresponds roughly to the African hot field defined by Zonenshain et al. (1991), or zone of high geoid residuals (see Duncan and Richards, 1991, fig. 1). The continent and break-up related hot spot tracks are not documented by continuous volcanic chains, like oceanic ones; for example, Pacific Hawaii–Emperor. The tracks plotted on maps (Figs. 1 and 2) are a combination of observation of volcanic activity and calculated positions of hot spots in relation to the moving plates. Since the introduction of the concept of hot spot role in plate tectonics by Wilson (1963) and Morgan (1971), numerous hot spot related papers have been published. An extensive (365 pp.) bibliography of plate tectonic related volcanism was compiled by the University of Texas PLATES project (Coffin, 1997). We used modified hot spot tracks calculated by Morgan (1971, 1972, 1981, 1983), Duncan (1981, 1984, 1990), Duncan and Richards (1991), Duncan and Storey (1992), Müller et al. (1993) and Lawver and Müller (1994).

Two remote hot spot locations are crucial to determine the position of Pangea during the Triassic and Jurassic time, to fix the position of the supercontinent prior to the break-up and disassembly. The position of the northern part of Pangea was constrained using Iceland and Jan Mayen hot spots. The Iceland hot spot was traced from its present day position to Greenland in the Paleocene, to Baffin Bay in the Late Cretaceous, to the Alpha Ridge in the Early Cretaceous (see Lawver and Müller, 1994), to the Chukchi Borderland in the Middle–Late Jurassic, to Franz Joseph Land in the Early Jurassic, to the Yenisei–Khatanga Trough in the Middle Triassic, and to West Siberia in the Late Permian–Early Triassic (see Lawver, 1993). The position of the southern part of Pangea was constrained using the Bouvet hot spot (see Duncan and Richards, 1991). This hot spot was tracked from its present day position to Western Antarctica in the Late Jurassic–Early Cretaceous and to South Africa in the Late Triassic–Early Jurassic. Using an interactive computer graphics technique we compiled an updated model of Pangean plate motions during the Triassic and Jurassic time, prior to the break-up of South Atlantic. The model for the last 130 million years (Cretaceous and Cenozoic) follows the widely accepted models constructed by PLATES and PALEOMAP software (see Lawver and Gahagan, 1993; Golonka et al., 1994; Golonka and Gahagan, 1997).

After we calculated the position and motion of major continents using a modified PALEOMAP model, we plotted 30 major hot spot locations in fixed position. This allows us to check the accuracy of the assumed and predicted locations versus the

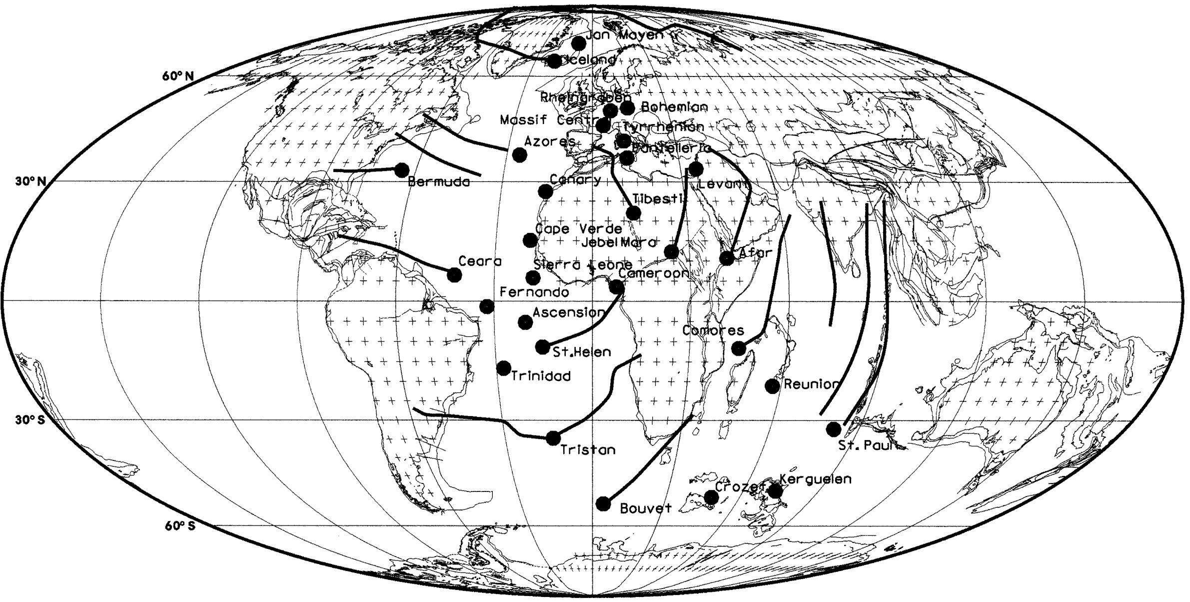

Fig. 1. Present day position and Mesozoic–Cenozoic tracks of the major Pangean hot spots.

actually observed volcanic, doming and rifting activity during several stages of continental break-up and disassembly.

3. Maps discussion

In the following discussion we frequently use the term 'hot spot moved', which is understood to mean that it changed location in relation to the overlying plate. This is, of course, not quite correct; the plate is moving over a relatively stationary mantle plume expressed by a hot spot. Nevertheless, the term makes it somewhat easier to describe the geodynamic process.

3.1. Late Triassic — 220 Ma (Fig. 3)

At this stage the Bouvet hot spot was approximately located in South Africa position, which is in good agreement with the location of the plume head (see White and McKenzie, 1989; Storey et al., 1992; Storey, 1995). There are indications of initial rifting and volcanic activity prior to the Early Jurassic extensive basalt lava flows. The rifting started probably as early as the Early Permian and continued through Permian and Triassic (Veevers, 1994; Bangert et al., 1997; Stollhofen and Stanistreet, 1997). The line of the Bouvet, Tristan and St. Helen hot spots could indicate rifting and basin formation, which preceded opening of the South Atlantic. Basins existed during the Triassic time in South Africa, Namibia, Parana and Parnaiba (see maps in Golonka and Ford, 2000, this volume). The line of the St. Helen–Trinidad hot spots could also indicate the Paleozoic trend of the Amazon basin. The Lower–Middle Triassic basalts occurred in the Parnaiba basin (see Gust et al., 1985; Khain and Balukhovski, 1993).

The Iceland hot spot was perhaps located below the Taimyr Peninsula, between the Yenisei–Khatanga area and Franz Joseph Land. This hot spot was very active during Late Permian–Early Triassic time, causing eruption of 1,200,000 km^3 of basalts in the Western Siberian basin (Zonenshain et al., 1990), within the short period from 255 to 245 Ma. According to Sharma (1997), the bulk of the Siberian lavas erupted within a period of about one million years at 250 Ma. Volcanic activity then progressed towards the Yenisei–Khatanga trough south of the Taimyr Peninsula, where the Middle Triassic lava flows

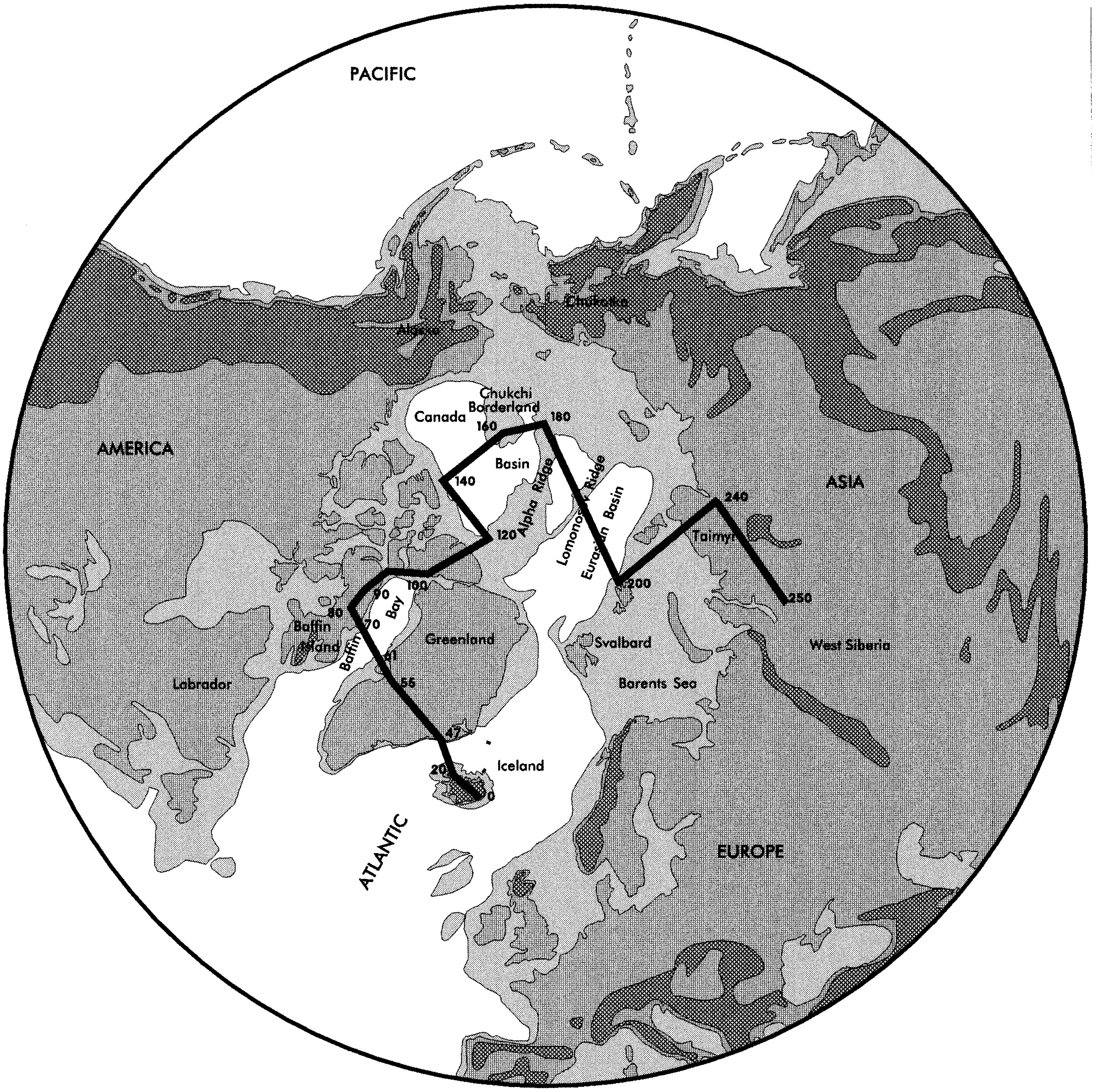

Fig. 2. Permian–Present Iceland hot spot track (Cretaceous–Present from Lawver and Müller, 1994, modified according to Storey et al., 1998; Tegner et al., 1998).

are present (Khain and Balukhovski, 1993). The Levant hot spot, situated between the Eurasian platform and Pontides terranes, could be connected with the opening of the proto-Black Sea, or the so-called Tauric Basin (Kazmin, 1990).

The Jebel Mara hot spot is located in the Eastern Mediterranean area where rifting occurred during the Permian and Triassic time (Stampfli et al., 1991; Guiraud and Bellion, 1996) accompanied by Mid–Upper Triassic extensive, alkaline basalt flows known from Levant to Morocco. The rifting was followed by seafloor spreading recorded

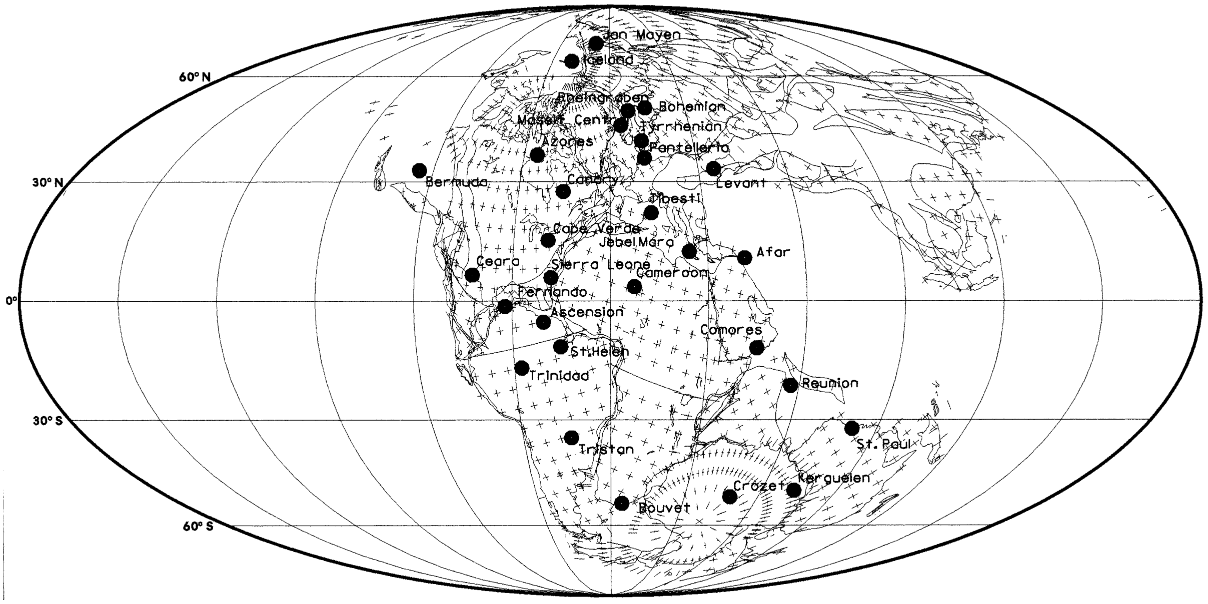

Fig. 3. Late Triassic (220 Ma) position of the major Pangean hot spots.

by Triassic Mamonia ophiolites from Cyprus (Robertson and Woodcock, 1979). The Afar, Comores, Reunion and St. Paul hot spots could be associated with the rifting and drifting along the Arabian and Indian margin, accompanied by alkaline to transitional magmatism (Robertson and Searle, 1990; Sengör et al., 1993; Guiraud and Bellion, 1996). These hot spots could be an expression of mantle upwelling that was one of the driving forces of the Cimmerian plates (Sengör, 1984), drifting from Gondwana to Eurasia. The Comores–Bouvet line is also related to the early stretching, predating the Karoo Rift System (Lawver and Gahagan, 1993), developed along the eastern coast of Africa. Around 230 Ma the rifts and seaway between India, Madagascar and the horn of Africa were already developed (Veevers, 1994; Manspeizer, 1994).

The Rheingraben, Tyrrhenian and Pantelleria hot spots are related to the Permian and Triassic Arctic–North Atlantic rift system as well as to the extensive Permian volcanism around the North Sea and minor Late Triassic volcanism west and east of Denmark (Ziegler, 1988, pls. 6, 7, 10). The Tibesti hot spot could be connected to Pyrenean rifting and volcanism (Ziegler, 1988). Volcanism and rifting in the Canadian Arctic are perhaps associated with the Azores hot spot. Early rifting in the Central Atlantic area is connected with the Sierra Leone hot spot. According to Withjack et al. (1998, fig. 9a), in the early stage of rifting in this area, active asthenospheric upwelling combined with distant plate tectonic forces produced initial thinning of the lithosphere, lithospheric displacement, widespread extension, possible doming, but no volcanic extrusion. The Fernando Po hot spot marked an extension of this rifting system into the area between North and South America, the future location of the Gulf of Mexico and proto-Caribbean area.

3.2. *Early Jurassic–Middle Jurassic — 200 and 180 Ma (Figs. 4 and 5)*

During Early–Middle Jurassic time the Bouvet hot spot was approximately located between South Africa and Antarctica. The hot spot activity was clearly expressed by initial break-up and strong magmatic activity on both sides of the break-up line. According to Cox (1992), the widespread Early Jurassic Karoo volcanism in southern Africa appears to have been generated from the large-

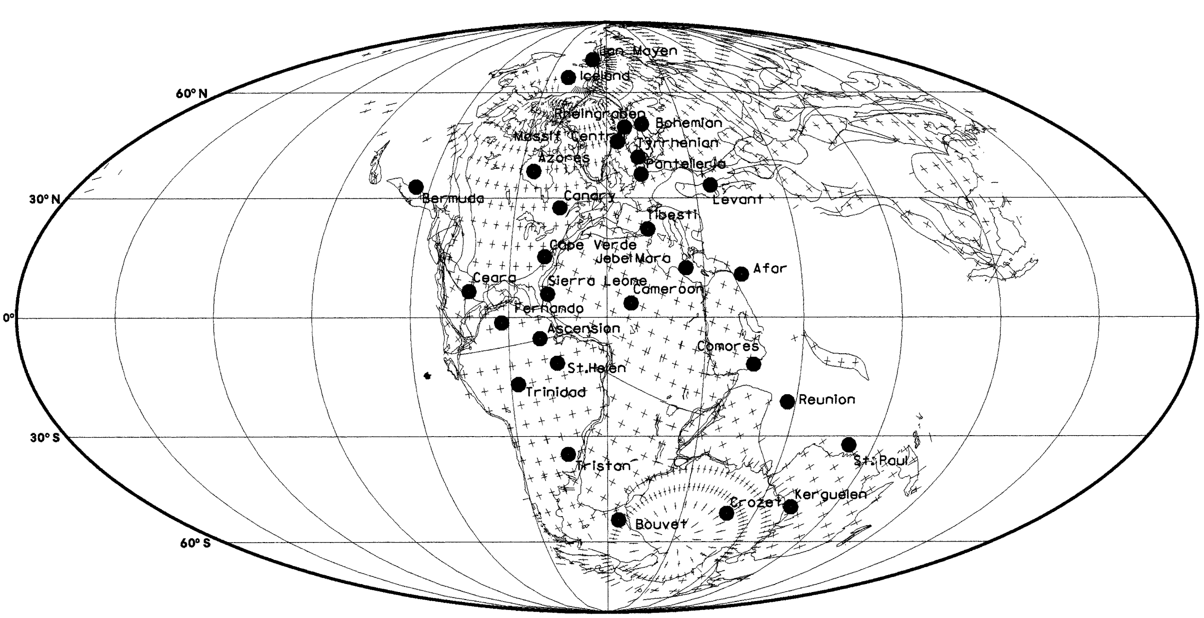

Fig. 4. Early Jurassic (200 Ma) position of the major Pangean hot spots.

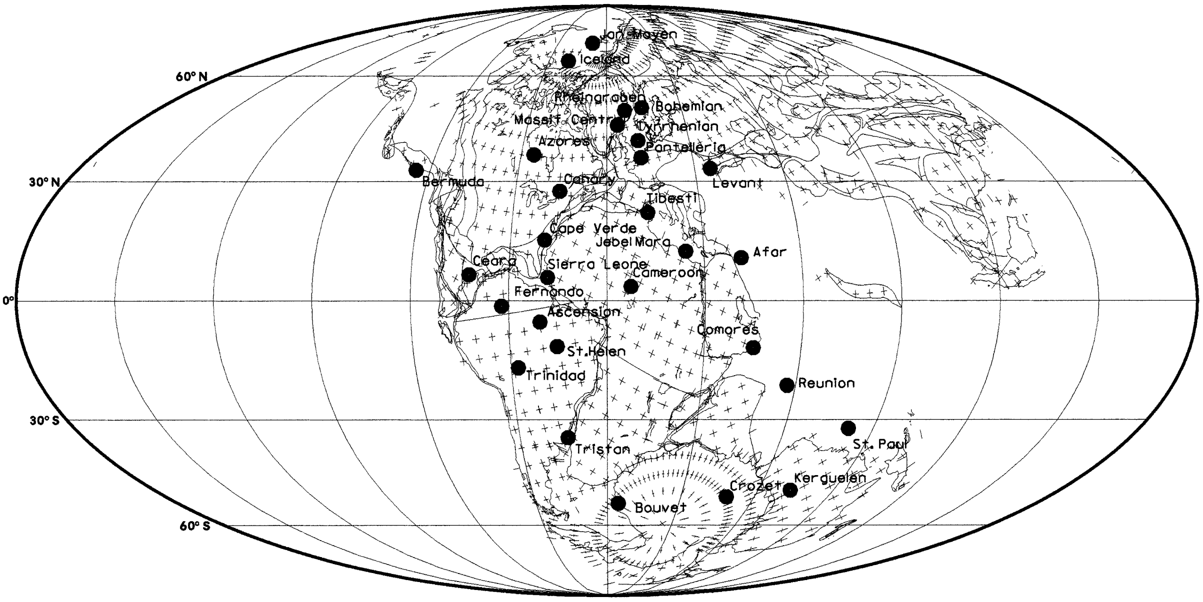

Fig. 5. Early–Middle Jurassic (180 Ma) position of the major Pangean hot spots.

scale mantle plume, originating in the sublithospheric mantle, with a considerable addition of material from the lithosphere. Cox (1992) postulated two stages of the break-up. The first stage was accompanied by volcanism in southern and southwestern Africa. Substantial eruptive activity occurred between approximately 198 and 173 Ma. The second stage started the separation of

Madagascar from Africa, marked by seafloor magnetic anomalies in the Somalia Basin. According to Lawver and Gahagan (1993), the seafloor spreading in the Western Somali Basin and the Mozambique basin began at 175 ± 10 Ma. Brewer et al. (1992) dated the Antarctic early magnetic episode as 193 ± 7 Ma. The widespread Ferrar magmatism occurred over a short interval 176 ± 18 Ma (Brewer et al., 1996). Cox (1992) described the zone of volcanism as a linear belt, which extends through the Transantarctic Mountains for 3000 km as far as Australia. Cox (1992) suggests a possibility of elongated mantle upwelling or connection with the subduction zone, which was part of the Pangean Rim of fire (see Golonka and Ford, 2000). The role of the Conrad hot spot remains unclear because the thick cover of ice prevents investigations in this area.

The Iceland and Jan Mayen hot spots moved relatively west of the Eurasian continent, approaching the area of the future opening of the Arctic Ocean. The early stage of Franz Joseph Land magmatism is dated, according to Dibner (1994), as Sinemurian (203 ± 14 Ma), see also Jurassic volcanic activity mapped in Franz Joseph Land–Svalbard area by Ziegler (1988, pls. 11–13) and Doré (1991, pls. XI, XII, XIV). Rheingraben, Tyrrhenian and Pantelleria continued to influence the Arctic–North Atlantic rift system. According to Ziegler (1988, pl. 11) volcanic activity occurred west of Norway, during the Sinemurian–Toarcian time, followed by widespread volcanism related to opening of the North Sea during the Middle Jurassic time (see also Doré, 1991, pls. XI, XII, XIV).

The Afar, Comores, Reunion and St. Paul hot spots continued to be located in the marginal Gondwana–Neotethys zone, causing a southward shift of ridges and rifting zones (Ricou, 1996). This shift caused rifting of the Argo block and possibly the Lesser Caucasus–Sanandaj–Sirjan plate (Ricou, 1996; Adamia, 1991; Sengör et al., 1991).

Sierra Leone, Cape Verde and Tibesti hot spots influenced the opening of the Central Atlantic–Ligurian Ocean system. According to Withjack et al. (1998, fig. 9b), during the late rifting phase, the lithosphere was thinned and forces associated with astenospheric upwelling increased substantially. Lithospheric displacement, caused by upwelling, combined with the collisional events in western North America, resulted in compression and inversion in the intervening zone. Diabase sill and dikes intruded into the continental crust and a large volume of the basaltic lavas extruded throughout eastern North America. Most of this magmatic activity occurred at 201 ± 2 Ma (Dunning and Hodych, 1990; Olsen, 1997; Withjack et al., 1998). The magmatic activity also occurred on the African side of the Central Atlantic Ocean and in the adjacent area of South America (Ziegler, 1988; Guiraud and Bellion, 1996). In the Ligurian Ocean, Ricou (1996) described sedimentary breccias covered or intercalated with tholeitic basalts and postdated by Callovian–Oxfordian radiolarites. Ricou (1996) argues that the return to quiet and volcanic-free sedimentation marks the end of spreading. While the Tibesti hot spot could mark the southern part of the Ligurian Ocean, the Levant hot spot could be connected with the northern one — the Pieniny Klippen Belt Ocean (Birkenmajer, 1986). The role and position of this hot spot, as well as the position of the Ceara point and its role in the opening of the proto-Caribbean area and Gulf of Mexico, remain somewhat speculative.

3.3. *Middle–Late Jurassic — 160 and 140 Ma (Figs. 6 and 7)*

During the Middle–Late Jurassic time, the Bouvet hot spot maintained its position close to the Africa–Antarctica break-up. At that time, seafloor spreading began along the line Bouvet–Comores in the Somali Basin and the Mozambique Channel (Rabinowitz et al., 1983; Simpson et al., 1979; Lawver et al., 1992; Lawver and Gahagan, 1993). The flow basalts occurred in the coastal basins of Madagascar and Mozambique (Coffin and Rabinowitz, 1988, 1992; Guiraud and Bellion, 1996). Lawver and Gahagan (1993) argued that Somali and Mozambique spreading must have been accompanied by seafloor spreading in the Southwest Weddell Sea. LaBrecque and Barker

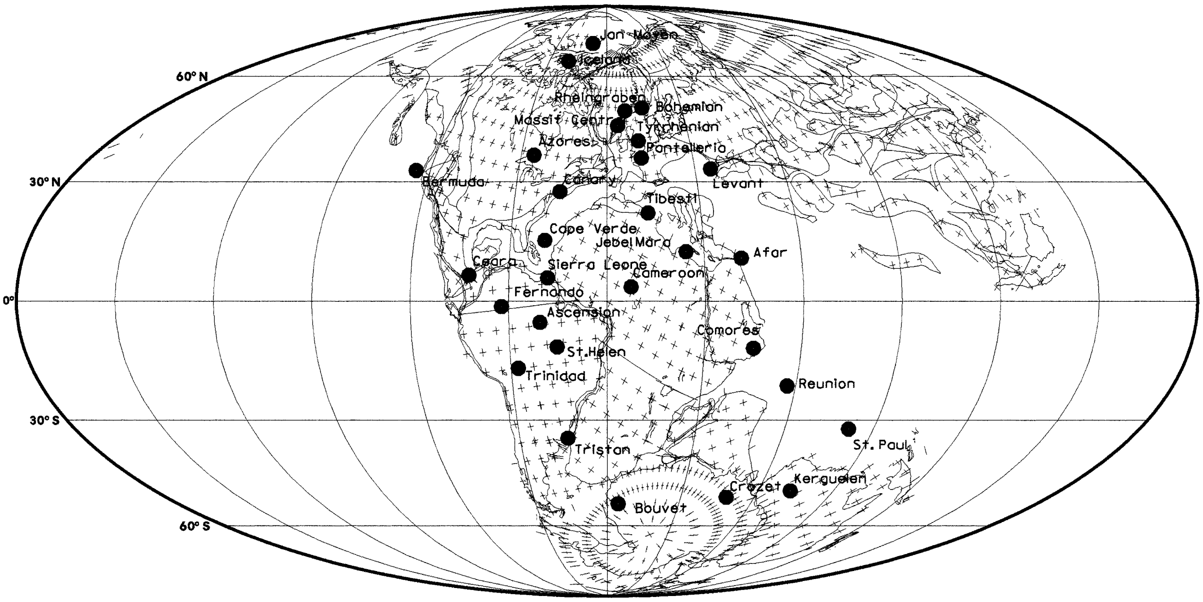

Fig. 6. Middle–Late Jurassic (160 Ma) position of the major Pangean hot spots.

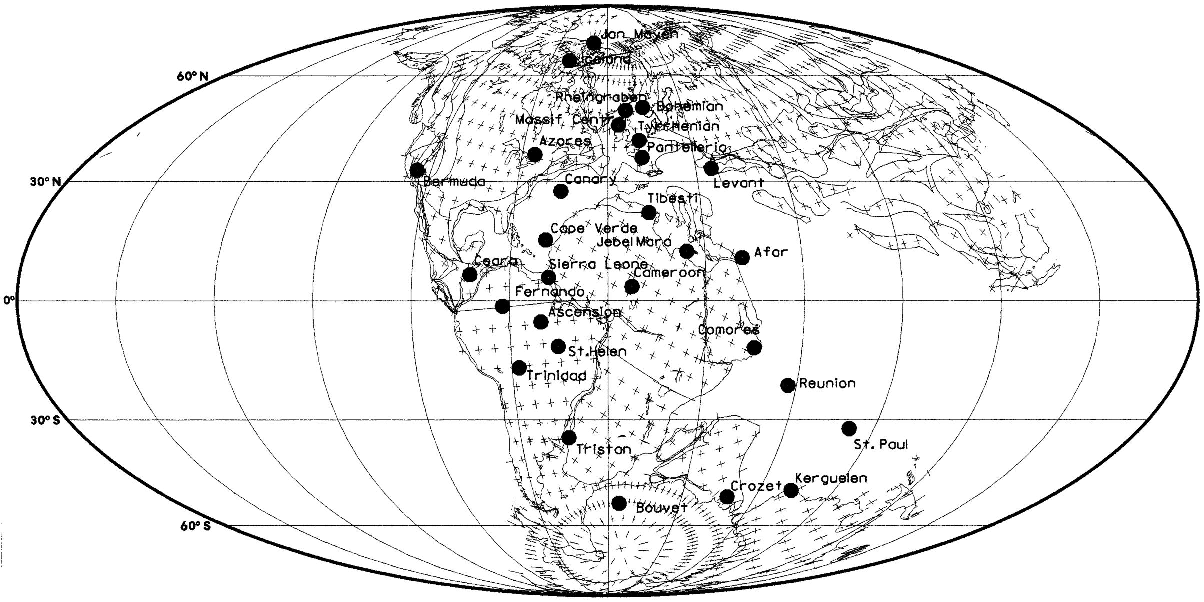

Fig. 7. Middle–Late Jurassic–earliest Cretaceous (140 Ma) position of the major Pangean hot spots.

(1981) proposed that the Weddell Sea contains oceanic crust of Middle Jurassic age (165 Ma, anomaly M29), however, according to Storey et al. (1996), this age has not been subsequently substantiated.

The Comores hot spot could also be related to the rifting, which was active during the Late Jurassic in Yemen (Guiraud and Bellion, 1996). By Late Jurassic times, the Crozet hot spot reached the position of future seafloor spreading between India and Antarctica.

Iceland and Jan Mayen hot spots moved into the direction of Chukchi borderland and future opening of the Canadian Basin. In the Late Jurassic, the progressive break-up of Pangea included a system of spreading axes, transform faults and rifts which connected ocean floor spreading in the central Atlantic and Ligurian Sea to rifting which continued through the Polish–Danish graben to Mid-Norway and the Barents Sea. Rifting in the Arctic region was part of this system and was caused by the trench-pulling forces which consumed the Anui–Anvil oceans (Zonenshain et al., 1990), in conjunction with a mantle convection and upwelling cell expressed by the hot spot volcanics of the Alpha Ridge and Chukchi Borderland. According to Hall (1990), the average density of the Chukchi Borderland crust is similar to the average crustal density of the Alpha Ridge (Weber and Sweeney, 1990), which was considered as a product of hot spot volcanism or Large Igneous Province (Vogt et al., 1979; Forsyth et al., 1986; Lawver and Müller, 1994; Lawver, 1993; Coffin and Eldholm, 1994). The Jurassic volcanism was observed on Northwind Ridge, which is part of the Chukchi Borderland, by Arthur Grantz (oral communication at Penrose Conference, 1995). Coffin and Eldholm (1994, fig. 1, table 1) also included Chukchi Plateau and Northwind Ridge into their list of Large Igneous Provinces (LIPS).

Via the processes of subduction pull and mantle upwelling, a system of narrow marine troughs and exposed rift-shoulder uplifts developed parallel to the Laurasian margin (Kos'ko, 1984; Polkin, 1984). These rift depressions subsequently developed into the East Siberian Sea Basin and the North Chukchi Basin (Grantz and May, 1987; Grantz et al., 1990; Kos'ko, 1984; Polkin, 1984). The central rift developed later into the Canadian oceanic basin (Lawver et al., 1990; Lane, 1994; Embry, 1994; Zonenshain et al., 1990).

Further south, the distribution of Rheingraben and other European hot spots, as well as Tyrrhenian and Pantelleria hot spots, matches reasonably well the rifting and volcanic activity depicted for Mesozoic seaways between Europe and the Arctic by Doré (1991, pl. XIV). Doré (1991) depicted volcanics west of Norway, north of Ireland, in the North Sea between the UK and Denmark, and on the London–Brabant Massif. A similar picture was presented also on Ziegler's (1988, pls. 12, 13) paleogeographic maps.

The Sierra Leone, Cape Verde and Tibesti hot spots still influenced the opening of the Central Atlantic–Ligurian Ocean system. The proto-Central Atlantic seafloor spreading regime became more passive (Withjack et al., 1998, fig. 9c). At the end of this period, the Canary hot spot moved into the proto-Central Atlantic area. This movement and change of some European hot spot locations to the area between the UK and Greenland caused the beginning of the reorganization of the Pangean break-up system. The Atlantic began to propagate into the area between Iberia and Canada. The North Sea–Poland rifts turned into aulacogenes. The Ligurian–Pieniny Oceans reached maximum width and stopped spreading.

The Tibesti hot spot was located further off Spain, on the northern margin of Africa, in Tunisia. The Tibesti and Jebel Mara mark the line along the northern African margin where, according to Guiraud and Bellion (1996), large east–west-trending rifts were initiated during the latest Jurassic–earliest Cretaceous, with volcanic intrusions on rift shoulders. The West and Central African rift, which developed during the Late Jurassic time (Guiraud and Bellion, 1996), could be associated with the Cameroon hot spot. The rift related magmatic activity, with alkalic and tholeitic types, occurred mainly in Benue trough (Wilson and Guiraud, 1992).

The Afar, Comores, Reunion and St. Paul hot spots continued to be located in the marginal Gondwana–Neotethys zone. Afar is perhaps related to rifting volcanism in the Euphrates Trough and Palmyrides (Guiraud and Bellion, 1996). The long lasting location of the hot spot chain and possibility of associated mantle upwelling plumes on the southern Neotethys margin could help to explain the concept of Tethys transit plates introduced by Ricou (1996). With this concept, Ricou (1996) could explain the systematic migration of continental blocks from the southern to the northern side of Tethys and the associated asymmetry of this part of Tethys, bounded by passive margins to the south and an active margin to north. The above mentioned set of hot spots was perhaps an active force from the Late Paleozoic to the Late Cretaceous.

3.4. Early Cretaceous — 120 Ma (Fig. 8)

This is the time of the break-up of Gondwana, which followed the Middle–Late Jurassic break-up between Gondwana and Laurasia.

According to Lawver and Gahagan (1993), significant new continental break-ups occurred at about 130 Ma: Africa and South America split apart to form the South Atlantic; India and Antarctica split apart, and Arctic Alaska moved, opening the Canada Basin (see also Golonka et al., 1994; Golonka and Scotese, 1995).

According to Wilson (1992), at least two major mantle plumes expressed by the hot spots of St. Helen and Tristan da Cunha have been influential in weakening the lithosphere along the line of the developing South Atlantic rift. The Tristan plume is associated with large volumes of flood basalt on the South American side in Parana and smaller volumes on the African side in Etendeka (Hawkesworth et al., 1992). Our reconstruction for 120 Ma shows the Tristan hot spot already in location between South America and Africa, while St. Helen is still some distance from the future Atlantic margin. This is in agreement with Müller et al.'s (1993, fig. 2) reconstruction and with a diachronous opening of South and Equatorial Atlantic (Nürnberg and Müller, 1991).

The Crozet (Conrad) and Kergulen hot spots were located between Australia–Antarctica and India. The Rajmahal Traps in India (Baksi et al., 1987) could be associated with the Crozet hot spot.

According to Lawver and Gahagan (1993), both Rajmahal Traps and Kergulen Plateau (Houtz et al., 1977; Davies et al., 1989) were created after seafloor spreading commenced between India and East Antarctica (see also Kent et al., 1997). According to Kent (1991), mantle plume existed at this area long before spreading. The Lawver and Gahagan (1993) assumption, that motion of India was driven by a subduction zone along the southern margin of Eurasia, does not seem to be valid, because of the possible and

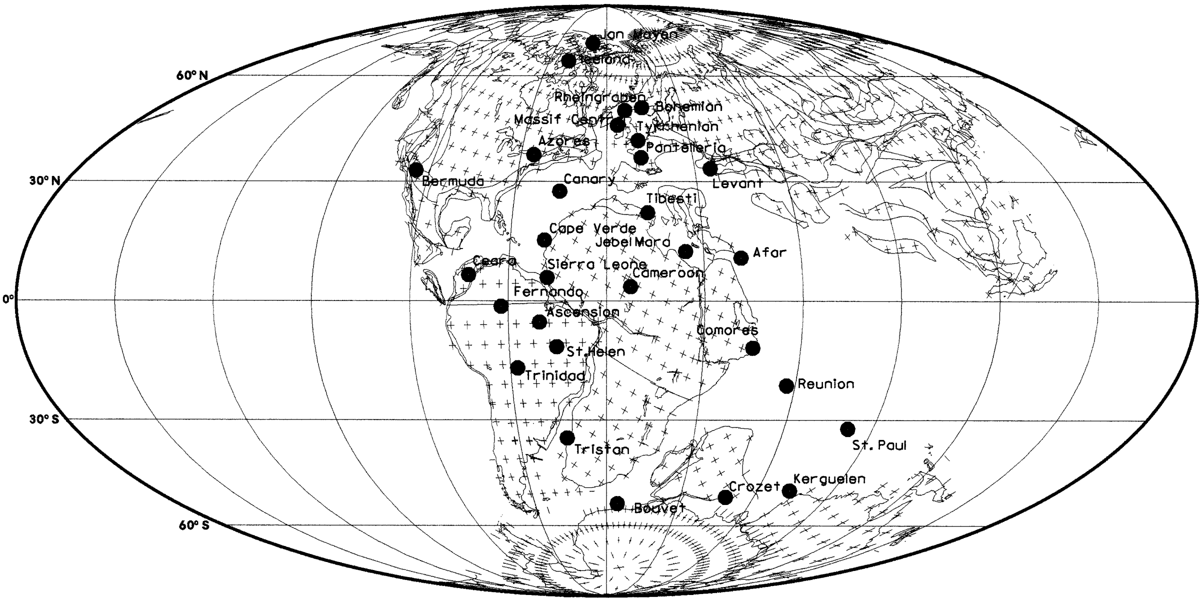

Fig. 8. Early Cretaceous (120 Ma) position of the major Pangean hot spots.

widely accepted existence of the spreading center between India and Eurasia (see Ricou, 1996, Map 7; Sengör and Natalin, 1996, fig. 21.45; Zonenshain et al., 1990, fig. 201; Golonka et al., 1994, fig. 55; Metcalfe, 1994, fig. 9b). The pushing force caused by mantle upwelling better explains the initial phase of the northward drift of India. In the later phase, however, the Eurasian subduction could have become the major force driving the India motion.

The Jebel Mara hot spot position coincides with the spreading in the Eastern Mediterranean (see Ricou, 1996, Map 8; Sengör and Natalin, 1996, fig. 21.41; Robertson et al., 1996, fig. 5). The tholeitic volcanism in the Antalya basin (Robertson et al., 1991), basaltic dikes and extrusives in the Troodos complex in Cyprus (Morris, 1996), could be related to the hot spot activity. Similarly, the Erastothenes Seamount (see Bogdanov et al., 1994), with density similar to a volcanic plateau rather than continental crust, could be the hot spot product. Rifting and drifting of the Taurus plate from Arabia and flow basalts along the northern margin of Arabia (Guiraud and Bellion, 1996) could also be related to the Afar hot spot.

According to Lawver and Müller (1994), the seafloor spreading in the Canada Basin started during the Early Cretaceous (see also Lane, 1994). Several authors (Vogt et al., 1979; Forsyth et al., 1986; Asudeh et al., 1988; Jackson et al., 1986; Lawver and Müller, 1994; Lawver, 1993; Coffin and Eldholm, 1994) argue that the Alpha Ridge complex was generated by mantle plume activity related to the Icelandic hot spot. Lawver and Müller (1994) conclude that the Iceland hot spot might have triggered the seafloor spreading that led to the formation of the Canada Basin. After opening the Canada Basin, Iceland and Jan Mayen hot spots moved toward the Canadian Arctic Islands and could have been associated with the Albian–Cenomanian emplacement of flood basalts on the Ellesmere Island and Axel Heiberg Island (Ricketts et al., 1985; Embry and Osadetz, 1988).

The central Atlantic was spreading and propagating towards the area between Iberia, Grand Banks and Flemish Cap, later north and towards the Rocall Trough (Ziegler, 1988, pls. 14, 15). The location of the Azores, Massif Central, Rheingraben, Bohemian, Tyrrhenian and Pantelleria hot spots is in fair agreement with patterns of rifting, spreading and volcanic activity on the map of Ziegler (1988). The rifting and spreading in the Biscay Bay might be associated with the vicinity of the Pantelleria hot spot. The Eastern Mediterranean–Biscay Bay–Labrador Sea break-up line roughly related to Afar, Jebel Mara, Tibesti, Pantelleria, Massif Central hot spots, began to form at that time.

3.5. Late Cretaceous — 90 and 65 Ma (Figs. 9 and 10)

The Late Cretaceous was a time of maximum disassembly of the former Pangean supercontinent. At the same time a significant reduction of the size of Tethys occurred, leading to the modern configuration of continents.

Spreading of the Central and Southern Atlantic continued with a significant increase of the Equatorial Atlantic (Nürnberg and Müller, 1991). At the end of this period, most of the present day Atlantic hot spots were located inside, or on the margins of the ocean. The Bermuda hot spot moved across North America during the Cretaceous time. This crossing was marked by igneous activity, which produced, among others, kimberlites and other alkalic rocks of the Arkansas province. According to Morris (1987), these rocks yielded absolute age in the range of 86–106 Ma. The Ceara hot spot might be associated with a large amount of the flood basalt in the Columbian Basin of the Caribbean Sea (Bowland and Rosencrantz, 1988).

The Indian plate was moving rapidly northward, opening the Indian Ocean (Royer and Sandwell, 1989; Lawver et al., 1992). The movement of India over the Reunion hot spot resulted in emplacement of large volumes of flood basalts, known as Deccan traps (Mahoney, 1988; Coffin and Eldholm, 1994). The volcanics of the Ninetyeast Ridge were also initiated at that time (Royer et al., 1991).

The northern movement of Africa, Arabia and India placed Jebel Mara and Afar hot spots inside the continents, south of the new Tethyan margin. This displacement perhaps contributed to the

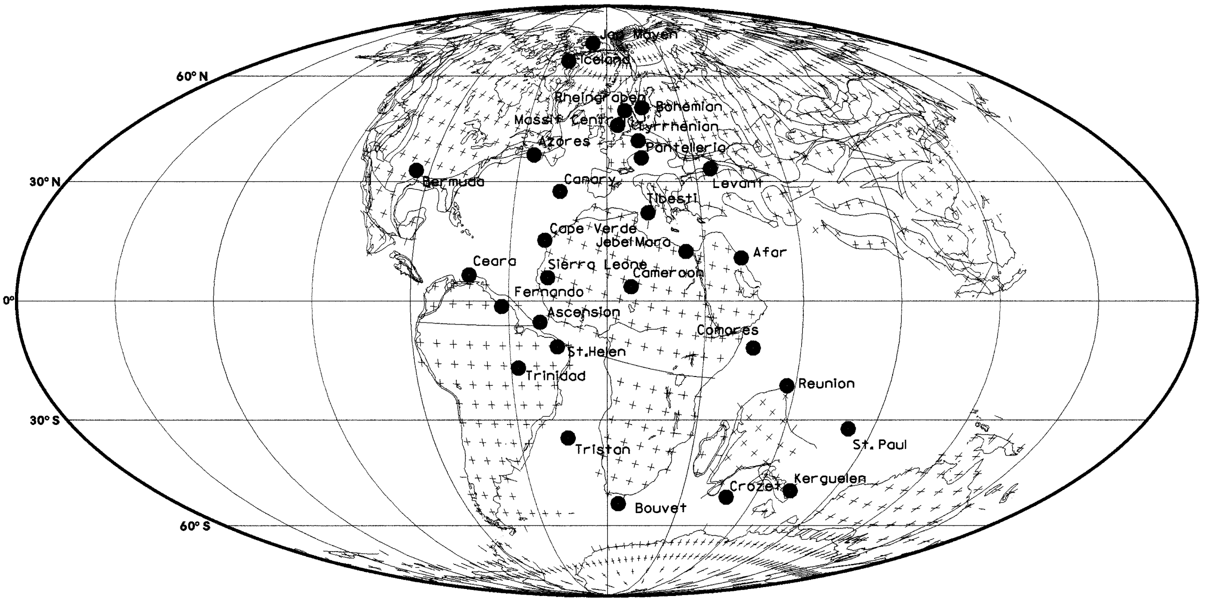

Fig. 9. Late Cretaceous (90 Ma) position of the major Pangean hot spots.

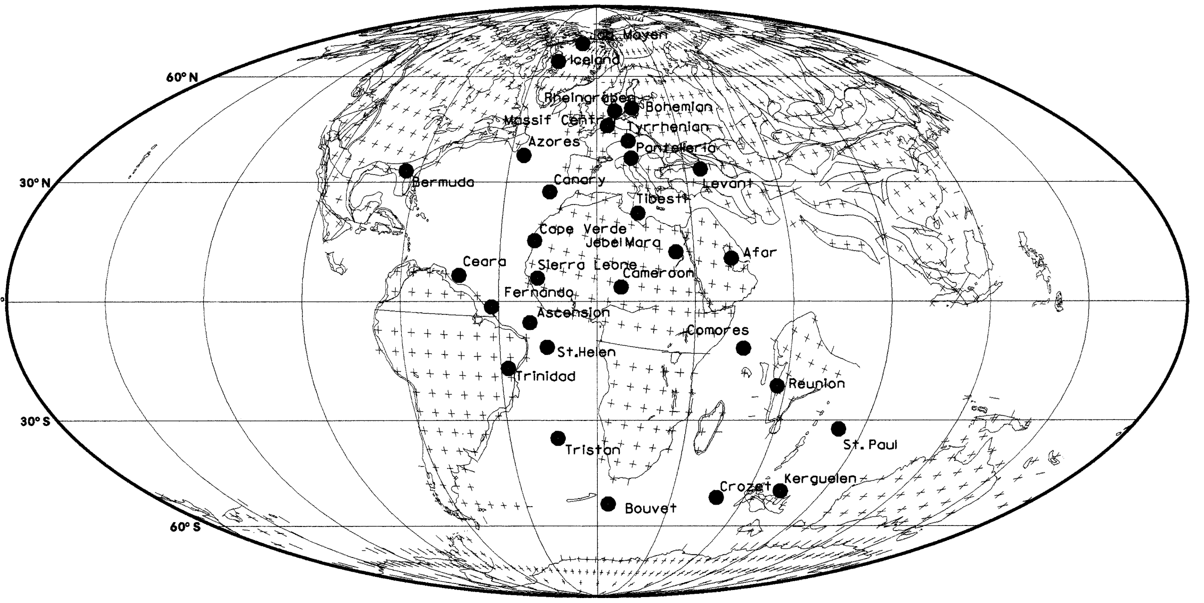

Fig. 10. Late Cretaceous–earliest Paleogene (65 Ma) position of the major Pangean hot spots.

change of the Arabian margin from passive to convergent (Ricou, 1996; Sengör and Natalin, 1996; Guiraud and Bellion, 1996).

Europe moved westward to approximately the present day longitudinal position over the Massif Central, Rheingraben, Bohemian, Tyrrhenian and Pantelleria hot spots. This movement, related to the rotation of the Eurasian continent, was a result of the opening in Arctic and collisions in northeastern and eastern Asia (Zonenshain et al., 1990). Greenland and adjacent areas of Canada moved over the Iceland hot spot (Lawver and Müller, 1994). The location of the Iceland hot spot between the Baffin Island and Greenland, approximately during the time span between 100 and 70 Ma (Lawver and Müller, 1994, fig. 1), resulted in spreading in the Labrador Sea, rifting in the Baffin Bay and emplacement of the volcanics on the western coast of Greenland (Gill et al., 1992, 1995; Holm et al., 1992; Larsen et al., 1992). The main line of spreading in the Atlantic realm, adjacent to Europe, was Biscay Bay–Labrador Sea (see Ziegler, 1988, pl. 16; Huyghe and Mugnier, 1994, fig. 4). The widespread inversion in the North Sea (Huyghe and Mugnier, 1994; Dronkers and Mrozek, 1991) and in Central Europe (Ziegler, 1988, 1990, 1992; Baldschuhn et al., 1991) could be a result of the stress induced by movement of Europe and ridge pushing from the Bay of Biscay spreading. The direction of Late Cretaceous Subhercynian and Laramide structures (Ziegler, 1988, pl. 16) is parallel to the Bay of Biscay and perpendicular to the Alpine–West Carpathian front as well as to the future spreading in the North Atlantic, between Norway and Greenland. According to Baldschuhn et al. (1991), the Coniacian to Campanian time of inversion in northwestern Germany does not coincide with the continent–continent collision events in the alpine realm. Unternehr and Van Den Driessche (1997) argue that North Sea compressive tectonics were not restricted to basin inversion, but also involve crust and/or lithospheric buckling, and that there is a close connection between North Atlantic Opening and compression in the southern North Sea during the Late Cretaceous. Change of location of the European hot spots probably contributed to this inversion.

3.6. Tertiary — 40 and 20 Ma (Figs. 11 and 12)

Tertiary is a time of the gradual transition from a maximum disassembly to the new assembly of continents. Spreading of the Central and Southern Atlantic continued with a significant increase of the Equatorial Atlantic (Nürnberg and Müller, 1991). During this period, the Bermuda hot spot was finally located inside the Atlantic and Cameroon on the Atlantic margin.

According to Lawver and Müller (1994), Greenland moves over the Iceland hot spot during the time span 60–40 Ma. The east coast of Greenland was affected by an Iceland mantle plume (White and McKenzie, 1989; Holm et al., 1992). Extrusion occurred on East Greenland mainly between 57 and 53 Ma (Noble et al., 1988). The late phase of volcanism yielded various ages 30–48 Ma (Nielsen, 1987; Larsen and Marcussen, 1992). Between 40 Ma and present day, the Iceland hot spot changed its location to the modern 64°N latitude and 16°W longitude (Oskarsson et al., 1985; Einarsson, 1991; Flóvenz and Gunnarson, 1991; Lawver and Müller, 1994). The newest research on the age of the Greenland volcanics seems to support their mantle plume origin with a slight age modification. ^{40}Ar–^{39}Ar dating by Storey et al. (1998) shows that volcanism commenced in West Greenland during 60.5 ± 0.4 Ma. The timing of the onset of volcanism in West Greenland coincides with the opening of the northern Labrador Sea. Storey et al. (1998, see also Graham et al., 1998) argues that the arrival of the Iceland mantle plume beneath Greenland was a contributing factor in the initiation of seafloor spreading in the northern Labrador Sea. According to Tegner et al. (1998), the tholeiitic magmatism along the East Greenland rifted margin largely occurred in three distinct pulses, at 62–59 Ma, 57–54 Ma and 50–47 Ma, relating the mantle malting episodes triggered by plume impact, continental break-up and passage of the plume axis. The Tegner et al. (1998) model implies northwestward drift of Greenland relative to the plume axis by ~ 3.8–5.0 cm/yr between ~ 60 and ~ 49 Ma. Saunders et al. (1997, p. 51, fig. 3, p. 82) depict a large asymmetric plume affecting the North Atlantic province Igneous Province in places between Baffin Island and West Greenland in the west, the British Isles in the east and Hold with Hope in NE Greenland in the north, a distance of more than 2000 km. The existence of such a large, asymmetric plume could explain the difficulties in drawing hot spot tracks and the discrepancies in the estimation of their stationary positions over a long period of

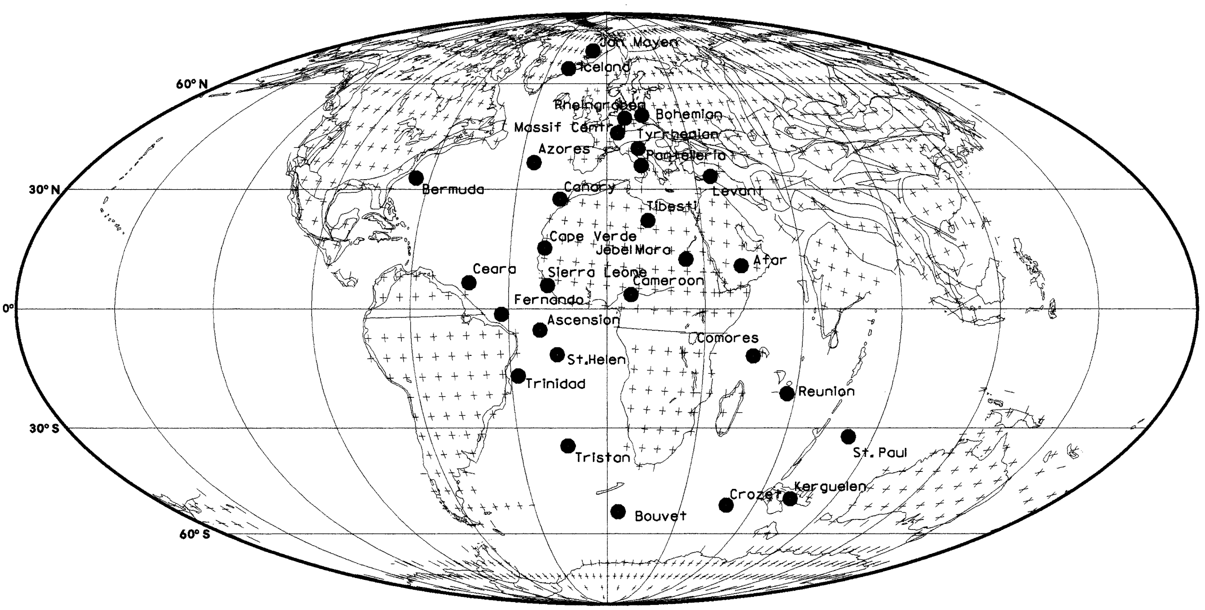

Fig. 11. Paleogene (40 Ma) position of the major Pangean hot spots.

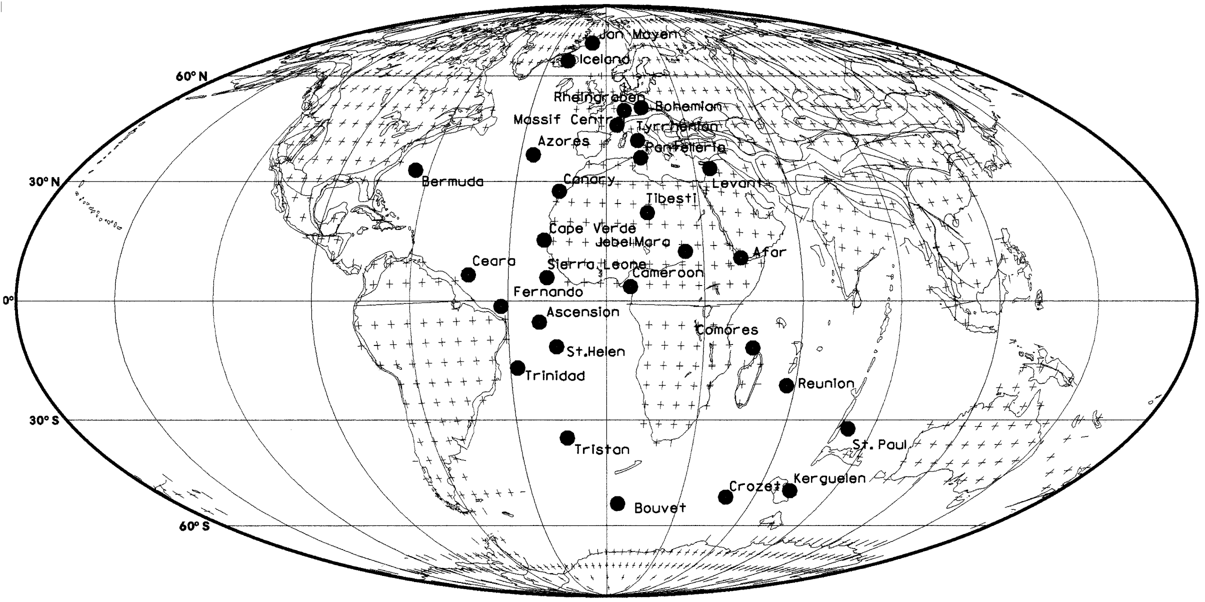

Fig. 12. Neogene (20 Ma) position of the major Pangean hot spots.

time. A single hot spot point could appear in different positions within the same large mantle plume.

The opening of the North Atlantic was linked to the mantle plume related to this hot spot by White and McKenzie (1989). According to White (1992), shortly after the Iceland plume initiated, the extension between Greenland and the northwest Europe margin did continue until it developed into a full oceanic spreading center. The voluminous volcanic complexes, containing wedges of seaward-dipping reflectors, were placed in the vicinity of the continent–ocean transition (Coffin and Eldholm, 1992; Skogseid et al., 1992). Boldreel and Andersen (1992) observed the compressional structures at several locations in the Faeroe–Rockall area, which may be associated with seafloor spreading of the Atlantic and with the complex Miocene spreading history of Iceland.

Within the Tertiary period, the central European hot spots were distributed close to the present day locations. The mantle upwelling, associated with these hot spots, was responsible for intensive lithosphere stretching and rifting. Rifting occurred mainly during the Oligocene and Miocene time, on the area between France and Ukraine (Ziegler, 1988, 1990, 1992; Bois, 1993; Wilson, 1994; Wilson and Downes, 1991; Rutkowski, 1986; Żytko et al., 1989), and was associated with the alkaline volcanism. According to Bois (1993), extension occurred in a part of the European plate, with the rifting of the Rhine, Limagne and Bresse Trough, at the same time when the Alpine compression underwent a climax. Part of this rift system was the Gulf of Lions related to the mantle plume expressed by volcanics in Massif Central and Provence, and on Corsica and Sardinia (Wilson and Downes, 1991; Bellon and Brousse, 1977). Rifting in this area was followed by oceanic seafloor spreading and drifting of Corsica and Sardinia (Burrus, 1984; Bois, 1993; Ricou, 1996). This movement and subsequent opening of the Tyrrhenian Sea pushed the Adria plate eastward, causing deformation of the Alpine–Carpathian system, reaching as far as Romania (Ellouz and Roca, 1994; Royden, 1988).

In Central Europe, the NW–SE-trending rift system is perpendicular or diagonal to the thrust front of the Western Carpathians (Żytko et al., 1989). The Tertiary magmatism connected with the Bohemian hot spot is crossing the Carpathians between Moravia and Upper Silesia on the one side and the Pannonian Basin on the other. The andesite volcanism inside the Carpathians (Książiewicz, 1977; Birkenmajer, 1986; Żytko et al., 1989) is the link between Bohemian and Pannonian extrusions. Kováč and Marko (1997) observed the crustal stretching, accompanied in places by mantle updoming, which forced the Middle Miocene synrift basin subsidence. Paleogene and Neogene rifting produced northwest–southwest-trending depressions, which affected the platform below Carpathian thrusts (Oszczypko, 1997). The Krakow area (Rutkowski, 1986), located only kilometers from the Carpathian thrust front, consists of a system of horsts and grabens formed by Neogene rifting and only minimally affected by the Alpine-Carpathian collisional deformations. Krysiak (1997) distinguished the Middle Miocene (Badenian) phase of deformation in the Carpathian foredeep in Poland. During this phase a gravitational stress field was acting together with small extension of NE–SW to E–W direction. At that time the NW–SE oriented faults became reactivated. It appears that mantle plume related extension plays a bigger role in the European hinterland tectonics than does Alpine compression. The North Sea subsidence, renewed during the Tertiary (Joy, 1992), could also be related to the Central European rifting.

The existence of the mantle plume related extension in Europe, perpendicular and diagonal to the Alpine–Carpathian system, supports the hypothesis of Boldreel and Andersen (1992). The Atlantic margin inversion tectonics are as much related to the opening (ridge pushing) of the Atlantic as to Alpine collision. The ridge pushing force on the northern side of the European plate, combined with the collision of the southern side, resulted in compression and basin inversion.

Africa drifted northeastward over Cameroon, Tibesti, Jebel Mara and Afar hot spots. The Afar hot spot plume influenced the opening of the Red Sea and the Gulf of Aden (White and McKenzie, 1989; Menzies et al., 1992). According to Guiraud and Bellion (1996), most volcanic fields in west and central Africa lay far from the rifted Mesozoic basin, often occurring where fracture zones cut across a domal structure which probably overlay localized mantle upwellings. The Afar, Jebel Mara and Cameroon hot spots are associated with past or existing rifting, while Tibesti and other small localities perhaps mark areas of future rifting. The Levant hot spot volcanism is associated with the

Dead Sea rifting. The hot spot track also left a large amount of volcanics in the area between the Arabian, Turkish and Transcaucasus plates (Bogdanov et al., 1994). The Tyrrhenian and Pantelleria hot spots were located in the Late Neogene time close to their present day positions. The rifting in the Pantelleria Trough, between Africa and Sicily, occurred in the Pliocene and Quaternary. The rift depicted by Casero and Roure (1994, fig. 1) perpendicularly cut the Sicilian–North African thrust front.

4. Conclusions

(1) Hot spots within the Pangean hot field appear to remain fixed over the Mesozoic and Cenozoic period of time. They provide a good frame of reference for determination of the longitudinal position of Pangea. They also enable us to construct a model of plate motion during the Pangean break-up and disassembly.

(2) The obtained plate motion model agrees reasonably well with observations on intraplate and mid-oceanic volcanics, including Large Igneous Provinces, and with hot spot related rifting and break-up events. The existence of asymmetric plumes could explain the difficulties in drawing hot spot tracks and the discrepancies in the estimation of their stationary positions over a long period of time. A single hot spot point could appear in different positions within the same large mantle plume.

(3) Hot spots are related not only to the opening of the Atlantic and Indian Ocean, but also to rifting and spreading in Tethys. The long lasting location of hot spots and associated mantle upwelling plumes could help to explain the forces driving the Tethys transit plates. They are also related to the opening of the Ligurian Ocean and Eastern Mediterranean.

(4) The Iceland hot spot contributed to the emplacement of Siberian traps and could have triggered the seafloor spreading and opening of the Canada Basin.

(5) The European hot spots are related to several Mesozoic and Cenozoic phases of rifting and orogenic activities in Central and Western Europe, as well as in the North Atlantic–North Sea region.

(6) Mantle plumes, associated with hot spots, play an active role in rifting and initial phases of spreading. The lithospheric displacement, caused by upwelling, combined with sometimes remote collisional forces on the other side of the continental plate, may result in compression and basin inversion.

Acknowledgements

We would like to thank Mobil Corporation for permission to publish this paper. We would like to express our gratitude to our numerous Mobil coworkers, especially Dave Ford, Jeff Kraus, Bob Pauken, Martha Withjack, as well as our PLATES colleagues Larry Lawver and Mike Coffin for valuable contributions and discussions. We thank Lars Stemmerik, Jörg Trappe and Gregers Dam for reviewing the paper and for discussions.

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