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Timing and Consequences of Bering Strait Opening: New Insights From 40Ar/39Ar Dating of the Barmur Group (Tjörnes Beds), Northern Iceland

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Abstract The Barmur Group (informally Tjörnes beds) sedimentary succession of northern Iceland is key to reconstructing the opening of the Bering Strait oceanic gateway because these rocks record migration of bivalve molluscs from the Pacific to the Atlantic via the Arctic. However, the timing of the migration event is poorly constrained owing to a lack of reliable absolute ages. To address this problem, we present the first Ar-Ar radiometric dates from four basaltic lavas that underlie, are intercalated with, and overlie the Barmur Group, and integrate them with existing paleomagnetic records. We show that the Barmur Group has a latest Miocene to early Pliocene age range (c. 6.0–4.4 Ma; C3r–C3n.2n), older than all previous age models. Thus, the Barmur Group does not record the mid-Piacenzian Warm Period, contra some previous suggestions. Abundant Pacific bivalve molluscs appeared in the Barmur Group during subchrons C3n.4n–C3n.3r at 5.235–4.896 Ma, over 1.3 million years earlier than previously suggested. Appearance of Pacific bivalves in the northern Atlantic occurred shortly after the 5.6–5.4 Ma age previously inferred for first appearance of Arctic bivalves in the Pacific. Thus, our data suggest that first opening of the Bering Strait gateway by the latest Miocene (c. 5.5 Ma) was soon followed by bidirectional trans-Arctic faunal exchange, and argue against a hypothesized two-stage faunal exchange process spanning c. 2 million years. Our results also confirm that first opening of the Bering Strait gateway was not directly associated with the growth of large northern hemisphere icesheets, which occurred several million years later.

Plain Language Summary The extent to which global climate change is influenced by the flow of seawater between the world's oceans is an important question in Earth science. Sedimentary rocks from the Tjörnes Peninsula in northern Iceland record the opening of the Bering Strait oceanic gateway, which connects the Pacific and Atlantic Oceans via the Arctic. The signature of this gateway opening event is the sudden appearance in Iceland of bivalve mollusc fossils that previously lived only in the Pacific Ocean. However, the timing of their arrival is uncertain owing to the lack of reliable age measurements. To solve this problem, we applied radioisotope dating methods to a succession of rocks called the Barmur Group from the Tjörnes Peninsula. We found that the sudden appearance of Pacific fossils occurred over a million years earlier than previously thought. Our data show that first opening of the Bering Strait gateway was soon followed by migration of marine faunas in both directions, in contrast to the existing hypothesis that Pacific-to-Atlantic migration significantly post-dated Atlantic-to-Pacific migration. Our results also confirm the hypothesis that establishment of the Pacific-Arctic-Atlantic oceanic connection did not directly trigger development of large northern hemisphere icecaps, which occurred several million years later.

1. Introduction

The Barmur Group sedimentary succession in north-eastern Iceland, informally known as the Tjörnes beds, is an important archive of late Neogene palaeoenvironmental change in the high-latitude North Atlantic (Figure 1a, Símonarson & Eiríksson, 2021a). The easily accessible, c. 600 m thick succession contains a variety of macro-fossils and microfossils that have been studied for a century (Bárðarson, 1925; Eiríksson & Símonarson, 2021). Notably, the Barmur Group is a key outcrop for dating the first opening of the Bering Strait oceanic gateway, which established a trans-Arctic marine connection between the Pacific and Atlantic Oceans (Marincovich & Gladenkov, 1999; Símonarson & Eiríksson, 2021a). Opening of the Bering Strait allowed relatively fresh Pacific water into the Arctic and North Atlantic, which may have reduced the strength of Atlantic Meridional
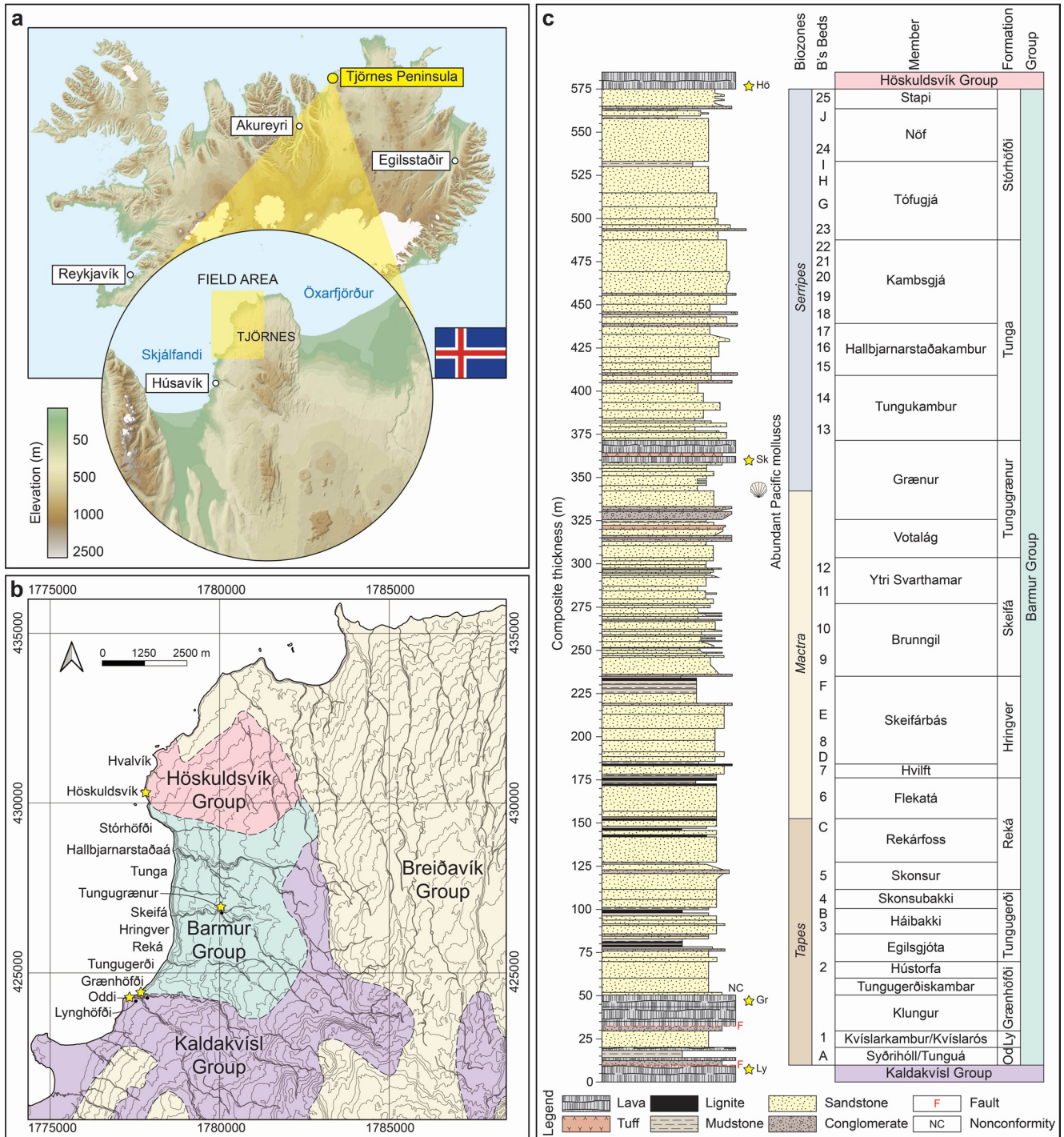
Figure 1. Location and geological setting of the Barmur Group. (a) Geographical location of the Tjörnes succession, northern Iceland. Field area highlighted by yellow box. (b) Geological map of the Tjörnes succession modified after Eiríksson (1980), using the geocentric coordinate system for Iceland (ISN2004/Lambert 2004; EPSG:5325). Place names discussed in the text are shown. Topographic basemap created in QGIS v.3.22 using the Landmælingum Íslands (National Land Survey of Iceland) Hæðarlíkan 2016 Digital Elevation Model. (c) Composite lithostratigraphic column of the Barmur Group after Eiríksson et al. (2021b), where width increases with grain size. The subdivision of the Barmur Group into formations and members is shown, alongside the molluscan biozonation, marine (Beds 1–25) and terrestrial units (Beds A–J) of Bárðarson (1925). Sample locations and abbreviations are indicated by yellow stars.

Figure 2. Comparison of existing age models from the Barmur Group with our new age model. Our new, older age for the base of the Höskuldsvík Group could be accommodated i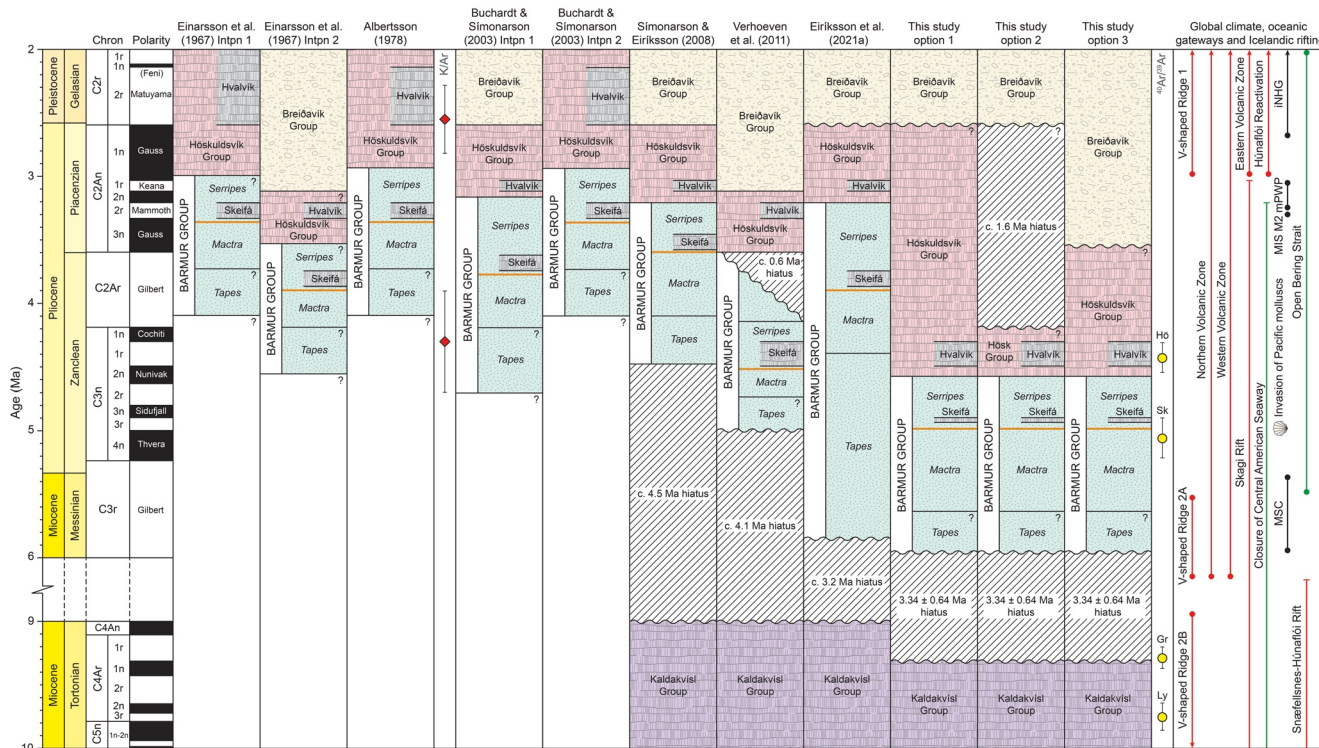n several possible ways (options 1–3). The units are correlated with the Geomagnetic Polarity Time Scale of Ogg (2020). The *Mactra/Serripes* biozone boundary, which marks the sudden arrival of abundant Pacific molluscs to northern Iceland, is highlighted orange for contrast. Global climate, oceanic gateways and Icelandic rifting events are also shown (Doré & Lundin, 1996; Garcia et al., 2003; Jones et al., 2002; Raffi et al., 2020; Straume et al., 2020; Walters et al., 2013). V-shaped ridges in the bathymetry surrounding Iceland result from thickness variations caused by temporal fluctuations in melt production rate at the Mid-Atlantic Ridge (Jones et al., 2002). $^{40}Ar/^{39}Ar$ composite ages from lavas as follows: Ly, Lynghöfði; Gr, Grænhöfði; Sk, Skeifá; and Hö, Höskuldsvík. MSC, Messinian salinity crisis; MIS M2, Marine Isotope Stage M2; mPWP, mid-Piacenzian Warm Period; and iNHG, intensification of the Northern Hemisphere Glaciation.

Overturning Circulation (AMOC), lowered high-latitude Atlantic surface temperatures, and promoted growth of northern hemisphere icesheets (Brierley & Fedorov, 2016; Hu et al., 2010). Previous studies have suggested that the Barmur Group may also record the mid-Piacenzian Warm Period (mPWP) (Cronin, 1991; Dowsett & Poore, 1991), the most recent geological time slice (3.264–3.025 Ma) when atmospheric carbon dioxide concentrations were similar to present, and surface temperatures were as predicted for the coming century (Dowsett et al., 2016). However, uncertainty over the age of the Barmur Group means that its potential to shed light on these significant changes in global oceanic circulation and climate has not been fully realized (Figure 2).

Reconstruction of the first opening of the Bering Strait oceanic gateway is based primarily on a handful of outcrops bordering the northern Pacific and northern Atlantic Oceans that contain marine bivalve molluscs. Mollusc assemblages in the Pacific and Atlantic realms were distinct during the middle to late Miocene, indicating that the Bering Strait gateway did not yet exist and a land-bridge connected Asia with North America (Marincovich, 2000; Marincovich & Gladenkov, 1999, 2001). The first post-Cretaceous opening of an oceanic gateway is signaled by the appearance of Atlantic molluscs in the Pacific, and vice versa (Gladenkov & Gladenkov, 2004; Gladenkov et al., 2002). The Barmur Group contains a plentiful and well-studied molluscan fauna (Durham & MacNeil, 1967; Símonarson & Eiríksson, 2021b; Strauch, 1963, 1972a, 1972b). The arrival of abundant Pacific bivalve molluscs defines the boundary between the *Mactra* and *Serripes* biozones (Figure 2). However, the bivalves themselves cannot be used for dating due to their wide biostratigraphic ranges (Marincovich & Gladenkov, 1999). Consequently, a fundamental problem which has dogged Bering Strait gateway reconstructions is that the faunal migration signals must be dated by other means. Dating of bivalve-bearing successions in the Pacific Ocean near the gateway, using marine diatom microfossils, has established a latest possible age range of 5.6–5.4 Ma for initial opening of the Bering Strait (Gladenkov & Gladenkov, 2004; Gladenkov et al., 2002).

The Barmur Group is potentially of great importance in Bering Strait reconstructions because the arrival of the Pacific molluscs occurs just below the Skeifá basaltic lavas, which should be dateable. But despite attempts by Albertsson (1976), no study has yet yielded a reliable radiometric age for the Skeifá lavas. Indeed, the variety of age models in Figure 2 reflects the lack of a reliable radiometric age framework for the entire Barmur Group. Age estimates range from c. 3.0 to 4.2 Ma (early to late Pliocene) for the top of the succession, and from c. 4.1 to 5.9 Ma (early Pliocene to latest Miocene) for the base of the succession. It is thus unclear whether the Barmur Group actually records the mPWP, and consequently it has been deleted from newer versions of the Pliocene Research, Interpretation and Synoptic Mapping (PRISM) global palaeoenvironmental reconstruction (Dowsett et al., 2016; Robinson et al., 2018). Most of the age models in Figure 2 are based on K-Ar dates for basaltic lavas that overlie and underlie the Barmur Group (Albertsson, 1976, 1978; Aronson & Sæmundsson, 1975). However, 1970s-vintage K-Ar ages for Neogene basaltic lavas are often unrealistically young (McDougall & Harrison, 1999). The fundamental underlying problems of low initial potassium content and hydrothermal alteration that leads to argon loss are both reported to affect the Tjörnes basalt samples (Albertsson, 1976, 1978; Aronson & Sæmundsson, 1975). Furthermore, the only Barmur Group age model that is based on biostratigraphic correlation (marine dinoflagellates; Verhoeven et al., 2011) is significantly older than the radiometric age models, in line with the possibility that the vintage K-Ar ages could be too young.

Despite these uncertainties in the age model for the Barmur Group, a late Pliocene or uppermost early Pliocene age (c. 3.4–4.5 Ma, Figure 2) has become established in the literature for the arrival of Pacific bivalves in Iceland (Albertsson, 1978; Buchardt & Símonarson, 2003; Einarsson et al., 1967; Eiríksson et al., 2021a; Símonarson & Eiríksson, 2008; Verhoeven et al., 2011). This age range is distinctly younger than the arrival of the Arctic and Atlantic bivalves in the Pacific, at 5.6–5.4 Ma (Gladenkov & Gladenkov, 2004; Gladenkov et al., 2002). The distinction between these two age estimates for faunal migration has led to a two-stage model for Bering Strait opening and the consequent development of oceanic flow (Marincovich, 2000). In the first stage, at around 5.5 Ma, the gateway opened but persistent Arctic-to-Pacific flow (southward, opposite to present) meant that although Arctic and Atlantic bivalve species immediately migrated to the Pacific, the Pacific bivalve species did not migrate to the Atlantic. In the second stage, net oceanic flow through the gateway changed to northward, like the present, which allowed Pacific bivalve species to migrate across the Arctic Ocean and into the Atlantic. The younger age estimates for the arrival of Pacific bivalves in Iceland (c. 3.4 Ma) are only shortly before the intensification of the Northern Hemisphere Glaciation (iNHG), which locally began with expansion of the Greenland icesheet from the southern uplands across northern Greenland (c. 3.5–3.0 Ma, Maslin et al., 1998) and culminated in establishment of cycles of lowland glaciation in Iceland (c. 2.7 Ma, Eiríksson, Guðmundsson, et al., 2021; Geirsdóttir & Eiríksson, 1994). Climate modeling studies show that opening of the Bering Strait can potentially promote growth of northern hemisphere icesheets by reducing high-latitude Atlantic surface temperatures, which has raised the possibility of a causal connection between gateway opening and the iNHG (Brierley & Fedorov, 2016). Alternatively, the iNHG could have been a tipping-point response to either a gradual reduction in atmospheric greenhouse gases (Bartoli et al., 2011; Lunt et al., 2008; Seki et al., 2010; Willeit et al., 2015) or changes in the AMOC associated with the closure of the Central American Seaway (De Schepper et al., 2013; Driscoll & Haug, 1998; Sarnthein et al., 2009).

Here, we address the uncertainty in age of the Pacific-to-Atlantic bivalve mollusc migration event, and the consequent uncertainty in Bering Strait gateway opening, by applying the Ar-Ar dating technique to four basaltic lavas below, within and above the Barmur Group. These are the first Ar-Ar ages for the pre-Quaternary Tjörnes succession, and they include the first reliable radiometric age for the Skeifá lavas that are closely associated with the bivalve mollusc migration event. We integrate the radiometric ages with existing paleomagnetic data to generate a new age model for the entire Barmur Group and surrounding rocks, in order to reassess the paleoclimatic implications of the first opening of the Bering Strait.

2. Geological Background

A c. 1,200 m thick sequence of latest Miocene or early Pliocene to Late Pleistocene sedimentary rocks known as the Tjörnes succession is exposed as coastal cliffs and valleys along the west side of the Tjörnes Peninsula, north-eastern Iceland (Figures 1a–1c). It is the thickest sedimentary succession of onshore Iceland, and has been intensively studied owing to its accessibility and the palaeoenvironmental change it records. The Tjörnes succession is divided stratigraphically into four units. The Kaldakvísl Group of plateau tholeiite basaltic lavas forms the basement. The Barmur Group, the main focus of this study, comprises lignites, siltstones, sandstones, conglomerates, and occasional basaltic lavas which are interpreted to have accumulated in an alternating shallow

marine to terrestrial environment (Eiríksson, 1980). These rocks were termed the Tjörnes beds before Eiríksson et al. (2021b) formally defined them as the Barmur Group. The overlying Höskuldsvík Group comprises mainly basaltic lavas intercalated with fluvial sedimentary rocks, which record a sub-aerial environment. At the top of the sequence, the Breiðavík Group consists of basaltic lavas intercalated with sedimentary rocks including diamictites, which show that the Breiðavík Group was deposited during Pleistocene glacial conditions (Eiríksson, 1985; Eiríksson & Geirsdóttir, 1991; Eiríksson et al., 1990, 1992, Eiríksson, Guðmundsson, et al., 2021; Eiríksson, Knudsen, & Símonarson, 2021; Geirsdóttir & Eiríksson, 1994). The entire Tjörnes sedimentary succession is deposited in an extensional basin formed within the inside corner between the Tjörnes Fracture Zone and the Northern Volcanic Zone rift axis (Eiríksson, 1980, 1981, 1985). Tectonic uplift during the Late Pleistocene produced the coastal exposure observed today, though deposition continues in the adjacent Skjálfandi basin (Einarsson et al., 1967; Sæmundsson, 1974; Thoroddsen, 1902).

Kaldakvísl Group lavas were dated as 9.9 ± 1.8 and 8.6 ± 0.4 Ma (late Miocene) by Aronson and Sæmundsson (1975) using the K-Ar method. The contact between the Kaldakvísl Group basement and the Barmur Group sedimentary succession is an erosional unconformity that is cut by a strike-slip fault zone where it is exposed in the Kaldakvísl river valley (Figure 1 of Einarsson et al., 1967; Eiríksson, 1980). To the north of the main contact, two basaltic lava flows were originally interpreted to be intercalated within the basal sediments of the Barmur Group (Bárðarson, 1925; Eiríksson, 1980, 1981). The uppermost of these lavas has been dated as 4.3 ± 0.4 Ma using the K-Ar method (Albertsson, 1976). More recent mapping indicates that these lower lavas may instead be faulted slivers of the Kaldakvísl Group (Eiríksson et al., 2021b).

The pioneering stratigraphic study of the Tjörnes beds, as the Barmur Group was then called, was conducted by Bárðarson (1925), who divided them into 25 shelly layers (labeled 1–25) and 10 terrestrial layers (labeled A–J). Bárðarson (1925) further assigned the beds into three bivalve molluscan biozones: the *Tapes* Zone (beds 1–5), the *Mactra* Zone (beds 6–12), and the *Serripes* Zone (beds 13–25). The boundary between the *Mactra/Serripes* biozones is of key importance to our study because it represents the sudden arrival of abundant Pacific-type fauna in Iceland. A few Pacific-type molluscs appear in the Barmur Group below the *Serripes* biozone (Símonarson & Eiríksson, 2021b). The abrupt appearance of at least 24 new Pacific-type mollusc species in shell bed 13 that were not present in bed 12 or lower defines the base of the *Serripes* biozone, and this bioevent is the widely used signal of the first opening of the Bering Strait oceanic gateway (Buchardt & Símonarson, 2003; Símonarson & Eiríksson, 2008, 2021a; Verhoeven et al., 2011). Importantly, the shallow marine sediments c. 17 m above the *Mactra/Serripes* biozone boundary contain intercalated basaltic pillow lavas surrounded by palagonitic tuff and breccia, exposed inland in the Skeifá river valley (Eiríksson et al., 2021b). Albertsson (1976) attempted twice to measure the absolute K-Ar age of the Skeifá basalts; one attempt was inconclusive, and a second yielded an age of 2.46 ± 0.46 Ma that was considered erroneously young. Nearly a century after the pioneering work, and after four decades of research, Eiríksson et al. (2021b) presented a comprehensive lithostratigraphic scheme for the Barmur Group that addresses gaps in the stratigraphy and correlates the coastal and inland exposures (Figures 1c and 2). Retaining the molluscan biozonation of Bárðarson (1925), they divide the Barmur Group into 10 formations, 23 members and 219 lithological units, with an aggregate thickness exceeding 575 m (Figure 1c).

Most studies consider that sediment and lava accumulation was fairly continuous across the boundary between the Barmur and Höskuldsvík Groups, although Verhoeven et al. (2011) propose an erosional hiatus of c. 0.6 My between the groups (Figure 2). Basaltic lavas of the Höskuldsvík Group have been dated as 2.55 ± 0.27, 2.36 ± 1.8, and 3.19 ± 0.26 Ma using the K-Ar method (Albertsson, 1976, 1978). Eiríksson et al. (2021a) considered the younger ages unreliable and based their age model for the group on the c. 3 Ma age (late Pliocene). There is an angular unconformity between the Höskuldsvík Group and overlying Breiðavík Group (Eiríksson, Guðmundsson, et al., 2021). The age of the Breiðavík Group is well-established to be Quaternary, post iNHG, based on the sedimentary record of glacial cycles covering the Icelandic lowlands, and Ar-Ar age determinations in the upper part of the succession correlated with a large amount of good quality paleomagnetic data (Camps et al., 2011; Eiríksson et al., 1990, 2021a).

3. Materials and Methods

3.1. Fieldwork

Sampling of four basaltic lavas was undertaken during September 2018 and March 2019 (Figures 1b and 1c). In the Skeifá river valley, we sampled the lowermost of the two Skeifá pillow lavas (Unit XIV:P of Eiríksson et al., 2021b) in order to date the appearance of abundant Pacific-type bivalve molluscs which lies c. 17 m beneath,

and by inference the opening of the Bering Strait. At Höskuldsvík, we targeted the oldest of the six lavas in the Höskuldsvík Group (Unit XXII:J of Eiríksson et al., 2021b) to constrain the age of the top of the Barmur Group and determine whether it records the mPWP. We sampled two separate lava flows either side of the Kaldakvísl river mouth to constrain the age of the base of the Barmur Group. To the south of the river mouth, we targeted the uppermost lava on Lynghöfði hill (hereafter "Lynghöfði lava"), considered one of the youngest exposed flows in the Kaldakvísl Group basement to the Barmur Group (Eiríksson et al., 2021b). To the north of the river mouth, we sampled the uppermost of the two lava flows exposed on Grænhöfði hill (hereafter "Grænhöfði lava"; Unit V:A of Eiríksson et al., 2021b), which was originally thought to lie within the Barmur Group (Bárðarson, 1925; Eiríksson, 1980, 1981), but was recently hypothesized to be a faulted sliver of the Kaldakvísl Group basement (Eiríksson et al., 2021b). All these lavas were excavated using a 1.8 kg long-handled lump hammer and cold chisels to remove weathered surfaces and to expose minimally altered basalt at the centre of each flow. Fresh and dense hand samples were collected at each field locality. Loose surficial material was removed using a scrubbing brush, before the samples were packaged in labeled cloth bags.

3.2. $^{40}Ar/^{39}Ar$ Dating

The basalt samples were initially thin sectioned at the University of Birmingham, UK and screened using a petrographic microscope to identify a subset with minimal signs of alteration in the groundmass (see Supporting Information S1). Selected hand samples were then prepared for $^{40}Ar/^{39}Ar$ dating at the Scottish Universities Environment Research Centre (SUERC, East Kilbride; UK). Visibly altered areas were removed using a lapidary trim saw. The samples were subsequently crushed using a club hammer to yield 2 mm fragments, before being ground in a disc-mill and sieved to produce a 250–500 μm separate. Following a rinse in deionized water to remove the fine fraction, the samples were leached in an ultrasonic bath at 50°C for 1 hr, first in 3N HNO_3 and then in 3N HCL to remove any trace alteration phases. This dual-acid leaching process was repeated at least three times until the acids remained clear. The leached samples were then ultrasonicated in deionized water, gently dried (temperature <50°C) and passed through a Frantz isodynamic magnetic separator to remove phenocrysts, xenocrysts and any remaining alteration products from the groundmass. The samples were then handpicked under a binocular microscope to harvest a homogenous and purified groundmass separate. Each analyzed sample represented approximately 120 mg of groundmass separate.

Samples and neutron flux monitors were packaged in Cu foil and stacked in quartz vials with the relative positions of packets precisely measured for later reconstruction of neutron flux gradients. The sample package was irradiated in the Oregon State TRIGA Reactor (Corvallis, Oregon; USA), Cd-shielded facility (CLICIT). Alder Creek sanidine with an established age of 1.1891 ± 0.0008 (1σ) Ma (Niespolo et al., 2017) was used to monitor ^{39}Ar production and to establish neutron flux values (J) for the samples. At SUERC, gas was extracted from the samples via step-heating using a mid-infrared (10.6 μm) CO_2 laser with a non-Gaussian, uniform energy profile and a 3.5 mm beam diameter rastered over a sample well. The samples were housed in a doubly pumped ZnS-window laser cell and loaded into a copper planchette containing four square wells (each measuring 1.6 cm^2). Liberated argon was purified of active gases (e.g., CO_2, H_2O, H_2, N_2, CH_4) using three Zr-Al getters: one at 16°C and two at 400°C. Data for the four groundmass samples were collected on a GVI ARGUS V multi-collector mass spectrometer using a variable sensitivity faraday collector array in static collection (non-peak hopping) mode (Mark et al., 2009). Time-intensity data were regressed to inlet time with second-order polynomial fits to the data. The average total system blank for laser extractions, measured between each sample run, was $6.4 \pm 0.1 \times 10^{-15}$ mol ^{40}Ar, $11.0 \pm 0.8 \times 10^{-17}$ mol ^{39}Ar, and $2.4 \pm 0.2 \times 10^{-17}$ mol ^{36}Ar. Mass discrimination was monitored on a daily basis, between and within sample runs by analysis of an air standard aliquot delivered by an automated pipette system (D values applied to individual steps are listed in the data set hosted on Zenodo). All blank, interference and mass discrimination corrections and age calculations were performed with MassSpec software (MassSpec, v.8.058, authored by Al Deino, Berkeley Geochronology Center). Decay constants and corrections are after Renne et al. (2010).

Each sample was run in duplicate or triplicate, with each single analysis converted into a plateau age (Figure 3). Plateau ages were accepted when at least three contiguous age steps are indistinguishable at the 2σ level, contain a minimum of 50% of the total ^{39}Ar released during the experiment, and define an inverse isochron indistinguishable from the plateau age at 2σ uncertainty. Additionally, the trapped component composition, derived from the inverse isochron, should be indistinguishable from air at 2σ. Age and uncertainty were calculated using the mean
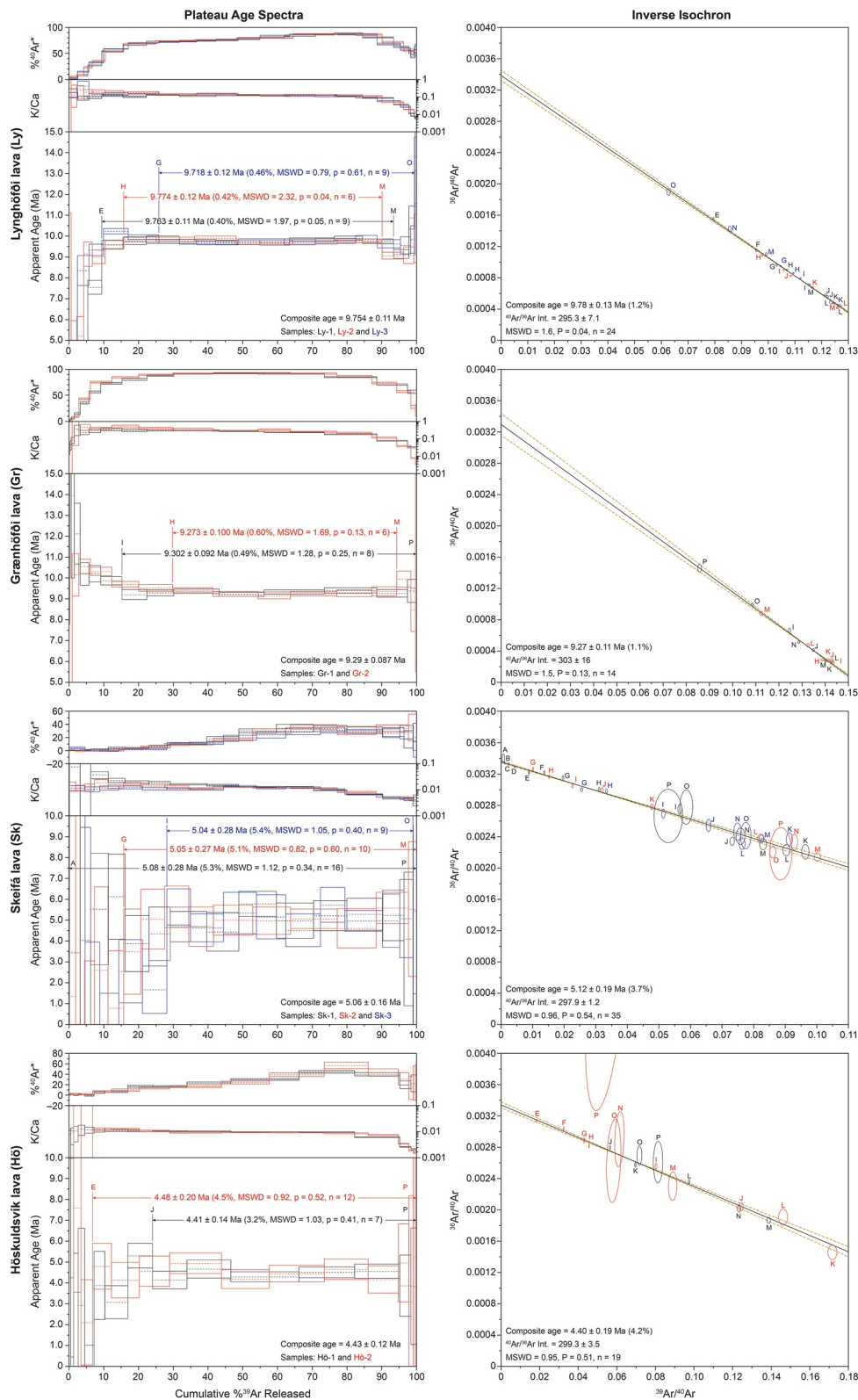
Figure 3.

weighted by the inverse variance of each step. The accepted plateau steps from the duplicate or triplicate runs were combined, and a weighted mean was calculated yielding a final "composite age," which is accepted as the best age estimate for the sample. Composite ages are presented at 2σ including uncertainty in J; uncertainties with and without J are presented in the data set hosted on Zenodo.

3.3. Magnetostratigraphy

We correlated our new ^{40}Ar/^{39}Ar ages with existing paleomagnetic data to refine the age model for the Barmur Group. We use the Geomagnetic Polarity Time Scale of Ogg (2020) throughout. A comprehensive review of the available paleomagnetic data from the entire Tjörnes succession is provided by Eiríksson and Símonarson (2021) and Eiríksson et al. (2021a). Relevant paleomagnetic data were presented by Hospers (1953), Doell (1972), Gladenkov and Gurari (1976), Eiríksson et al. (1990), and Kristjánsson (2004). The data are not of uniform stratigraphic distribution, nor of uniform quality. Kristjánsson (2004) reported 31 generally good quality measurements from the upper part of the Barmur Group, which together with the data set of Doell (1972) have allowed us to confidently correlate our radiometrically dated samples from the Höskuldsvík and Skeifá lavas with unique magnetic subchrons. Minimal paleomagnetic data is available for the lower part of the Barmur Group.

4. Results

4.1. Age of the Skeifá Lava and the Pacific-To-Atlantic Mollusc Migration

The lowermost flow in the Skeifá pillow lavas, intercalated within the Barmur Group, has an ^{40}Ar/^{39}Ar composite plateau age of 5.06 ± 0.16 Ma, in agreement with an isochron age of 5.12 ± 0.19 Ma (Figure 3). The Skeifá lavas are considered reversely magnetized (Eiríksson et al., 2021a). Doell (1972) obtained a reliable reverse polarity measurement from the upper Skeifá lava (denoted Unit I37). Kristjánsson (2004) reported four out of six samples of the lower Skeifá lava (denoted SA1) were reversed, though uncertainties on all six readings were among the largest in his data set. However, all available data sets give reliable reverse polarity readings for the sedimentary rocks immediately surrounding the Skeifá lavas (Doell, 1972; Gladenkov & Gurari, 1976; Kristjánsson, 2004), and there is no field evidence for significant breaks between sedimentary deposition and lava emplacement (Eiríksson et al., 2021b). Thus we accept the reverse designation of our radiometrically dated Skeifá lava. The age range we determined is 5.31–4.90 Ma (2σ range for both the plateau and isochron ages). The only reverse polarity interval to overlap the radiometrically determined range is subchron C3n.3r, at 4.997–4.896 Ma (Figure 4). We therefore assign the lower Skeifá lava, and by inference the entire Skeifá lava package, to magnetic subchron C3n.3r. These lavas were emplaced during the Zanclean stage (Early Pliocene), significantly earlier than has been suggested in all previous age models (Figure 2).

The *Mactra/Serripes* bivalve mollusc biozone boundary marks the abrupt appearance of abundant Pacific-type fauna within the Barmur Group (Durham & MacNeil, 1967; Einarsson et al., 1967; Eiríksson et al., 1990; Símonarson & Eiríksson, 2008, 2021a). This bioevent is the signature of Bering Strait gateway opening. The *Mactra/Serripes* boundary is observed c. 17 m below the Skeifá pillow lavas at Tungugrænur (Eiríksson et al., 2021b). Eiríksson et al. (2021b) placed the *Mactra/Serripes* boundary within the same reverse polarity chron as the Skeifá lavas. Considering the distribution of mollusc fossils in the Tungugrænur section, the *Mactra/Serripes* boundary could also lie within the underlying normal polarity chron. Thus, we assign the *Mactra/Serripes* boundary to magnetic subchrons C3n.4n–C3n.3r (5.235–4.896 Ma). In detail: reversely magnetized paleomagnetic sample set SA-1 (Kristjánsson, 2004) is from Skeifá lavas designated Units XIV:P–S in the lithostratigraphic scheme of Eiríksson et al. (2021b); reversely magnetized sedimentary samples SA-2, SA-3, and SA-4 lie within Units XIV:O, XIV:N–J, and XIV:I respectively; and normally magnetized sedimentary sample SA-5 also lies within Unit XIV:I (J. Eiríksson, *pers. comm.*). Eiríksson et al. (2021b) placed the *Mactra/Serripes* biozone boundary at the boundary between Units XIV:I and XIV:J, but the biozone boundary could lie anywhere between mollusc fossil occurrences within basal Unit XIV:I and Unit XIV:L (Figure 5.54 of Eiríksson

Figure 3. ^{40}Ar/^{39}Ar age spectra and inverse isochrons for the Lynghöfði, Grænhöfði, Skeifá, and Höskuldsvík lava samples. The left panel shows step-heating plateau age spectra with %^{40}Ar*, K/Ca and age versus %^{39}Ar released per step for each color-coded replicate. The ages presented in the plateau age spectra are calculated using air as a trapped component. Box heights are 2σ. The right panel shows isochron analyses which yield an age and a composition of the trapped component for a number of points (n). The isochrons include a black regression line, dashed 2σ error envelope and colored circles, which represent the points that make up the respective plateau ages for each replicate. The mean square weighted deviation and P (Chi-squared value) are also shown.

Figure 4. A new age model for the Barmur Group constructed using our ^{40}Ar/^{39}Ar ages and the reinterpretation of existing paleomagnetic records (Doell, 1972; Kristjánsson, 2004), correlated to the Geomagnetic Polarity Time Scale of Ogg (2020). Paleomagnetic sampling positions and numbering system of Doell (1972) and Kristjánsson (2004) are shown relative to their respective stratigraphic horizons after Bárðarson (1925) and Eiríksson et al. (2021b). The legacy K-Ar ages of Albertsson (1976, 1978) are also shown for reference. Composite lithostratigraphic column and molluscan biozonation as in Figure 1. ^{40}Ar/^{39}Ar composite age abbreviations as in Figures 2 and 3.

et al., 2021b; J. Eiríksson, *pers. comm.*) Thus, the biozone boundary could lie within the reversely magnetized section XIV:L–I, which is assigned to subchron C3n.3r by dating the Skeifá lavas, or it could lie within the underlying normally magnetized section XIV:I–H, which we assign to subchron C3n.4n (Figure 4). In summary, the bioevent which signifies Pacific-to-Atlantic faunal migration through the Bering Strait occurred between 5.2 and 4.9 Ma during the Zanclean stage (Early Pliocene), significantly earlier than has been suggested in all previous age models (Figure 2).

4.2. Age of the Upper Barmur Group

The lowermost lava in the Höskuldsvík Group, immediately overlying the Barmur Group, yields an ^{40}Ar/^{39}Ar composite plateau age of 4.43 ± 0.12 Ma, in good agreement with the calculated isochron age of 4.40 ± 0.19 Ma (Figure 3). This result is significantly older than the K-Ar age of 2.55 ± 0.27 Ma reported for the same lava (Albertsson, 1976). Given the well-known susceptibility of the K-Ar technique to argon loss, questions over the quality of the Höskuldsvík Group samples raised by Albertsson (1976), and that Albertsson (1976) also reported a relatively older K-Ar age of 3.19 ± 0.26 Ma for stratigraphically younger lavas within the Höskuldsvík Group, we are confident that the new ^{40}Ar/^{39}Ar age of c. 4.4 Ma is more reliable than the previous age determinations.

Normal polarity magnetism was measured by Doell (1972) in eight samples collected from the flow that we dated (denoted I38). Our radiometrically determined age range is 4.59–4.21 Ma (2σ range for both the plateau and isochron ages). This range overlaps with both the C3n.2n (Nunivak) subchron at 4.631–4.493 Ma and the C3n.1n (Cochiti) subchron at 4.300–4.187 Ma. We prefer to assign the lowermost Höskuldsvík Group lava to the C3n.2n subchron (4.631–4.493 Ma), which overlaps with the uncertainty ranges of both the composite plateau and isochron ages, whereas the alternative subchron would overlap with the isochron age range only. This choice is supported a posteriori by the correlations below.

Having correlated the Skeifá lava with subchron C3n.3r and the lowermost Höskuldsvík Group lava with subchron C3n.2n (4.631–4.493 Ma), we now correlate the Barmur Group sediments between them with the paleomagnetic timescale (Figure 4). The lowermost Höskuldsvík lava conformably overlies the Barmur Group. There is no evidence of erosion (Eiríksson et al., 2021b). Furthermore, the basal part of the lava flow is brecciated and contains inclusions of underlying sediment, implying that the Barmur Group substrate was unlithified at the time of lava emplacement (Eiríksson et al., 2021b), and suggesting that the uppermost sediments of the Barmur Group are of similar age to the lava. The quality of paleomagnetic data for the uppermost Barmur Group bed (above bed J) is relatively poor, but these beds are interpreted as normally magnetized (Kristjánsson, 2004). We therefore assign them to the C3n.2n subchron, together with the Höskuldsvík Group lava we dated. The underlying Barmur Group sediments within the *Serripes* biozone that are exposed along the coast are a conformable package (Eiríksson et al., 2021b). Kristjánsson (2004) reported reversed polarity between Barmur Group beds I and J, near the top of the succession, which we correlate with subchron C3n.2r (4.799–4.631 Ma). Beneath this, he reported an interval of normal polarity in the coastal section between Barmur Group beds 13 and H, which we correlate with subchron C3n.3n (4.896–4.799 Ma). The coastal exposure described above is not continuous with the inland exposure which includes the Skeifá lavas. Eiríksson et al. (2021b) carried out a detailed program of logging and mapping to correlate the two exposures. They place the Skeifá pillow lavas and surrounding sediments between beds 13 and 12 in their composite lithostratigraphic column (Figure 1c). The inland Skeifá river valley section correlates with an erosional unconformity beneath bed 13 at the coast, which explains why the lavas are not exposed there. This scheme places the reversely magnetized Tungugrænur succession that includes the Skeifá lava and the *Mactra/Serripes* boundary directly below the coastal section we have correlated with subchron C3n.3n (Figure 4). Thus, the Skeifá lavas lie within subchron C3n.3r and the *Mactra/Serripes* boundary within subchron C3n.3r or C3n.4n, as we showed independently in Section 4.1. In summary, the *Serripes* biozone of the Barmur Group contains a record of each and every magnetic subchron between the Skeifá and Höskuldsvík lavas we have dated.

4.3. Age of the Lower Barmur Group

The Lynghöfði lava, thought to be one of the youngest lavas exposed in the Kaldakvísl Group basement to the Barmur Group (Eiríksson et al., 2021b), yields an ^{40}Ar/^{39}Ar composite plateau age of 9.754 ± 0.11 Ma in agreement with an isochron age of 9.78 ± 0.13 Ma (Figure 3). Our new age is reasonably well in line with

the K-Ar ages from the Kaldakvísl Group obtained by Aronson and Sæmundsson (1975), which ranged from 9.9 ± 1.8 to 8.6 ± 0.4 Ma, though the $^{40}Ar/^{39}Ar$ age is more reliable. Thus we confirm previous estimates that the Kaldakvísl Group is Tortonian (Late Miocene) in age.

The Grænhöfði lava, which may lie below or within the Barmur Group, yields an $^{40}Ar/^{39}Ar$ composite plateau age of 9.29 ± 0.087 Ma in agreement with the isochron age of 9.27 ± 0.11 Ma (Figure 3). Hospers (1953) detected normal polarity in this flow, so we correlate it with subchron C4Ar.1n (9.426–9.311 Ma). Albertsson (1976) reported a K-Ar age of 4.30 ± 0.17 Ma for the same lava but he considered this to be a minimum (youngest possible) age. Our more reliable $^{40}Ar/^{39}Ar$ age justifies Albertsson's caution. We find that the Grænhöfði lava is about 0.5 My younger than the Lynghöfði lava. Thus, our results support the hypothesis of Eiríksson et al. (2021b) that the Grænhöfði lava is not part of the Barmur Group, but instead is a faulted sliver of the Kaldakvísl Group basement.

The contact between the Kaldakvísl Group and the overlying Barmur Group is an erosional unconformity (Eiríksson et al., 2021b). Weathering and reddening of the Kaldakvísl Group beneath the contact implies a significant hiatus in deposition. Our new ages show that the maximum (oldest possible) age for the base of the Barmur Group is c. 9.3 Ma, but it may well be significantly younger. There are no other lavas that are undoubtedly part of the Barmur Group beneath the lowest Skeifá lava, which we have dated as 5.06 Ma. Thus, the only way to use radiometric dating of lavas to estimate the age of the base of the Barmur Group is to estimate the sedimentation rate in the upper Barmur Group and extrapolate it downwards. Eiríksson et al. (2021b) demonstrate that 217 m of sediments occur between the lowermost Skeifá lava and the basal lava of the Höskuldsvík Group. Our $^{40}Ar/^{39}Ar$ data show the time interval between these two lavas is 0.63 ± 0.28 Ma, which equates to a sedimentation rate of 0.03 cm/yr (0.02–0.06 cm/year accounting for analytical error). We follow previous studies in assuming a fairly consistent rate of sedimentation for the entire Barmur Group (Albertsson, 1978; Buchardt & Símonarson, 2003; Einarsson et al., 1967; Símonarson & Eiríksson, 2008). The stratigraphic thickness between the lowermost Skeifá lava and the base of the Barmur Group resting on the erosional surface at Grænhöfði is 308 m (Eiríksson et al., 2021b). Linear extrapolation then gives an age of 5.95 ± 0.56 Ma (terminal Miocene) for the base of the Barmur Group (Figure 4). The corresponding hiatus represented by the unconformity at the base of the Barmur Group is 3.34 ± 0.64 My. Our extrapolated terminal Miocene age for the basal Barmur Group agrees with the estimated age of 5.85 ± 0.5 Ma proposed by Eiríksson et al. (2021a), and is compatible with the occurrence of late Miocene foraminiferal species, such as *Cibicidoides limbatosuturalis*, in the lower section of the *Tapes* biozone (Knudsen et al., 2021). Our age estimate for the earliest sediments is also broadly in line with the basin formation mechanism. The Tjörnes Basin exists within the inside corner of the Northern Volcanic Zone plate spreading axis and the Tjörnes Fracture Zone, which had formed by c. 7 Ma (Garcia et al., 2003; Sæmundsson, 1974; Sigmundsson et al., 2020).

4.4. Age of the Höskuldsvík Group

Verhoeven et al. (2011) proposed that a hiatus of 0.6–1.0 My exists between the Barmur Group and the overlying Höskuldsvík Group, in contrast to all other age models (Figure 2). Our radiometric dating shows a time interval of about 0.6 My between the Skeifá lava within the Barmur Group and the basal lava of the Höskuldsvík Group, and the sedimentary rocks between these tie points record each and every magnetic subchron. We therefore doubt that a significant hiatus occurs at the top of the Barmur Group. Our age for the base of the Höskuldsvík Group is up to 1 My older than previous estimates (Figure 2), implying the overlying Tjörnes succession accumulated over a considerably longer period of time than has previously been proposed. The implications for the Icelandic record of lowland glaciation are discussed in Section 5.4.

5. Discussion

5.1. Pacific-To-Atlantic Faunal Migration

Mollusc assemblages in the Pacific and Atlantic/Arctic realms were distinct between the middle Cretaceous and the middle to late Miocene, indicating that the Bering Strait oceanic gateway did not yet exist, and a land-bridge connected Asia with North America (Marincovich & Gladenkov, 2001). Opening of the Bering Strait gateway is signaled by the first appearance of Atlantic bivalve molluscs in the Pacific, and vice versa. We have dated the arrival of abundant Pacific bivalves in Iceland in the North Atlantic to 5.2–4.9 Ma, during the early Pliocene
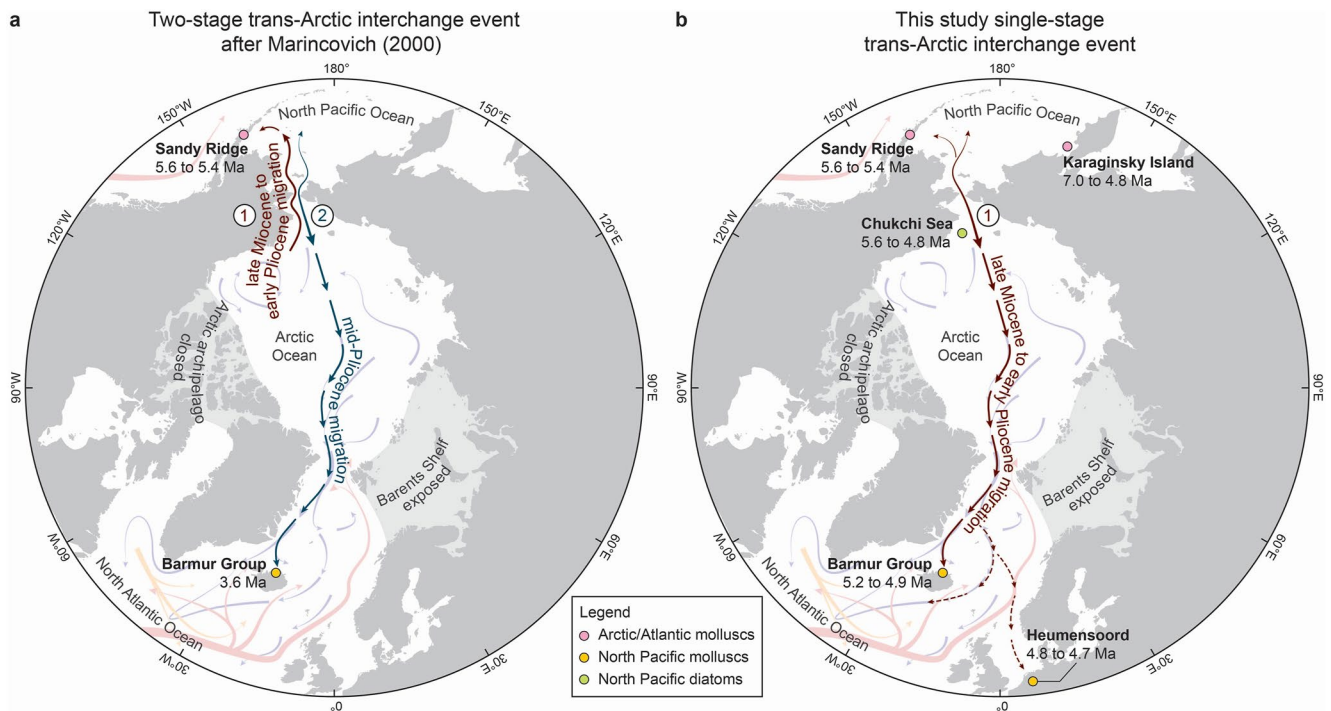
Figure 5. Summary of late Neogene trans-Arctic molluscan migration models, showing a schematic comparison between: (a) the two-stage late Miocene to early Pliocene (5.6–4.8 Ma; dark mahogany arrows) and mid-Pliocene (3.6 Ma; dark teal arrows) event proposed by Marincovich (2000) and (b) the single-stage late Miocene to early Pliocene event (arriving in Iceland at c. 5.2–4.9 Ma) advocated herein. A single and earlier phase of trans-Arctic interchange is further supported by the distribution of late Miocene/early Pliocene Pacific diatoms in the Chukchi Sea and strontium dating of Pacific molluscs preserved at Heumensoord, Netherlands (Beets, 1992; Gladenkov & Gladenkov, 2004). Late Neogene continental outlines created in QGIS v.3.22 following the tectonic reconstructions of Torsvik et al. (2002). Light red, orange, and blue arrows indicate surface, intermediate, and deep ocean currents, respectively.

(strictly, to magnetic subchrons C3n.4n–C3n.3r, at 5.235–4.896 Ma). Our age for this faunal exchange event is over 1.3 million years earlier than previous estimates (Buchardt & Símonarson, 2003; Einarsson et al., 1967; Eiríksson et al., 2021a; Símonarson & Eiríksson, 2008). Most of the previous younger age estimates were underpinned by 1970s-vintage K-Ar radiometric ages. The K-Ar dating method is well known to underestimate the age of basalts that have low initial K contents or are subject to radiogenic Ar loss through hydrothermal alteration, as observed in the Tjörnes succession (Aronson & Sæmundsson, 1975). In such cases, it is within expectation that modern $^{40}Ar/^{39}Ar$ dating methods should return ages up to several million years older than respective vintage K-Ar dates (McDougall & Harrison, 1999).

Marincovich (2000) proposed an age of 3.6 Ma for the Pacific-to-Atlantic faunal exchange event by correlating the reported first appearance of the Pacific bivalve *Mya arenaria* at the *Mactra/Serripes* boundary in the Barmur Group, Iceland (Figure 5a), with its first appearances in the supposedly correlative Coralline Crag Formation of England and Rushmere Member (Yorktown Formation) of the eastern USA (Campbell, 1993; MacNeil, 1965). However, Símonarson and Eiríksson (2021a, 2021b) conducted a comprehensive study of the genus *Mya* and showed that the reports of *Mya arenaria* in the Barmur Group were mistaken; the specimens were actually *Mya schwarzbachi*. Furthermore, the Coralline Crag Formation has now been dated as 4.4–3.8 Ma (De Schepper et al., 2009) and the base of the Rushmere Member as 3.3 Ma (Dowsett et al., 2021), so first appearances of any fauna at these locations compared with the Barmur Group must be diachronous. Thus, the 3.6 Ma age estimate for the Pacific-to-Atlantic faunal migration should be discounted. Verhoeven et al. (2011) dated the sudden arrival of Pacific molluscs in the Barmur Group at around 4.5 Ma using dinoflagellate biostratigraphy (Figure 2). We consider their estimate is a minimum (youngest possible) age because the age-diagnostic *Reticulatosphaera actinocoronata* extends well above the *Mactra/Serripes* boundary and up to Barmur Group bed 17, and has a known highest occurrence of 5.05–4.44 Ma in the Nordic Seas (Channell et al., 1999; Poulsen et al., 1996). Available biostratigraphic dating constraints for the Barmur Group are therefore in line with our radiometric estimate of 5.2–4.9 Ma for the Pacific-to-Atlantic faunal exchange event. Other lines of biostratigraphic evidence

from the Arctic and north Atlantic support a latest Miocene to earliest Pliocene age for Pacific-to-Atlantic biotic exchange (Figure 5b). Pacific-to-Arctic migration of floral elements through the Bering Strait during the time period 5.6–4.8 Ma has been inferred from the diatom distribution in a vibro-cored section from the Chukchi Sea, close to the north of the Bering Strait (Gladenkov & Gladenkov, 2004). Beets (1992) determined a $^{87}Sr/^{86}Sr$ age of 4.8–4.7 Ma for the first appearance of Pacific molluscs (including *Mya truncata*) in Pliocene sediments from the Heumensoord-46A/260 borehole in the Netherlands (Meijer, 1993).

The first opening of the Bering Strait has previously been dated by observations of Arctic-to-Pacific faunal exchange. Marincovich and Gladenkov (2001) estimated that the latest possible age for the first appearance of the Arctic bivalve *Astarte* in the Bear Lake Formation at Sandy Ridge, southwestern Alaska (i.e., in the northern Pacific), was 5.5–4.8 Ma. The dating was done using age-diagnostic diatoms excavated from within the bivalve shells. The age range is compatible with estimated ages of the first appearances of *Astarte* in other northern Pacific sections from Kamchatka and Japan (Gladenkov & Gladenkov, 2004). The published range of 5.5–4.8 Ma uses the Berggren et al. (1995) timescale; the equivalent age range within the Ogg (2020) timescale we use here is 5.6–4.8 Ma. Gladenkov et al. (2002) refined the most likely age of Arctic-to-Pacific mollusc faunal exchange to 5.5–5.4 Ma on the Berggren timescale (5.6–5.4 Ma on the Ogg timescale) using evidence from the Milky River Formation at Sandy Ridge. Thus, our new age range of 5.2–4.9 Ma for arrival of abundant Pacific mollusc fauna in Iceland is similar to, but does not quite overlap, the most reliable published age range of 5.6–5.4 Ma for Arctic-to-Pacific migration.

Marincovich (2000) proposed a two-stage faunal exchange model in which Arctic-to-Pacific migration occurred on first opening of the Bering Strait by the early Pliocene, followed several million years later by Pacific-to-Atlantic migration during the late Pliocene (Figure 5a). Our results cast doubt on this model (Figure 5b). If the age ranges are taken at face value, the arrival of abundant Pacific molluscs in Iceland in the Atlantic (5.2–4.9 Ma) could have occurred 0.2–0.7 million years after the arrival of Arctic molluscs at Sandy Ridge in the Pacific (5.6–5.4 Ma). However, the discussion above showed that the first recorded arrivals of Pacific-type mollusc fauna at different sites in the North Atlantic and Arctic vary by up to 1.9 million years (compare our bound of 5.2 Ma for the Barmur Group with the bound of 3.3 Ma for the Rushmere Member of the Yorktown Formation from Dowsett et al., 2021). Given this evidence for diachroneity, it is probably unwise to interpret trans-Arctic faunal exchange in two distinct stages on the basis of just two widely separated stratigraphic successions. The difference in age range between the faunal events in Iceland and Alaska could reflect a period of several hundred thousand years for molluscs to cross the Arctic, and it could also reflect site-specific limitations on the occurrence of molluscs. Presence of sparse Pacific-type mollusc fauna within the *Tapes* and *Mactra* biozones of the Barmur Group (Símonarson & Eiríksson, 2021b) is in line with the hypothesis that the molluscs crossed the Arctic quickly after first gateway opening, but the first appearance of abundant Pacific-type molluscs in Iceland was moderated by site-specific conditions. Thus, the most parsimonious explanation for the available faunal exchange data is that first opening of the Bering Strait in the latest Miocene (c. 5.5 Ma) was soon followed by marine faunal exchange in both directions.

Though the two-stage model of Marincovich (2000) was based primarily upon the previously accepted late Pliocene estimates for arrival of Pacific molluscs in Iceland, it was apparently supported by general circulation model (GCM) experiments that predict southward surface currents through the Bering Strait following its first opening (Maier-Reimer et al., 1990). Initial southward flow was hypothesized to have prevented Pacific-to-Atlantic faunal exchange, which began only after flow reversed to its present northward direction, possibly related to closure of the Central American Seaway (Horikawa et al., 2015; Marincovich, 2000). We do not necessarily reject the flow patterns predicted by such circulation models because we doubt they can be confidently related to planktonic faunal dispersal patterns: GCM palaeoclimate models predict currents averaged over time periods of over 500 years, very considerably longer than the planktonic larval stage of bivalve molluscs which lasts days to months.

5.2. Bering Strait Gateway After Its Initial Opening

The long-term tectonic driver for the first Cenozoic opening of the Bering Strait oceanic gateway is subduction of the Pacific Plate beneath Alaska (Marincovich et al., 1990; Scholl et al., 1992). At present, flat-slab subduction of the Yakutat block (an oceanic plateau within the northeastern Pacific Plate) is causing high crustal strain rates and high topography in southeastern Alaska (Elliott & Freymueller, 2020; Redfield et al., 2007). Present-day

lateral extrusion of Alaskan crust away from this high-strain region and toward the west and south (i.e., escape tectonics) is indicated by GPS measurements (Elliott & Freymueller, 2020). These crustal motions are associated with extensional earthquake focal mechanisms on normal faults in the Bering Sea region at present, including in the Bering Strait itself (Elliott & Freymueller, 2020). Regional tectonic models suggest that the northward motion of the Pacific Plate first brought the Yakutat block into contact with the Aleutian subduction zone during the late Miocene (Redfield et al., 2007). Thus, the establishment of the modern tectonic scenario in the Alaska-Bering Sea region in the late Miocene was soon followed by opening of the Bering Strait gateway near the Miocene/Pliocene boundary (by c. 5.5 Ma). The plate motion scenario and tectonic configuration do not appear to have changed significantly since the late Miocene (Redfield et al., 2007). Thus, the regional tectonic driver probably acted to maintain an open gateway from the early Pliocene to present.

Nevertheless, there is abundant, long-standing evidence that the Bering Strait gateway closed and re-opened multiple times after its first opening c. 5.5 Ma (e.g., Hopkins, 1967). These cycles of re-opening are thought to be eustatically driven. At present, the gateway is c. 85 km wide and up to 55 m deep (Woodgate & Aagaard, 2005). The rise in eustatic sea-level following the last glacial maximum was approximately 130 m (Lambeck, 2004). Thus, eustatic sea-level changes associated with the Pleistocene glacial cycles temporarily closed the gateway and re-established the Bering land-bridge. There is a considerable literature on migrations of land animals, including humans, across the Pleistocene land bridge (e.g., Bennett et al., 2021; Goebel et al., 2008; Hopkins, 1959; Moreno-Mayar et al., 2018). Climate modeling studies suggest that an open Bering Strait gateway tends to cool the North Atlantic-Arctic region and promote formation of sea-ice, in comparison with a closed gateway scenario (Brierley & Fedorov, 2016; Hu et al., 2010). This result raises the question of the relationship between the history of Bering Strait opening and Plio-Pleistocene climate cooling, including the iNHG (Brierley & Fedorov, 2016; De Schepper et al., 2015). Before discussing this question, it is helpful to consider whether the gateway was predominantly open or closed during the period between its late Miocene initial opening at c. 5.5 Ma and the late Pliocene iNHG.

The bivalve molluscs used to signal Bering Strait opening have long temporal ranges, which is why they themselves are not used to date the opening (Marincovich & Gladenkov, 1999). The Pacific and Atlantic/Arctic faunas were distinct up to the Miocene because the Bering land bridge had existed continuously since the Cretaceous (Fiorillo et al., 2008; Símonarson & Eiríksson, 2021a). Closure of the Bering Strait during a glacial cycle, or potentially for several million years, would not allow time for the faunas to become distinct again. Thus, the mollusc migration bioevent is a proxy for the first opening of the Bering Strait gateway, and it provides no useful information on subsequent temporary closures.

Plio-Pleistocene marine sediments that crop out along the coast of Alaska either side of the Bering Strait provide a record of relative sea-level which can be used to reconstruct gateway opening. Three Plio-Pleistocene depositional episodes are recognized, termed the Colvillian (oldest), Bigbendian and Fishcreekian transgressions (Carter, Brigham-Grette, & Hopkins, 1986; Carter, Brigham-Grette, Marincovich, et al., 1986). Fossil molluscs show that all these sediments post-date initial gateway opening (Brigham-Grette & Carter, 1992). The marine packages crop out above modern sea-level, which is interpreted to indicate an open Bering Strait gateway during all three depositional phases (Kaufman & Brigham-Grette, 1993). The Colvillian sediments indicate temperatures warmer than the present, with no permafrost or sea-ice; temperatures were similar or slightly cooler during the Bigbendian; and air temperatures were significantly cooler during the Fishcreekian, though marine conditions remained warmer than present (Brigham-Grette & Carter, 1992). Unfortunately, the Alaskan Plio-Pleistocene sediments have limited potential for dating, and the mollusc migration bioevent itself has been used as a tie point. Until now, this bioevent has been assumed to occur at c. 3.0–3.5 Ma (Gladenkov, 1981; Hopkins, 1967, 1972). Since the Colvillian transgression occurred after gateway opening, its age was interpreted as 2.7–2.48 Ma, and the age of the Fishcreekian as 2.48–2.14 Ma (Brigham-Grette & Carter, 1992). When our new estimate of c. 5 Ma for the mollusc migration tie point is applied instead, the Colvillian transgression could easily have occurred before 3 Ma, and possibly during the early Pliocene. The evidence for relatively warm surface sea-water temperatures during the Colvillian and Bigbendian periods is in line with age assignments between 5 and 3 Ma, because the Continental Offshore Stratigraphic Test boreholes in the Bering Sea record relatively warm temperatures during this period (Lagoe, 1992). In the Chukchi Sea, just north of the Bering Strait, the first sediments that overlie the Upper Cretaceous basement, and are thought to post-date gateway opening, are a marine succession deposited between 5 and 2 Ma (dated independently of molluscs) in a climate warmer than today (Gusev et al., 2009). In summary, the evidence from sedimentary successions close to the Bering Strait gateway suggests that the gateway

was open for a significant part of the 5 to 2 Ma period following its initial opening, and this early open period preceded local climatic cooling. An unconformity overlies the Pliocene succession, and the overlying sediments are thought to be Middle to Upper Pleistocene in age (Brigham-Grette & Carter, 1992; Gusev et al., 2009). This evidence perhaps suggests that the first regression to close the Bering Strait gateway for a significant period after its initial opening occurred during the latest Pliocene to early Pleistocene.

A continuous history of Bering Strait gateway opening can be estimated from the eustatic sea-level curves. O'Regan et al. (2010, Figure 4f) presented a sea-level curve from oxygen isotopes corrected for global cooling (Lisiecki & Raymo, 2005; Miller et al., 2005; Zachos et al., 2001), and superimposed the level that would imply closure of the Bering Strait gateway (50 m below modern sea-level). Whilst this prediction of gateway opening history ignores any possible tectonic vertical motions or changes in dynamic support, it does align with the predictions based on the sedimentary record close to the gateway discussed above. The eustatic sea-level curve suggests that the gateway was predominantly open for almost all of the Pliocene and the early Pleistocene (before 5 to 2 Ma). More frequent and longer lasting closures during glacial periods began at c. 1.6 Ma, and the gateway was predominantly closed after 1 Ma.

5.3. Climatic Consequences of Bering Strait Opening

The extent to which global climate change is influenced by inter-ocean flow has received attention for decades (Haug & Tiedemann, 1998; Maier-Reimer et al., 1990). Brierley and Fedorov (2016) show a GCM modeling study of the effect of opening and closing the Bering Strait while keeping other parameters constant. An open Bering Strait allows relatively fresh Pacific water into the Arctic and North Atlantic, which reduces the strength of AMOC, and reduces high-latitude Atlantic surface temperatures. Hu et al. (2010) found an essentially similar result for glacial-interglacial cycles. Eustatic sea-level fall during the glacial periods temporarily closes the Bering Strait, increases the strength of AMOC, causes high-latitude Atlantic warming, and thus promotes northern hemisphere icesheet melt-back. On the bases of these climate modeling results and late Pliocene (post 3.2 Ma) estimates for Bering Strait gateway opening, Brierley and Fedorov (2016) hypothesized that opening of the Bering Strait could have been a significant influence on the iNHG. Our results argue against this hypothesis. The Bering Strait gateway was open by the latest Miocene c. 5.5 Ma and remained predominantly open during the Pliocene and into the early Pleistocene (Section 5.2). The iNHG involved significant expansion of northern hemisphere ice sheets in the late Pliocene and culminated in the establishment of glacial-interglacial cycles by the early Pleistocene. Local to Iceland, the iNHG is expressed as expansion of the Greenland icesheet from the southern uplands across northern Greenland c. 3.5–3.0 Ma (Maslin et al., 1998), and establishment of cycles of lowland glaciation in Iceland by c. 2.7 Ma (Eiríksson, Guðmundsson, et al., 2021; Geirsdóttir & Eiríksson, 1994). Thus, the Bering Strait gateway was open for over 2 million years prior to the iNHG. The AMOC, as indicated by the %Northern Component Water proxy and sediment drift accumulation rates south of Iceland, was relatively strong during the period between 5 and 2.7 Ma when the Bering Strait gateway was open (Parnell-Turner et al., 2015; Poore et al., 2006). The combined evidence argues against a simple, direct link between first opening of the Bering Strait gateway, northern hemisphere cooling and AMOC weakening.

At present, flow of Pacific water northward through the Bering Strait supplies about one third of the total fresh-water input to the Arctic (Woodgate & Aagaard, 2005). Introduction of relatively fresh water to the Arctic during periods with an open Bering Strait gateway is thought to promote the formation of sea ice. Both sea ice and relatively fresh sea water are exported from the Arctic to the Atlantic via the Fram Strait and the East Greenland Current (EGC). It has been proposed that formation of the EGC at 4.5 Ma, and coeval development of sea ice in the Iceland Sea, were driven by the initial opening of the Bering Strait (Clotten et al., 2019; De Schepper et al., 2015). This hypothesis was made on the basis of the Verhoeven et al. (2011) age model for the Barmur Group in Iceland, which places the Pacific-to-Atlantic mollusc migration bioevent at 4.5 Ma (De Schepper et al., 2015). We have shown that the mollusc migration bioevent occurred between 5.2 and 4.9 Ma, which preceded formation of the EGC and Iceland Sea sea-ice by at least 400 thousand years. Given the fragmentary record of sea-level change near the Bering Strait (Section 5.2), it could perhaps be argued that the gateway was too shallow for significant low salinity Pacific water to enter the Arctic Ocean when it first opened, even though mollusc larvae could migrate, and that input of Pacific water sufficient to form sea ice and initiate the EGC did not occur until 4.5 Ma. On the other hand, development of sea ice within the Arctic Ocean and Nordic Seas was diachronous. Seasonal sea ice was already present at the ACEX site in the central Arctic (Lomonosov Ridge) during the Upper Miocene

(O'Regan et al., 2010; Stein et al., 2016), before first opening of the Bering Strait gateway. When the Bering Strait gateway first opened at c. 5.5 Ma, no noticeable change in ice-rafted debris occurred at the ACEX site (O'Regan et al., 2010). Although seasonal sea ice appeared in the Iceland Sea at 4.5 Ma, seasonal sea ice did not occur along the Eurasian margins of the Arctic Ocean until c. 4.0 Ma (Knies et al., 2014). Thus, we see no compelling evidence for a simple, direct link between the first opening of the Bering Strait, development of sea-ice in the Arctic Ocean and Nordic Seas, and initiation of the EGC.

5.4. The Late Pliocene-Quaternary Record From the Tjörnes Succession

We have shown that the top of the Barmur Group is up to 1.5 million years older than previous estimates (Figure 2). This revision has significant implications for the interpretation of palaeoenvironmental data from the Barmur Group. The Barmur Group contains a variety of macrofossils and microfossils that have been used extensively for palaeoenvironmental reconstruction (Bárðarson, 1925; Buchardt & Símonarson, 2003; Cronin, 1991; Dowsett & Poore, 1991; Field et al., 2017; Pflug, 1959; Schwarzbach & Pflug, 1957; Símonarson et al., 2021; Strauch, 1972b; Verhoeven & Louwye, 2013; Verhoeven et al., 2013). In particular, sea-surface temperature estimates from this locality (previously known as the Tjörnes beds) were included in the first four generations (0–3) of the PRISM reconstruction of the mPWP (Cronin, 1991; Dowsett & Poore, 1991; Dowsett et al., 1994, 1996; Dowsett et al., 1999, 2010). We have dated the top of the Barmur Group to 4.631–4.493 Ma (Early Pliocene). The Barmur Group therefore does not contain the mPWP. Our result supports the removal of the Barmur Group/Tjörnes beds data from the latest PRISM4 sea surface temperature reconstruction (Dowsett et al., 2016; Robinson et al., 2018). However, the PRISM4 global topographic reconstruction shows a closed Bering Strait (Haywood et al., 2016, 2020). A more realistic topographic boundary condition for the mPWP would show an open Bering Strait (Section 5.2).

Our revised age for the Barmur Group also has a significant impact on the age model for the overlying Tjörnes succession, which is important because these rocks provide the only onshore exposure record of the onset of lowland glaciation in Iceland (Geirsdóttir & Eiríksson, 1994). The first evidence of lowland glaciation defines the boundary between the Höskuldsvík Group (cycles of basaltic lavas intercalated with sub-aerial, non-glacial sediments) and the Breiðavík Group (cycles of lavas intercalated with glacial diamictites). Our revised age model for the Barmur Group could be accommodated in several ways, which are not mutually exclusive. One possibility is that the Höskuldsvík Group accumulated continuously over a considerably longer period of time than has previously been proposed (Figure 2, Option 1). In this scenario the Höskuldsvík Group might record the mPWP. But although such an mPWP record might mitigate its absence in the Barmur Group in principle, the chances of obtaining useful palaeoenvironmental data from the Höskuldsvík Group sub-aerial lava field environment seem small. Another possibility is that a break in deposition occurred between the Höskuldsvík and Breiðavík Groups (Figure 2, Option 2). This possibility is supported by the observation of an angular unconformity between these groups (Eiríksson, Guðmundsson, et al., 2021). The related erosion might be linked to the first establishment of lowland glaciation in Iceland, since a 6 m thick lodgement till (Unit I:A of Eiríksson, Guðmundsson et al., 2021) rests directly upon the unconformity. A final possibility for the upper Tjörnes sequence age model is that the base of the Breiðavík Group could have a different age than currently thought (Figure 2, Option 3). The commonly accepted age is c. 2.6 Ma (Eiríksson et al., 2021a). This age is based on interpolation between Ar-Ar ages of <1.2 Ma from the upper Breiðavík Group (Camps et al., 2011) and the 1970s K-Ar ages for the Höskuldsvík Group that we have revised here. A similar interpolation with our Ar-Ar age for the Höskuldsvík Group would suggest the lowermost Breiðavík Group is up to 1 million years older than 2.6 Ma, potentially bringing the age of the Icelandic lowland glaciation into line with the northward expansion of ice in Greenland (3.5–3.0 Ma, Maslin et al., 1998), but this interpolation is not valid if an unconformity is present beneath the Breiðavík Group. Verhoeven et al. (2011) suggested an age of >1.95 Ma for the Hörgi Formation near the base of the Breiðavík Group on the basis of dinoflagellate cyst biostratigraphy, but they did not date the basal Breiðavík Group. Thus, the age of the onset of lowland glaciation in Iceland is not well constrained. We are currently in the process of testing these possibilities for the upper Tjörnes sequence age model by Ar-Ar dating of the lavas from the upper Höskuldsvík and lower Breiðavík Groups.

6. Conclusions

We obtained four new Ar-Ar radiometric ages for basaltic lavas that lie within, above and below the Barmur Group (formerly Tjörnes beds) of northern Iceland, and integrated them with existing paleomagnetic data, in order to better exploit the many existing records of palaeo-environmental change from this section.

Our Ar-Ar age for the Skeifá lava shows that the first arrival of abundant Pacific bivalve molluscs in Iceland, which is widely accepted as a signal of first opening of the Bering Strait, occurred within magnetic subchrons C3n.4n–C3n.3r, at 5.235–4.896 Ma. This age estimate is over 1.3 million years earlier than previous estimates, which were all skewed by less reliable 1970s-vintage K-Ar ages. Our new age range for the first Pacific-to-Atlantic faunal exchange is similar to, but does not quite overlap, the most reliable published age range of 5.6–5.4 Ma for Arctic-to-Pacific migration. The difference in age might reflect site-specific limitations on mollusc habitability, since sparse Pacific molluscs have been noted prior to the arrival of abundant Pacific molluscs in Iceland, and it might also reflect the time taken for Pacific molluscs to migrate across the Arctic. Thus, first opening of the Bering Strait gateway in the latest Miocene, c. 5.5 Ma, was soon followed (within a few hundred thousand years) by trans-Arctic faunal exchange in both directions. Our revised date for Pacific-to-Atlantic mollusc migration removes the main piece of evidence for a previously hypothesized two-stage trans-Arctic migration event lasting over a million years.

Re-evaluation of trans-Arctic marine faunal exchange, the record of transgressions from sedimentary successions adjacent to the Bering Strait gateway, eustatic sea-level, and tectonic motions of Bering Strait suggests that the Bering Strait gateway was predominantly open for all of the Pliocene and the early Pleistocene (before 5 to 2 Ma). More frequent and longer lasting closures during glacial periods began at c. 1.6 Ma, and the gateway was predominantly closed after 1 Ma. Thus, we see no compelling evidence for previously proposed simple, direct links between the first opening of the Bering Strait oceanic gateway (c. 5.5 Ma), development of sea-ice in the Iceland Sea and initiation of the EGC (c. 4.5 Ma), and iNHG as signaled by major icesheet expansions in Greenland and Iceland (c. 3.5–2.7 Ma).

The topmost sediments in the Barmur Group and the lowermost lava in the Höskuldsvík Group lie within magnetic subchron C3n.2n at 4.631–4.493 Ma (Early Pliocene), older than all previous age models. The Barmur Group does not record the mid-Piacenzian Warm Period. There is no significant hiatus at the boundary between the Barmur and Höskuldsvík Groups. The upper Barmur Group (*Serripes* biozone) records each and every magnetic subchron down to the Skeifá lava, giving confidence in our new age model. Our revised, significantly older age for the Barmur Group implies that the upper Tjörnes succession accumulated over a correspondingly longer time period, which might be accommodated by longer durations for the Höskuldsvík and/or Breiðavík Groups, and/or a significant hiatus between these groups. Improving the age model for the upper Tjörnes sequence is an important aspiration because the lower Breiðavík Group provides the only onshore exposure record of the onset of lowland glaciation in Iceland.

The Kaldakvísl Group immediately underlying the Barmur Group has an Ar-Ar age of 9.8 ± 0.1 Ma (late Miocene). A lava at Grænhöfði previously thought to be within the Barmur Group has an Ar-Ar age of 9.3 ± 0.1 Ma. This lava is actually a faulted sliver of Kaldakvísl Group basement. We estimate that the age of the base of the Barmur Group is 6.0 ± 0.6 Ma (terminal Miocene) by linear extrapolation of the sedimentation rate determined for the upper Barmur Group. This age agrees with age-diagnostic dinoflagellate cysts and foraminifera, and also with the age of formation of the Tjörnes Basin.

Data Availability Statement

Data sets related to this article can be found at Hall et al. (2022), available via the Zenodo open data repository.

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