

# Iceland hotspot track

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## ABSTRACT

We use a model of plate motions relative to major hotspots underneath the African, Indian, North American, South American, and Australian plates to compute the track of the Iceland hotspot after 130 Ma. The present-day hotspot is located under eastern Iceland offset about 240 km east of the Reykjanes and Kolbeinsey ridges. At 40 Ma, the Kangerlussuaq region of East Greenland would have been directly above the hotspot. The anomalous postdrift uplift of the East Greenland margin can also be explained by passage of the rifted margin over a hotspot. At 60 Ma, the Umanak Fjord region of the west coast of Greenland was above the hotspot, where picrites and hyaloclastites of nearby Disko Island are dated at ~64 to 59 Ma. Our reconstruction shows Ellesmere Island above the hotspot between 130 and 100 Ma. Latest Albian to early Cenomanian volcanic rocks on Axel Heiberg Island and northern Ellesmere Island indicate a nearby hotspot at that time. At 130 Ma, our model locates the hotspot near the northern margin of Ellesmere Island, close to the intersection of the Alpha Ridge with the coast. The hotspot would have been located beneath the Arctic Alaska–Chukotka plate when it formed the Mendeleev Ridge, and as the spreading center migrated over the hotspot, it transferred to the North American plate, where it formed the Alpha Ridge. Our model suggests that the initiation of the Iceland hotspot predates the opening of the North Atlantic by at least 70 m.y. and that the massive early Tertiary volcanism along the North Atlantic plate margins reflects the effect of rifting in the vicinity of existing thinned crust, rather than the arrival of a plume head.

## INTRODUCTION

Iceland constitutes the location of one of the major mantle hotspots found on Earth. However, the hotspot's path is not documented by a continuous volcanic chain with an associated age progression as is true elsewhere—e.g., Hawaii. During most of the early Tertiary, the Iceland hotspot may have been located beneath Greenland, where, because of thick inland ice cover, only rock outcrops near the coast are accessible. Morgan (1981) proposed that the track started at 55 Ma with the Skaergaard basalts at the east coast of Greenland. In a following paper, Morgan (1983) presented an Iceland hotspot track that starts in northwest Greenland at 90 Ma, but did not discuss geologic implications. Forsyth et al. (1986) suggested for the first time that the Alpha Ridge in the Arctic Ocean might be an early expression of the Iceland hotspot. They suggested a hotspot path roughly similar to Morgan's (1983) track, on the basis of the 50 and 60 Ma positions of the Iceland plume from Vink (1984) and the 68 and 80 Ma positions based on a plate model from Bernero et al. (1985) (Fig. 1). Müller et al. (1993) have used dated volcanic hotspot tracks from the North American, South American, African, and Indian-Australian plates to construct a series of best-fit plate rotations relative to present-day hotspots. In this paper, we attempt to reconstruct the Iceland hotspot's path for the past 130 m.y. by keeping it fixed relative to those used in the Müller et al. model. The computed path for the Iceland hotspot, summarized in 10 m.y. intervals (Fig. 1), is significantly different from previously proposed Iceland hotspot tracks.

## ICELAND HOTSPOT TRACK

The Iceland hotspot is now located at approximately lat 64°N, long 16°W, on the basis of a combination of earthquake data (Einarsson, 1991), seismic crustal structure data (Flóvenz and Gunnarsson, 1991), and the location of the eastern zone of intraplate volcanism (Oskarsson et al., 1985). That place is 240 km east of the trace of the North American–Eurasian plate boundary (Fig. 1) that would connect the Reykjanes Ridge in the North Atlantic with the Kolbeinsey Ridge in the Norwegian–Greenland Sea. The active plate boundary on Iceland appears to be displaced about 150 km to the east at the eastern rift zone (Oskarsson et al., 1985), but the western zone of intraplate volcanism

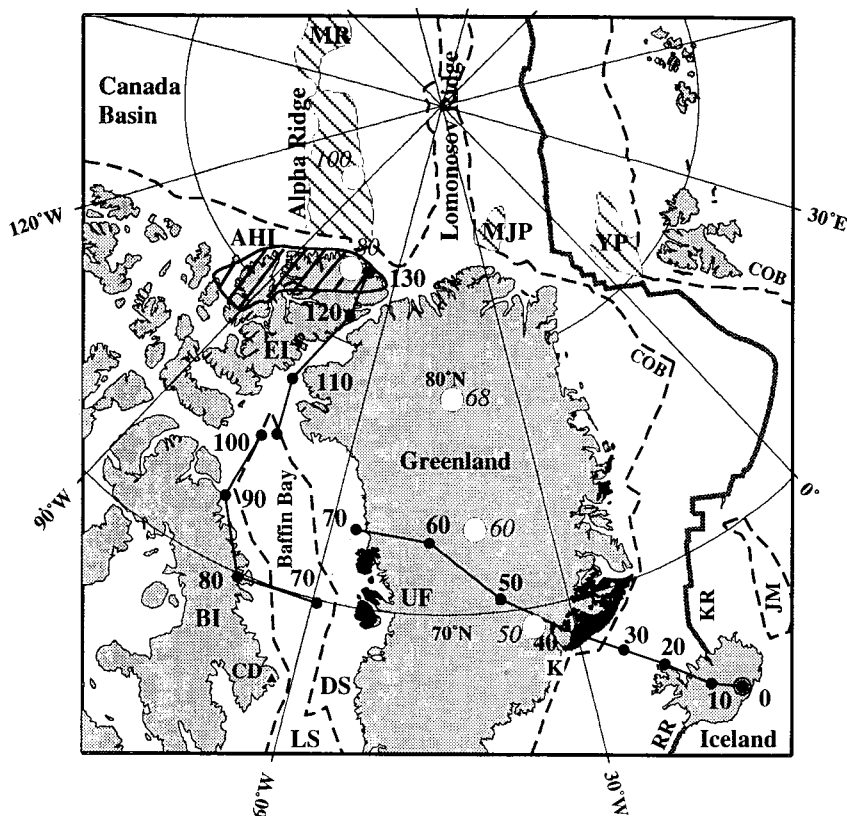


Figure 1. Synthetic hotspot track (North American plate fixed through time). Solid dots show paleoposition of hotspot every 10 m.y. AHI—Axel Heiberg Island; BI—Baffin Island; CD—Cape Dyer; DS—Davis Strait; EI—Ellesmere Island; JM—Jan Mayen; K—Kangerlussuaq, East Greenland; KR—Kolbeinsey Ridge; LS—Labrador Sea; MJP—Morris Jessop Plateau; MR—Mendeleev Ridge; RR—Reykjanes Ridge; UF—Umanak Fjord, West Greenland; YP—Yermak Plateau; COB—continent-ocean boundary based on bathymetry. Dotted track between 70 Ma positions indicates that new sea floor was created after passage over hotspot. All ages referred to are based on time scale of Kent and Gradstein (1986). Open circles indicate plume positions proposed by Forsyth et al. (1986).

may be symptomatic of a westward shift of the present plate boundary back to a straight-line connection between the Reykjanes and Kolbeinsey ridges when the influence of the hotspot is no longer felt.

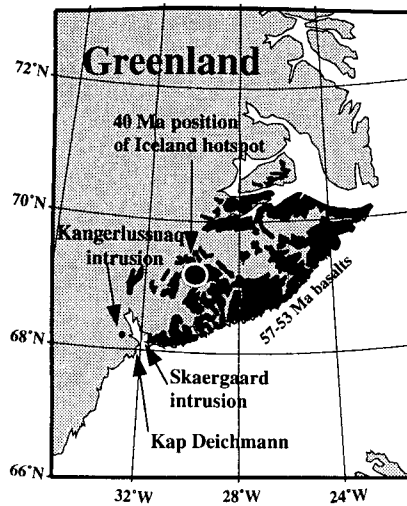
Relative plate rotations tabulated by Lawver et al. (1990) have been used to reconstruct motions of the plates over a fixed Iceland hotspot (Fig. 1). The Iceland hotspot would have been located beneath the eastern margin of Greenland at 40 Ma and the western margin at 60 Ma. Two separate locations are shown for the 70 Ma position, where the distance between the two points is equivalent to the post-70 Ma separation between Baffin Island and Greenland caused by Labrador Sea and Baffin Bay opening (Roest and Srivastava, 1989). Similarly, two locations are shown for the hotspot's 100 Ma position, reflecting subsequent separation of the hotspot path by relative motion between Baffin Island and Ellesmere Island in the Tertiary (see Lawver et al., 1990). For the 130 to 100 Ma time period, the computed path of the Iceland hotspot crosses southern Nares Strait and Ellesmere Island.

At 130 Ma, the northern margin of Ellesmere Island, opposite the Alpha Ridge, would have been over the hotspot. The idea that the Alpha Ridge was produced by the action of a hotspot was first suggested by Vogt et al. (1979), who noted a similarity to Iceland. Lawver et al. (1983) proposed that the Mendeleev and Alpha ridges were formed by a hotspot that started on the Siberian side, and as the ridge passed over the hot spot, the trace transferred to the North American plate. Forsyth et al. (1986) suggested that the hotspot that formed the Alpha Ridge continued under Greenland and is the present Iceland hotspot.

The pre-chron 34 (84 Ma) part of our proposed Iceland hotspot track is subject to large uncertainties, in particular because relative plate rotations for the Cretaceous magnetic normal superchron must be linearly interpolated between 118 and 84 Ma. Given these limitations, uncertainties of our model accuracy are likely to be at least as large as 5° of latitude and 10° of longitude for the pre-84 Ma part of the track.

### VOLCANIC ROCKS

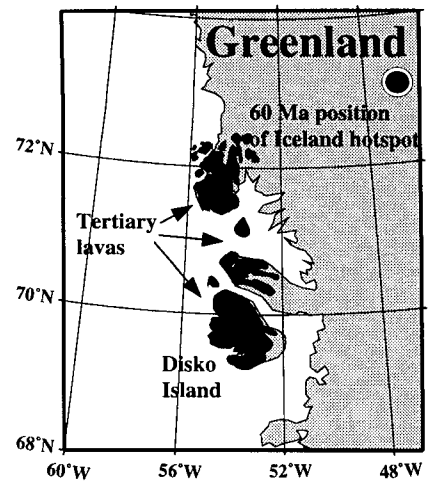
As summarized in Noble et al. (1988), the East Greenland basalts were extruded between 57 and 53 Ma from high-level magma chambers onto thinned continental crust, from a linearly elongate off-shore source. Figure 2 (modified from Noble et al., 1988) shows the Kangerlussuaq (new spelling) and Skaergaard intrusions of eastern Greenland as being nearly over the hotspot at 40–35 Ma. Those two intrusions are dated at 50



**Figure 2. Generalized geology of East Greenland showing distribution of main intrusive centers along Blossville Kyst; black indicates intrusive centers, gray indicates extrusive basalts. Kangerlussuaq intrusion is dated at 50 Ma. Kap Deichmann is 40 Ma quartz syenite. Large black dot is 40 Ma paleoposition for Iceland hotspot. Figure is modified from Noble et al. (1988).**

Ma, but there are younger intrusions, in particular the main intrusion of the Kap Deichmann quartz syenite dated at 39.8 Ma and the inland Borgtinderne nepheline syenite, 45 km from the coast, dated at  $44.6 \pm 2.5$  Ma (Noble et al., 1988). The linear elongate nature of the extrusive basalts is most easily explained by normal passive rifting of thinned continental crust, whereas the later syenites might be explained by an anomalous thermal source in the upper mantle partially melting the granitic crust.

On the west coast of Greenland near Disko Island (Fig. 3) are large outcrops of primitive picritic lavas (Clarke, 1970) and hyaloclastites that cover 55 000 km<sup>2</sup> to a depth of 1–2 km (Gill et al., 1992). A total of 694 m of subaerially extruded weathered lava flows (Rollo, 1985) were cored in the Hellefisk 1 well (lat 67°53'N, long 56°44'W). Their chemistry is nearly identical to that of the oldest Disko Island member (Holm et al., 1993), and if they are included as West Greenland basalts, then the basalts may cover an area almost twice as large. The oldest exposed volcanic rocks are preserved in a hyaloclastite facies (Larsen et al., 1992) with a nannoplankton zone age of NP3 (64.4 Ma; Berggren et al., 1985). Larsen et al. (1992) concluded that the main plateau-building phase in West Greenland occurred between NP3 and NP8 (59.5 Ma), magnetic polarity chrons C27R to C25R (64.29 to 58.64 Ma; Kent and Gradstein, 1986). Gill et al. (1992) found that the olivine composition



**Figure 3. Sketch map of West Greenland coast between 68° and 74°N, showing distribution of subaerial and submarine Tertiary lavas (after Clark, 1970). Large black dot is 60 Ma Iceland hotspot location in fixed North American absolute framework. Figure is modified from Dickin (1988).**

of the West Greenland picritic liquid had a content of MgO as high as 20%, which implies that the asthenospheric potential temperature was as high as 1480 °C. The entire West Greenland sequence was extruded over a period of 5 to 6 m.y., and the high heat input required to generate the picrites was sustained for 3.5–4.5 m.y. (Larsen et al., 1992). Gill et al. (1992) noted the relatively minor volume of picrites in East Greenland and the North Atlantic volcanic province and concluded that the voluminous, unusually magnesian picritic lavas of West Greenland are more consistent with formation directly above a hotspot rather than on the cool periphery of a mantle plume as suggested by White and Mackenzie (1989). The White and Mackenzie (1989) model for a mantle plume, based on the Courtney and White (1986) model, predicts significantly cooler lithosphere on the edge of the mantle plume (–100 to –300 °C relative to the center of the plume), inconsistent with the 1480 °C temperature found for the West Greenland lava flows. The West Greenland lavas were at a distance of ~800 km from the assumed site of the White and Mackenzie (1989) mantle plume beneath East Greenland, and they erupted 5 to 7 m.y. before the East Greenland basalts, thought by White and Mackenzie (1989) to be directly over the center of the plume.

There are early Tertiary age basalts along Cape Dyer on the southeastern margin of Baffin Island (Clarke and Upton, 1971) that resemble the West Greenland lavas in age, stratigraphic position, and magma type. The flows are picritic and olivine rich. Hyndman

(1973) was the first of many to suggest that thicker crust in Davis Strait, as compared to that in the Labrador Sea and Baffin Bay, was evidence of having been influenced by a hotspot.

On northern Ellesmere Island and on Axel Heiberg Island, flood basalts up to 1 km in thickness within the Strand Fiord formation (Ricketts et al., 1985), tentatively dated as late Albian to early Cenomanian (105–95 Ma) on the basis of palynological studies (Embry and Osadetz, 1988), might reflect an early expression of the Iceland hotspot, although our model path shows a more southern location of the hotspot during this time south of Ellesmere Island (Fig. 1). However, we must keep in mind that this part of our proposed Iceland hotspot track is subject to larger uncertainties than the post-84 Ma track.

#### CANADA BASIN

The tectonic origin of the Canada Basin has been discussed by numerous authors (see Lawver and Scotese, 1990, for a summary), and there is still much controversy as to its age. Early aeromagnetic data (Taylor et al., 1981) showed magnetic anomalies of very low amplitude. Embry and Dixon (1990) reported subsidence results that placed the time of the breakup unconformity for the Canada Basin at late Albian (~100 Ma), but Embry (1994) recently reinterpreted the same results to be Hauterivian to Barremian (~125 Ma). He placed the initiation of rifting as early as Bajocian (~180 Ma), but surmised that actual sea-floor spreading did not start until the late Hauterivian. The reversal stratigraphy and paleomagnetic pole position of the Kuparuk River Formation suggest that the North Slope was still adjacent to the Sverdrup Rim at about anomaly M11 time (133 Ma), but that rifting commenced shortly thereafter (Halgedahl and Jarrard, 1987). Lawver and Baggeroer (1983) estimated the age of the Canada Basin as 90–125 Ma on the basis of heat flow vs. age, depth vs. age, and surrounding geology. Passage of this region over the Iceland hotspot might have triggered the sea-floor spreading that led to the formation of the Canada Basin.

Jackson et al. (1986) have shown that the northeast Alpha Ridge has morphological features, seismic crustal structure, rock types, heat flow, and magnetic and gravity signatures that are similar to several large oceanic plateaus in the Pacific. Asudeh et al. (1988) have analyzed seismic refraction results from the Canadian Expedition to Study the Alpha Ridge (CESAR) experiment and have found a striking similarity between the structure of the Alpha Ridge and Iceland and

parts of the Hawaii-Emperor seamount chain. They therefore have concluded that the Alpha Ridge complex is an Icelandic-type structure generated by mantle plume activity.

#### UPLIFT OF NORTH ATLANTIC MARGINS

The mantle plume model of White and Mackenzie (1989) predicts ~500 m of uplift of rifted margins associated with mantle that is 100 °C hotter than normal and ~1000 m of uplift for mantle 200 °C above normal. However, Stuevold et al. (1992) found little evidence along the Vøring margin for regional uplift during early Tertiary formation, although the stratigraphy and composition of the sedimentary units imply a later, predominantly Neogene continental uplift. Holm et al. (1992) stated, "No thermal doming took place in East Greenland before or during continental break-up, and the East Greenland rifting is considered to have been passive." In fact, Joy (1992) and Larsen and Marcussen (1992) discussed an increase in subsidence along the East Greenland margin around the end of the Paleocene that resulted in seaward-dipping reflectors.

Larsen (1990, Fig. 4) showed the post-Paleocene uplift along most of the East Greenland margin to be ~2 km, and in one instance it was >5 km. Larsen (1990) did not know the exact timing of the uplift but indicated that it may have accelerated in the late Oligocene. Larsen and Marcussen (1992) stated that the present-day high elevation of the Scoresby Sund early Tertiary age basalts has been produced by a large regional uplift of the margin that postdated the North Atlantic breakup by 20 m.y. or more. On the basis of seismic stratigraphy, fission-track data, thermal maturity data, geomorphology, and geology, the highest uplift (Larsen, 1990) is near Kangerlussuaq, very close to the 35 Ma location of the Iceland hotspot shown in Figure 2.

In West Greenland, magmatism started at least 4 m.y. and possibly as much as 6 m.y. prior to rifting in the North Atlantic: such timing is not consistent with greatest uplift directly over a mantle plume presumably located 800 km to the east (Holm et al., 1992). In addition, the oldest picritic Tertiary lavas found in western Greenland are mounds of pillow breccias and hyaloclastites that were erupted directly into an aqueous environment (Larsen et al., 1992). The youngest lavas are subaerial and are even found overlying crystalline basement in eastern Nuussuaq (new spelling) (Pedersen and Larsen, 1987), indicating uplift rather than subsidence during emplacement. The only way that Holm et al. (1993) could explain their

geochemical results for West Greenland picrites was to propose a second plume under West Greenland at the same time that the Iceland plume was presumably causing North Atlantic breakup. Our model suggests instead that the Iceland hotspot was not under the North Atlantic but under West Greenland at that time, so there is no need for a second plume.

#### CONCLUSIONS

An updated model for motion of the Australian, Indian, African, and North and South American plates relative to present-day hotspots, using well-dated continuous hotspot tracks, allows us to compute a hotspot track for the Iceland hotspot. The track is in good agreement with dated Paleogene volcanic rocks on Greenland and Baffin Island and latest Aptian to early Cenomanian volcanic rocks on Axel Heiberg and Ellesmere islands. The position of the hotspot at 40 Ma underneath eastern Greenland helps explain anomalous postdrift uplift of the East Greenland margin (Larsen and Marcussen, 1992).

Thick late Cenomanian to Maastrichtian volcanic rocks on northern Ellesmere Island are younger than the time of our computed hotspot position for this area (130–110 Ma). This discrepancy may reflect larger uncertainties of the pre-100 Ma part of the hotspot trace, since our plate model is constrained by only two hotspot tracks for the time period 130–100 Ma. If the 130 Ma position of the Iceland mantle plume was not beneath northern Ellesmere Island, as shown by our track, but farther northward, it could explain generation of the Alpha and Mendeleev ridges as hotspot tracks during a post-chron M-11 (133 Ma) rotational opening of the Canada Basin, as proposed by Halgedahl and Jarrard (1987).

The modern location of the hotspot, 240 km east of the Reykjanes and Kolbeinsey ridges, indicates that it has not been captured by the Mid-Atlantic Ridge and that the westward motion of the Eurasian-North American plate boundary with respect to the mantle has continued unaffected by the Iceland hotspot. Although the early Iceland hotspot has not left a complete volcanic trace, the presence of the Alpha and Mendeleev ridges, Lower to middle Cretaceous volcanic rocks on Axel Heiberg and Ellesmere islands, and the geometry of our computed hotspot track give evidence that the "Iceland plume" may be at least twice as old as initial opening of the northernmost North Atlantic.

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