

Interlinking the Hotspot Track in the Arctic and its Implications for Paleo-plate Reconstruction

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Abstract: The Siberian–Icelandic hotspot track is the only preserved continental hotspot track. Although the track and its associated age progression between 160 Ma and 60 Ma are not yet well understood, this section of the track is closely linked to the tectonic evolution of Amerasian Basin, the Alpha-Mendeleev Ridge and Baffin Bay. Using paleomagnetic data, volcanic structures and marine geophysical data, the paleogeography of Arctic plates (Eurasian plate, North American Plate, Greenland Plate and Alaska Microplate) was reconstructed and the Siberian–Icelandic hotspot track was interlinked between 160 Ma and 60 Ma. Our results suggested that the Alpha-Mendeleev Ridge could be a part of the hotspot track that formed between 160 Ma and 120 Ma. During this period, the hotspot controlled the tectonic evolution of Baffin Bay and the distribution of mafic rock in Greenland. Throughout the Mesozoic Era, the aforementioned Arctic plates experienced clockwise rotation and migrated northeast towards the North Pacific. The vertical influence from the ancient Icelandic mantle plume broke this balance, slowing down some plates and resulting in the opening of several ocean basins. This process controlled the tectonic evolution of the Arctic.

Key words: hotspot track, large igneous province, paleogeography reconstruction, Alpha-Mendeleev ridge, the Arctic

1 Introduction

The hotspot hypothesis envisages the feeder structures to be fixed relative to one another, with the continents and seafloor drifting overhead (Morgan 1981). The hypothesis predicts that time-progressive chains of volcanoes develop on the surface. Hotspot tracks have always been used to track the movement of Earth's tectonic plates (Bryan and Ernst, 2008). The Siberian–Icelandic hotspot track is the only preserved hotspot track on earth. However, the track is not documented by a continuous volcanic chain with an associated age progression, as is true elsewhere e.g. the Emperor-Hawaii seamount chain. For the most part, the Icelandic hotspot has been beneath the continental crust, which has a larger crustal thickness compared to oceanic crust (Morgan 1981). The complex tectonic evolution of the Arctic Ocean made the track more complicated (Lewchuk 2004).

Abundant research on the Icelandic hotspot has been

undertaken. Morgan (1981) proposed that the track started at 55 Ma with the Skaergaard basalts on the east coast of Greenland. In a follow-up paper, Morgan (1983) presented an Icelandic hotspot track starting in Northwest Greenland around 90 Ma but did not discuss the geological implications. Forsyth et al. (1986) were the first to suggest that the Alpha-Mendeleev Ridge in the Arctic Ocean might be an early expression of the Icelandic hotspot. Based on deep geodynamic and paleomagnetism research, Lawver and Muller (1994), Lawver et al. (2002) and Kuzmin et al. (2010) suggested that the Icelandic hotspot was located under the Siberian trap area at the Permo–Triassic boundary. Furthermore, presently the Icelandic hotspot is situated above the African large low-shear-velocity province (LLSVP) indicating that the Siberian plate was above the African LLSVP around 250 Ma.

There remains much debate regarding how to resolve the Icelandic-Siberian hotspot track anomaly that manifested during the period between 160 Ma and 60 Ma (Lundin and Doré, 2004; Kuzmin et al., 2010). It is likely

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that this uncertainty is closely linked to the tectonic evolution of Amerasian Basin, the Alpha–Mendeleev Ridge and Baffin Bay.

Thus, based on volcanic geological and paleomagnetic data, combined with plate kinematics, this paper attempts to reconstruct the Icelandic–Siberian hotspot track, especially between 160 Ma and 60 Ma. This may provide new insight into the tectonic evolution of Amerasian Basin and the Baffin Bay as well as the geological origins of the Alpha–Mendeleev Ridge.

2 Geological Settings

2.1 Siberian Traps

The Siberian Traps represent the largest continental flood basalt province, though estimates vary significantly, and they have been linked to the late-Permian extinction, the largest known mass extinction (Wignall, 2001). The Siberian Traps large igneous provinces (LIPs) located on both the Siberian craton and in the West Siberian Basin are $3.4 \times 10^5 \text{ km}^2$ and $1.5 \times 10^5 \text{ km}^2$ in size, respectively (Fig. 1a, Wignall, 2001). These estimates do not include the Kara and Barents undersea basins. The volume of this LIP could be as much as $4 \times 10^6 \text{ km}^3$, though the post-erosion volume is only 10% of the original (Courtillet et al., 1999). U–Pb ages of basalt show that this magmatism started around $251.7 \pm 0.4 \text{ Ma}$ and ended around $251.1 \pm 0.3 \text{ Ma}$ (Kamo et al., 2003).

Deep boreholes and seismic sections reveal that similar basaltic lavas are buried deep within the West Siberian Basin (Reichow et al., 2002; Reichow et al., 2009). The basin is filled with a thick sequence of Triassic continental and Jurassic and Cretaceous marine, sedimentary rocks. From seismic studies and deep boreholes, the basalt sequences are at least 2 km thick in the rifts (Reichow et al., 2002). The rifts are associated with high magnetic intensity, consistent with thick accumulations of basaltic rocks. Those characteristics lead one to believe that the centre of the Siberian Traps LIP is located in the West Siberian basin instead of the Siberian craton (Fig. 1).

2.2 High Arctic Large Igneous Province

The Alpha–Mendeleev Ridges form a bathymetrically contiguous (2500 m depth contour), 1700 km long and 200–700 km wide feature between the Makarov–Podvodnikov and the Canadian basins. This is also one of the least studied parts of the Arctic owing to extremely heavy pack ice preventing shipborne expeditions. Multichannel seismic reflection data reveals large-scale normal faulting across the Mendeleev Ridge flanks (Dove et al., 2010). Gravity modelling indicates a maximum crustal thickness of 32 km beneath the Alpha–Mendeleev

Ridge crest, with crustal thinning along both slopes; no lateral heterogeneity is required to reproduce the observed anomalies (Dove et al., 2010). This is consistent with the results of Russian seismic refraction experiments (Poselov et al., 2011) that imaged the crust–mantle boundary for 32 km along the ridge crest. This ridge crust is four times thicker than normal oceanic crust. When comparing the Alpha–Mendeleev Ridge to typical intra oceanic volcanic provinces such as the Ontong Java Plateau (Gladchenko et al., 1997) and the Mozambique Ridge (Gohl et al., 2011), we found similar velocities and magnetic structures. Interpretations of coherent sub-basement reflectors (Pease et al., 2014) are ambiguous, suggesting volcanic flows, lithified Mesozoic or older sediments, or sediments intercalated with basalt flows as is commonly observed in oceanic plateau environments (Berger et al., 1992). All the evidence above suggests that the formation of the Alpha–Mendeleev Ridges was related to hotspots.

Magnetic data reveals that the Alpha–Mendeleev Ridges formed during the Cretaceous normal quiet period (Weber and Sweeney, 1990) constraining the Alpha–Mendeleev Ridges to a mid–late Cretaceous age (120–87 Ma). Aeromagnetic and aero-gravity data (Døssing et al., 2013a, 2013b) revealed numerous Lower Cretaceous (~138–120 Ma) giant dyke swarms in Franz Josef Land and Queen Elizabeth Islands (Liu Zhonglan et al., 2016). The swarms point towards a 250 km wide doughnut-shaped anomaly on the southern Alpha–Mendeleev Ridge, indicating that the centre of the High Arctic Large Igneous Province (HALIP) mantle plume was located at the southern end of the Alpha–Mendeleev Ridge.

In addition to the Alpha–Mendeleev Ridges, the igneous rocks in Svalbard and Franz Josef Land are also considered to be related to HALIP. Diabasodden Suite, an extensive system of predominantly basic intrusive doleritic rocks, represents the HALIP in Svalbard and Franz Josef Land. Two main igneous centres have been proposed: (1) Central Spitsbergen and (2) the eastern Svalbard dolerite belt (Senger et al., 2014). Modern radiometric dating (U–Pb) on three samples suggests a shorter-lived intrusion pulse at ca. 124.5 Ma (Corfu et al., 2013).

2.3 Iceland magmatism

Iceland is one of the most active volcanic regions in the world, with eruptions occurring on average roughly every three years. The Iceland Basalt Plateau is situated at the junction of two large submarine physiographic structures, the Mid–Atlantic Ridge and the Greenland–Iceland–Faroe Ridge (Fig. 1c). It rises more than 3000 m above the surrounding sea floor, has a crustal thickness of 10–40 km and covers about 350,000 km² (Gudmundsson, 2000). About 30% of this area (~103,000 km²) is above sea level,

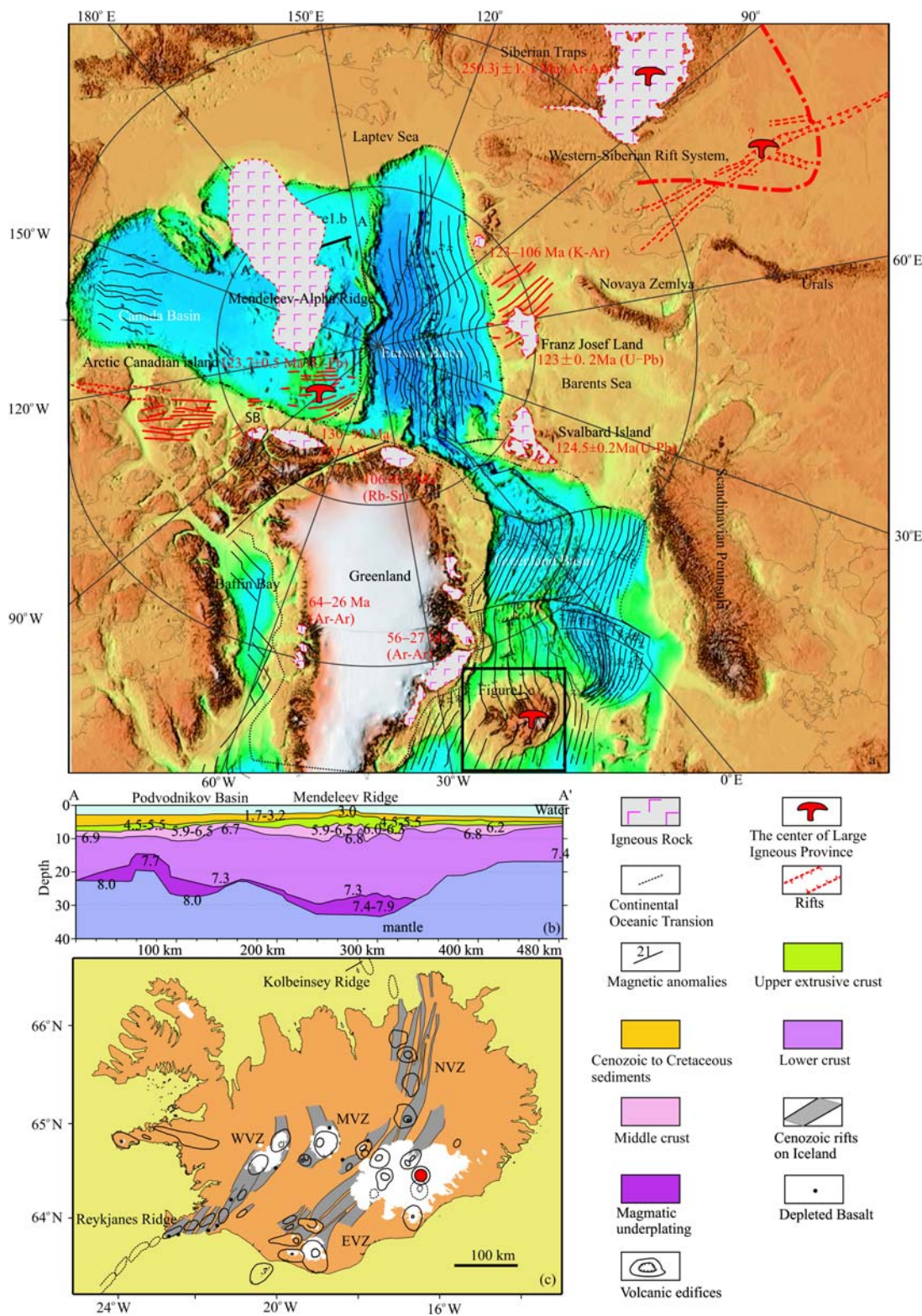


Fig. 1. Volcanic structure of the study area (Bathymetric data after Li Jianghai et al., 2016a; Magnetic anomalies after Grantz et al, 2011; Mafic dyke surrounding the Alpha Ridge after Døssing et al., 2013a; Geochronologic data of magmatism: Siberian Trap after Reichow et al., 2009; Delong island, Franz Josef Land and Svalbard after Senger et al., 2014 and Corfu et al., 2013; Arctic Canadian island after Jowitt et al., 2014; North Greenland after Tegner et al., 2011; and East and West Greenland after Henriksen et al., 2000. Lithospheric structure of the Mendeleev after Pease et al., 2014; Volcanic edifices on Iceland after Thordarson and Larsen, 2007; and Depleted Basalt ($Nb/Zr < 0.06$) after Fitton et al., 2002). (a), Distribution of igneous rock and mafic dykes; (b), Lithospheric structure of the Mendeleev Ridge. Digits signify seismic velocities in $km\ s^{-1}$; (c), Cenozoic magmatism on Iceland. WVZ, Western Volcanic Zone; MVZ, Mid-Iceland Volcanic Zone; NVZ, Northern Volcanic Zone; EVZ, Eastern Volcanic Zone.

and the remainder forms the 50–200 km wide shelf around the island.

The development of the Iceland Basalt Plateau is considered by most to be the product of an interaction between a spreading plate boundary and a mantle plume (Vink, 1984; White et al., 1995; Bjarnason et al., 1996). From seismic refraction data, the centre of the present Iceland hotspot is located at 64°N, 16°W (Einarsson, 1991), approximately 240 km away from the Kolbeinsey Ridge and the Reykjanes Ridge. The development is thought to have begun about 24 Ma, although the oldest rocks exposed on land in Iceland are only 14–16 million years old (Thordarson and Larsen, 2007). The Iceland mantle plume has been active for the last 65 million years and formed the ~2000 km long North Atlantic Igneous Province (NAIP), including Iceland which is the only remaining active part (Thordarson and Larsen, 2007).

The current distribution and arrangement of active volcanism in Iceland results from the superposition of the spreading plate boundary over the Iceland mantle plume as well as the relative motion of these two structures. The surface expressions of this interaction are the neovolcanic zones, discrete 15–50 km wide belts of active faulting and volcanism (Fig. 1c). These volcanic zones include northern (NVZ), mid-Iceland (MVZ), western (WVZ) and eastern (EVZ) volcanic rift zones.

3 Methods and Results

3.1 The absolute position of the Alaska Microplate between 160 Ma and 120 Ma

The absolute paleoposition of the Alaska Microplate is important for understanding tectonic evolution during the Mesozoic in the Arctic. Paleomagnetic data is useful for determining paleo-latitude and azimuth angle but not for reconstructing paleo-longitude. For a major plate, such as the American Plate, its paleo-longitude can be constrained by the seafloor magnetic anomaly that occurred during Mesozoic and Cenozoic Era (Li et al., 2008; Golonka, 2011). However, the paleo-latitude and absolute paleoposition of the Alaska Microplate have yet to be confirmed (Lewchuk, 2004; Kuzmichev, 2009). This study aims to determine the absolute paleoposition of the Alaska Microplate including the paleo-latitude using Paleomagnetic data and the paleo-longitude using the relationship between hotspot and intraplate magmatism.

Applying the V90 criterion (Van der Voo, 1990), we

used paleomagnetic data for the Alaska Microplate during the 200–100 Ma period, with a quality factor of $Q \geq 3$ (Table 1). When using paleomagnetic data at a single time node to reconstruct a plate position, it is necessary to use either the North Pole or the South Pole as the reference point for the projection (Wang Honghao et al., 2016). Based on a previous study by Lewchuk, (2004), we used the North Pole as the projection reference point. In addition, we split the paleomagnetic data into 10 Ma spacings using Gplate software (Boyden et al., 2011).

Magnetic data reveal lots of Lower Cretaceous (~138–120 Ma) mafic dyke swarms in the southern Alpha-Mendelev Ridge, Franz Josef Land and the Queen Elizabeth Islands (Døssing et al., 2013a, 2013b; Hamilton, 2016). The swarms point towards a 250 km wide doughnut-shaped anomaly and suggest that the centre of the HALIP mantle plume was located at the southern Alpha-Mendelev Ridge during the Lower Cretaceous (~138–120 Ma) (Fig. 1, Section 2.2). Furthermore, the Alpha-Mendelev Ridge was formed between 130 Ma and 140 Ma (Pease et al., 2014) and dissociated the Alaska Microplate from the American Plate at the same time. Thus, the northern part of the Alaska Microplate must have been near the Iceland mantle plume before the Alpha-Mendelev Ridge formed.

Paleomagnetic data was used to fix the latitude of the Alaska Microplate around 160 Ma at 65°N. Combined with the relationship between hotspots and intraplate magmatism, we confirmed the absolute paleoposition of the Alaska Microplate at 65°N, 18°W (Fig. 2). We recognize that the Alaska Microplate and the Alpha-Mendelev Ridge were an ensemble around 120 Ma, thus confirming its relative location between the Alaska Microplate and the Iceland hotspot (Fig. 2). As for 130 Ma, 140 Ma and 150 Ma, the relative location between the Alaska Microplate and the Iceland hotspot could be determined assuming a constant motion of the Alaska Microplate.

3.2 The absolute position of the Greenland Plate between 100 Ma and 40 Ma

With the continuous northward motion of the Pangea continent, the influence of the Iceland mantle plume on the Alaska Microplate gradually decreased after 120 Ma. However, the Iceland mantle plume effect on Greenland started after 100 Ma. Less debate surrounds the paleo-latitude of the Greenland Plate compared to the location of

Table 1 Pale Magnetism data of Alaska Microplate from 160 Ma to 100 Ma

Number	Age	Lithology	Dec	Inc	α_{95}	Plat	Plon	Ref.
a	160 Ma	Basalt	354.6	86.3	6.1	59.8	166.8	Lewchuk, 2004
b	100 Ma	Intrusive rock	228.8	84.3	3.0	56.5	197.1	Symons et al., 2009
c	126 Ma	Silt	218.2	76.9	7.5	34.6	105.3	Lewchuk, 2004

Note: Dec = declination in stratigraphic, Inc = inclination in stratigraphic, Plat = paleolatitude, Plon = paleolongitude.

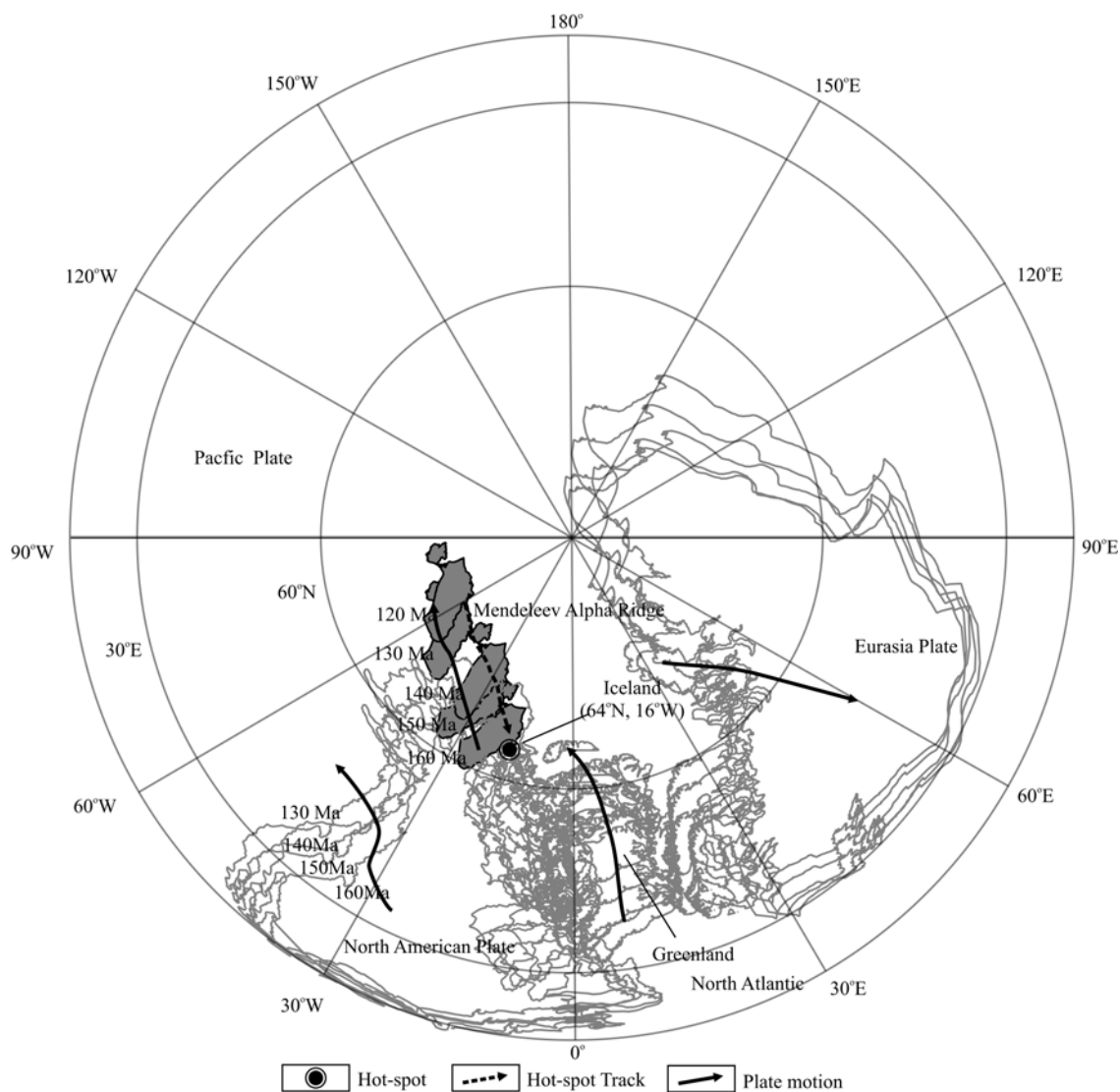


Fig. 2. Icelandic Hotspot Track during 160–120 Ma, and its relationship with the tectonic evolution of the Canada Basin (stereographic polar projection).

The paleo-latitudes of the Alaska Microplate were solved from Table 1, while its paleo-longitudes were defined from the relationship between igneous rock distribution and hotspot location. The paleogeography of the North American Plate, the Eurasian plate and the Greenland Plate after Torsvik and Cocks, 2013.

the Alaska Microplate. Thus, this study directly used the results of the paleo-latitude provided by Torsvik and Cocks (2013). We ascertain the paleo-longitude of the Greenland plate from the relationship between hotspots and intraplate magmatism just like for the Alaska Microplate (section 3.1).

Paleomagnetic data show that the Greenland plate moved northward between 100 Ma and 60 Ma and its paleo-latitude decreased with time (Torsvik and Cocks, 2013). The distribution of magmatism (Fig. 1) indicates that the Greenland plate did not move in a longitudinal direction (Fig. 3). The Iceland mantle plume forced the Greenland Plate departure from the American plate and created the opening of Baffin Bay around 92 Ma (Roest and Srivastava, 1989). Between 60 Ma and 40 Ma, the

Greenland plate moved quickly westward causing Baffin Bay to stop spreading (Storey et al., 1998). Numerous mafic magmatisms ageing between 50 Ma and 40 Ma were found at the eastern margin of Greenland (Funk et al., 2011). These magmatisms also reveal the fast movement of the Greenland plate. A new study researching the heat flow of Greenland indicates that this velocity can reach up to 11 cm/yr. (Rogozhina et al., 2016).

4 Discussions

4.1 Hotspot track and tectonic evolution of the Canadian Basin

There remains much debate concerning the tectonic evolution of the Arctic Ocean (Lawver et al., 2002;

Kuzmichev, 2009). Despite using an accepted two-phase evolution model of the Eurasian and Amerasian Basins, the tectonic evolution of the Amerasian Basin is still unclear. Previous tectonic evolution models of the Amerasian Basin include the following (Li Jianghai et al., 2016a, 2016b): 1) a rotational transform model (Miller et al., 2010; Lawver et al., 2002); 2) a polygonal rotation model (Kuzmichev, 2009); and 3) a back-arc model (Miller et al., 2010). Thick sediments from the Mackenzie Delta exhibit disturbance by the HALIP indicating that the magnetic anomaly from the Canadian Basin cannot clearly constrain the tectonic evolution of the Amerasian Basin.

Our absolute paleoposition results include paleolatitude, derived from paleomagnetic data, and paleolongitude, derived from the relationship between

magmatism and mantle plume. Between 160 Ma and 120 Ma, the Alaska Microplate moved northward and rotated anticlockwise by 60°. These results are in agreement with findings from a previous study by Symons et al. (2009). As the Alaska Microplate moved northward and rotated anticlockwise, the Alpha-Mendelev Ridge formed on the outside boundary (far from the Mackenzie Delta) of the microplate, while the triangular Canadian Basin formed simultaneously. This model can successfully explain the inactive ridge structure in the magnetic anomaly map (Jakovlev et al., 2012). Due to the anticlockwise rotation, a slip fault occurred on the Eurasian Plate. Those faults can still be found on the Lomonosov Ridge (Pease et al., 2014). Thus, our results support the rotational transform model, which states that the Amerasian Basin formed

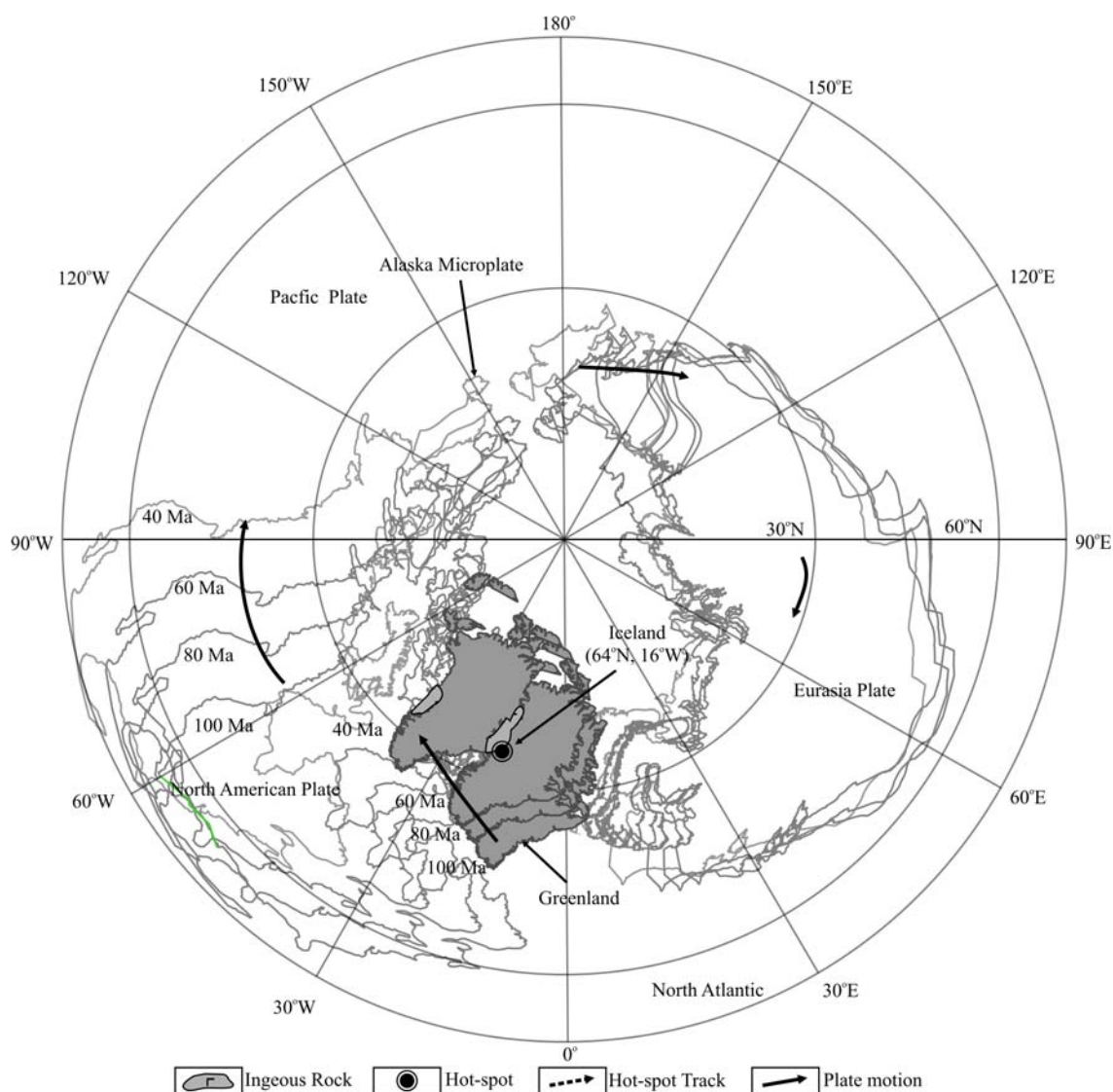


Fig. 3. Iceland Hotspot Track during 100–40 Ma and its relationship with the tectonic evolution of Baffin Bay (stereographic polar projection).

The paleogeography of the North American Plate and the Eurasian plate after Torsvik and Cocks, 2013. The paleo-latitude of the Greenland plate after Torsvik and Cocks, 2013. The paleo-longitude of the Greenland plate was defined from the relationship between igneous rock distribution and hotspot location.

during the Alaska Microplate anticlockwise rotation and departure from the American plate.

4.2 Hotspot track and plate motion

The Siberian–Icelandic hotspots have affected the tectonic evolution of the Amerasian Basin, Baffin Bay and the North Atlantic Ocean. Furthermore, the hotspot track crossed multiple plate boundary and recorded the plate motion of the Siberian plate, the Alaska Microplate and the North American Plate (Fig. 4).

Between 160 Ma and 120 Ma, under the influence of the Iceland mantle plume and the anticlockwise rotation of the Alaska Microplate, the triangular Canadian Basin was formed. The Alpha-Mendelev Ridge, as a part of the hotspot track, holds records of this tectonic event. At the same time as the opening of the Canadian Basin, the Kolyma Block started moving towards, and collided with the Siberian plate during the Lower Cretaceous. This

collision resulted in the closing of the Paleo-Pacific Ocean forming the Verkhoyansk fold belt at the eastern margin of the Siberian plate. The collision between the Alaska Microplate and the Eurasian plate around 120 Ma resulted in the formation of the New Siberian–Chukchi fold belt. In the meantime, the American Basin stopped spreading.

The Iceland mantle plume began affecting the tectonic evolution of Baffin Bay and the North Atlantic Ocean around 100 Ma and recorded the kinematic characteristics of the Greenland Plate and the North American Plate. Between 100 Ma and 80 Ma, the northern margin of the North American Plate was located above the Iceland mantle plume due to the mantle plume moving the North American Plate eastward faster and slowing the Greenland plate. The North American Plate and the Greenland plate had the same kinematic direction but different velocities during this period. This difference in velocities formed the Baffin Bay between the two plates. Around 60 Ma, with

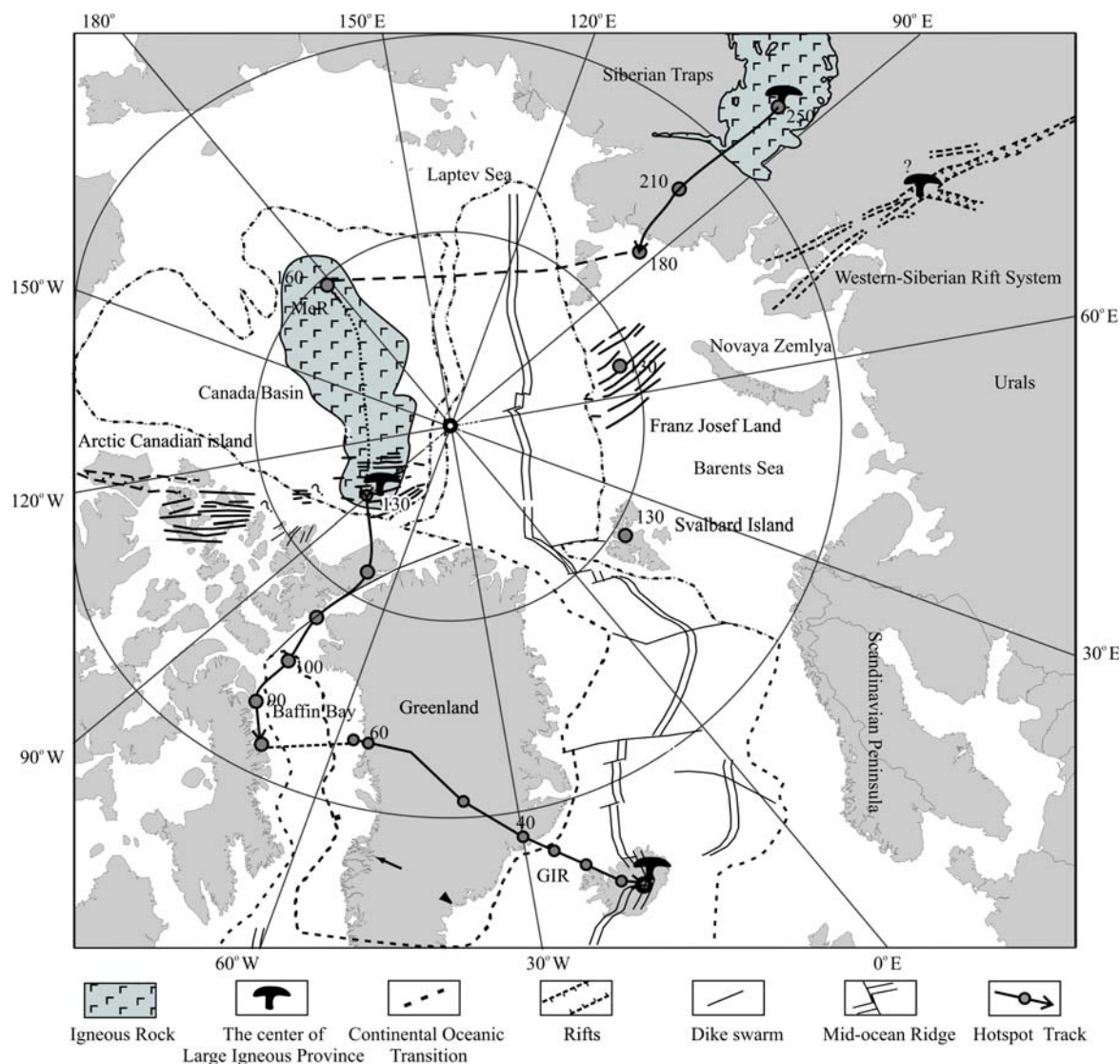


Fig. 4. The Iceland Hotspot Track between 250 Ma and 0 Ma.

the eastward movement of the Greenland plate, Baffin Bay stopped spreading and the magmatism in the western Greenland margin started to become active. The heat flow and subsequent sub-ice sheet river substantiated this relative motion.

5 Conclusions

(1) The Siberian-Icelandic hotspot track is the only preserved hotspot track on earth. However, the track is not documented by a continuous volcanic chain with an associated age progression as is true elsewhere, e.g. the Emperor-Hawaii seamount chain. For the most part, the Iceland hotspot was beneath continental crust, which has a larger crustal thickness compared to oceanic crust, resulting in a complex and discontinuous track.

(2) The Iceland hotspot affected the tectonic evolution of different ocean basins during different periods. Between 160 Ma and 120 Ma, the hotspot made the Alaska Microplate move apart from North American Plate. The triangular Canadian Basin and the Alpha-Mendelev Ridge formed at the same time. Around 100 Ma, the relative location of the Iceland mantle plume and the Greenland Plate controlled the evolution of Baffin Bay.

(3) Throughout the whole Mesozoic, the major Arctic plates (Eurasian plate, North American Plate, Greenland Plate and Alaska Microplate) experienced clockwise rotation and northeastern migration towards the North Pacific, with the vertical influence from the ancient Iceland mantle plume breaking this balance and slowing down some plates. This dynamic process controlled the evolution of ocean basins in the Arctic.

(4) Our results of plate reconstruction provide new insight into the tectonic evolution of the Canadian Basin and Baffin Bay and the geological origin of the Alpha-Mendelev Ridge. However, more precise chronological data about mafic igneous rocks, heat flow surveys and magnetic anomalies data from Amerasian Basin are still required in order to fully understand the tectonic evolution of the Arctic.

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