

Chapter 6

An Age Model for the Miocene to Pleistocene Tjörnes Sequence, North Iceland



Jón Eiríksson, Leifur A. Símonarson, and Karen Luise Knudsen

Abstract According to a new revised age model which is consistent with published paleomagnetic and radiometric data, marine sedimentation in the Tjörnes Basin started close to the Miocene-Pliocene boundary. The oldest part of the north-west dipping sedimentary sequence, the *Tapes* Zone, is not a continuous, conformable sequence, but has been dislocated laterally within the Tjörne Fracture Zone. Its basal age was previously determined by dinoflagellate stratigraphy. Above the boundary between the *Tapes* and *Maetra* Zones the sequence is continuous, but the development of a graben to the east of the present coastline changed the focus of accumulation. An erosional surface developed to the west of this graben, resulting in a gap in the presently exposed coastal section. The uppermost part of the *Maetra* Zone is correlated to a level within the uppermost Gilbert reversed polarity chron with an estimated age of 3.8 Ma. *Serripes* Zone sediments span the interval 3.8–3.2 Ma, and the lowest tillite bed of the Tjörnes sequence in the Furuvík creek is dated to the Gauss-Matuyama boundary at 2.58 Ma. Volcanic units both in the coastal sections on east Tjörnes and in the Grasafjall and Búrfell mountains in central Tjörnes expose Matuyama-Brunhes chron boundary at 0.78 Ma.

Keywords Tjörnes · Tjörnes age model · North Iceland · Paleomagnetic dating · Radiometric dating · Pliocene biostratigraphy · Quaternary biostratigraphy

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6.1 Introduction

By the mid-nineteenth century the marine fossiliferous sequence on Tjörnes, North Iceland (Fig. 6.1), had been assigned to the Pliocene with reference to the Crag Formation in England (Winkler, 1863). The most recent age model for the Tjörnes sequence as a whole was published by Verhoeven, Louwe, Eiríksson, and De Schepper (2011), who concluded that the oldest marine deposits were of Pliocene or terminal Miocene age, and that the sequence also contained Quaternary marine deposits. Modern age estimates for the Tjörnes sequence are based on more than one independent technique. Recent geological mapping of the Tjörnes Peninsula has contributed to determination of the relative age of rock units, and to identification of unconformities and potential gaps or hiati in the Miocene to Pliocene part of the sequence, as well as definition of lithostratigraphic units (Fig. 6.2). Until now, stratigraphic relationships in the traditional Tjörnes beds have been presented as sketches of the coastal outcrops with no three-dimensional mapping, very poor registration and identification of faults, and sometimes, erroneous strike and dip determinations. The present authors have collected new data on the field relations, thereby improving stratigraphic control (Eiríksson et al., 2020b; Eiríksson et al., 2020c). Secondly, the fossil material and biostratigraphic correlations based on both macro- and microfaunas and floras are used to obtain a time framework. Thirdly, published radiometric dates from volcanic rocks in the sequence are applied in order to obtain absolute ages. This has involved published K/Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ dates. The volcanic rocks on Tjörnes have turned out to be poor material for these dating methods, due to both low potassium content and geothermal alteration. Typical dating errors for single dates amount to 0.2 to 0.6 Ma, even with the most modern methods (e.g. Camps et al., 2011). Finally, paleomagnetic measurements have been used to correlate lithological units to a time scale. A detailed Paleomagnetic record for both the volcanic and sedimentary rocks is available from the top of the Tjörnes sequence down to and including the *Maetra-Serripes* Zone boundary. Below that the measurements are not considered reliable (cf. Kristjánsson, 2004).

In this chapter, we review the available chronological data and present a new revised age model for the sequence based on these data, which differs from previously published age models. The differences are primarily related to new geological mapping of stratigraphic units in the lower part of the Tjörnes sequence, and the mapping and interpretation of tectonic features. Recently published radiometric dates refine the age model for the upper part of the Tjörnes sequence. Nevertheless, considerable uncertainties associated with many of the units remain, but we attempt to address these uncertainties in conjunction with the age model.

In the following sections, available age model data and geological features of specific intervals of the Tjörnes sequence (for stratigraphical units, see Figs. 6.2 and 6.3) are reviewed, followed by details of the new age model.



Fig. 6.1 Location map of Tjörnes Peninsula with inset map of Iceland

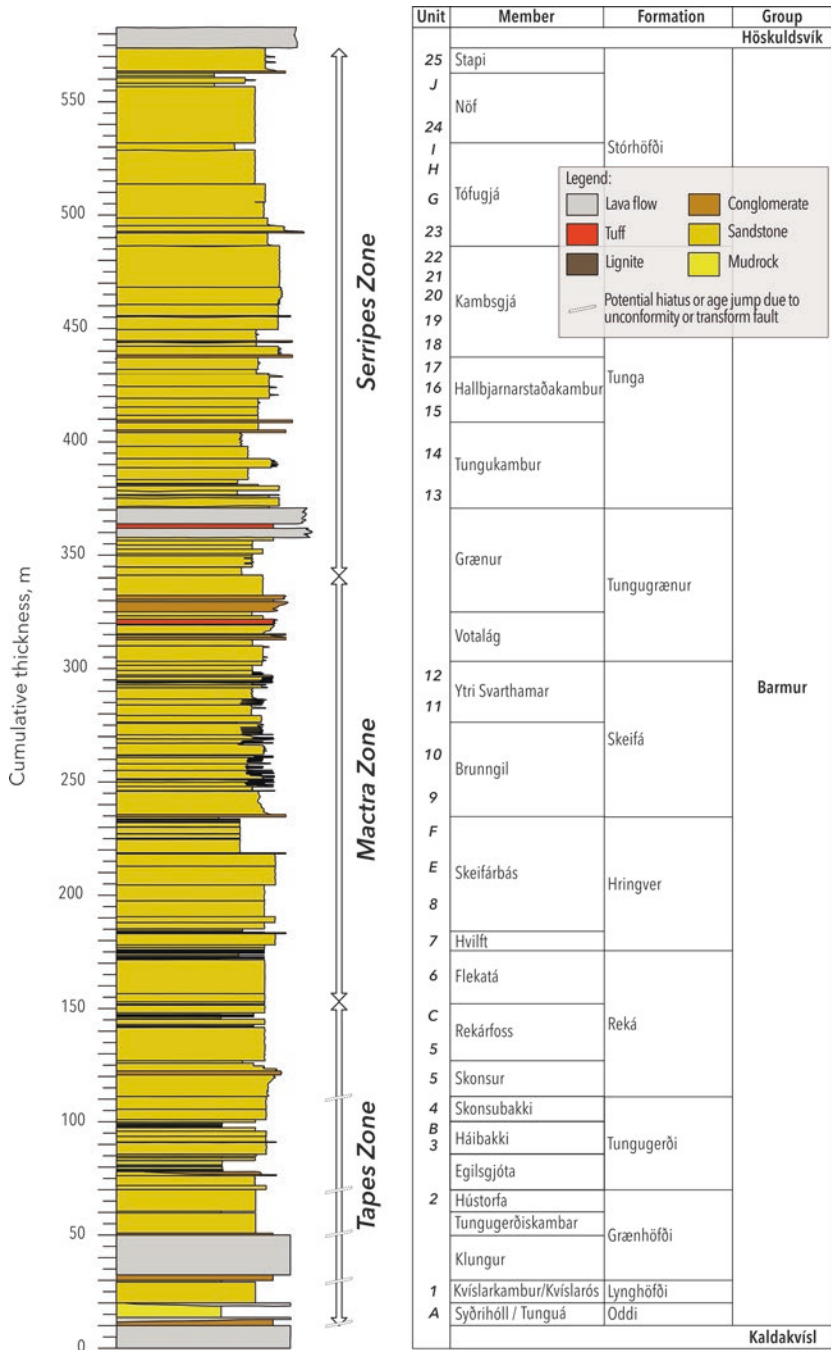
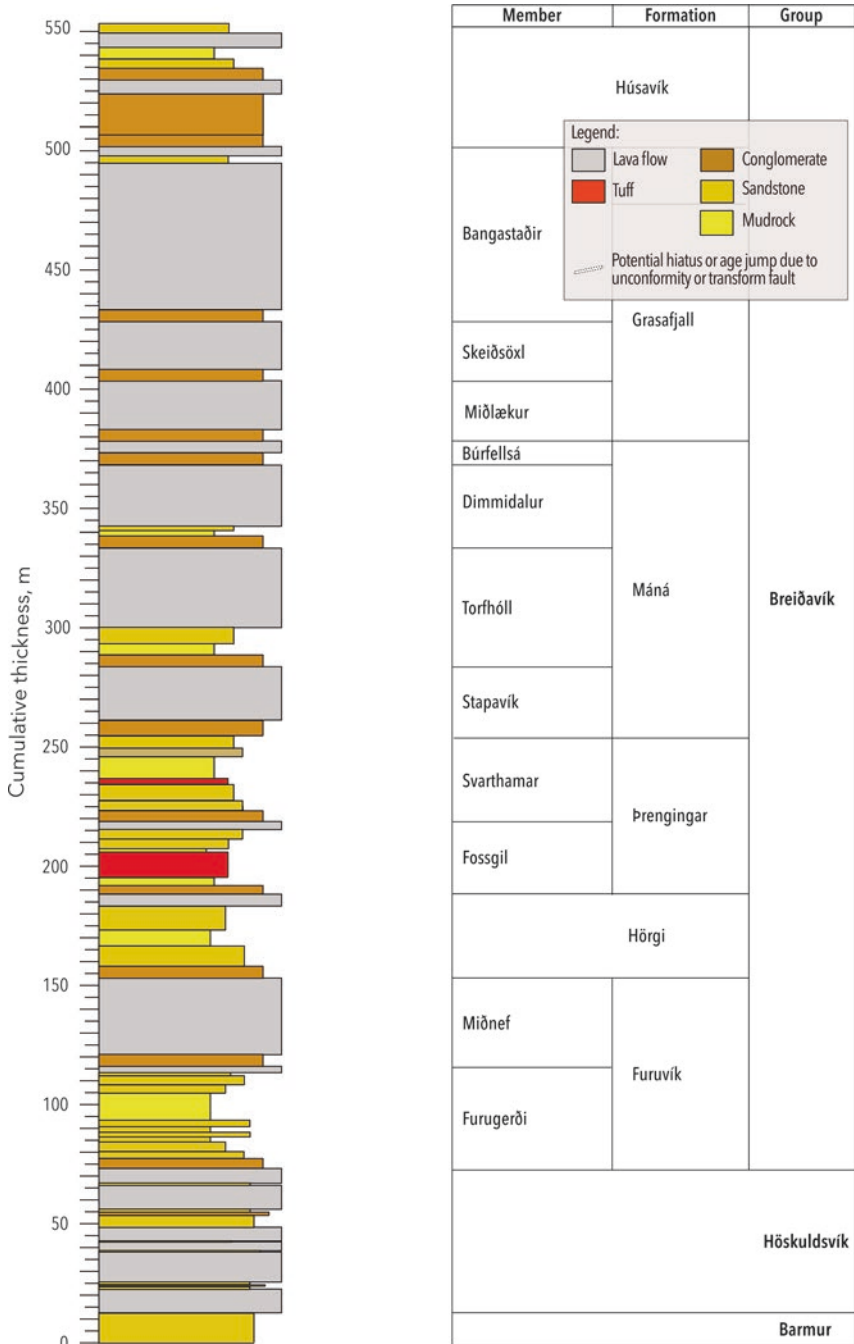


Fig. 6.2 Composite stratigraphic column for the Barmur Group (Eiríksson et al., 2020c). The subdivision of the Barmur Group in formations and members is shown. Bárðarson's (1925) marine (1–25) and terrestrial units (A–J) are entered on the left-hand side of the members



6.2 The Kaldakvísl Lava Group. Chronological Data from the Basement Lavas South of Tunguá and Kaldakvísl

The bedrock underlying Pliocene sediments and Quaternary volcanics and sediments on Tjörnes Peninsula consists of a thick sequence of north-west dipping lava flows, typically separated by thin redbeds. Only limited data are available on the relative age of different lithological units within this basement, which is assigned to the Kaldakvísl Lava Group (Fig. 6.2). Consequently, it is not possible to arrange the available dates in stratigraphical order, except dates from the Syðrihóll locality (Fig. 6.1). Sæmundsson (1974) estimated the thickness of the basal plateau lavas of Tjörnes at 1000 m. Radiometric ages range from approximately 6 to 10 Ma for the sequence exposed near the river Kaldakvísl (Albertsson, 1976; Aronson & Sæmundsson, 1975). The authors refer to the values as minimum ages. One of the Neogene lava flows on the east side of Tjörnes was dated radiometrically to 7.4 ± 0.2 Ma by Albertsson (1976). All available dates from the Kaldakvísl lava zone indicate an upper Miocene age.

6.3 The Barmur Group

The traditionally named Tjörnes beds are exposed along the west coast of Tjörnes from the mouth of the river Kaldakvísl northward to Höskuldsvík, as well as in river canyons on the west side of Tjörnes (Fig. 6.1). The name Barmur Group (Eiríksson et al., 2020c) is used here instead of the informal term Tjörnes beds. The base of the Barmur Group is exposed close to the mouth of the river Kaldakvísl. While the Kaldakvísl Lava Group environment was dominated by the emplacement of sub-aerial lava flows, soils, and thin sediments, the Barmur Group rocks consist mainly of marine sediments with several lignite seams and a few lava flows and pillow lavas, especially close to the base. In Höskuldsvík, the Barmur Group sediments are overlain by terrestrially emplaced lava flows.

6.3.1 *Previous Age Models for the Traditional Tjörnes Beds*

Generally, the Tjörnes beds have been described as a 450–550 m thick, north-west dipping, conformable sequence of alternating marine and terrestrial sediments, extending from Bárðarson's (1925) lignite unit A south of the Kaldakvísl river mouth (Fig. 6.1) to marine sandstone 25 in Höskuldsvík (cf. Bárðarson, 1925; Eiríksson et al., 2020c; Strauch, 1963). Based on the mollusc fauna of the Barmur

Group marine units, the Tjörnes beds have been considered of Pliocene age (Bárðarson, 1925; Gardner, 1885; Strauch, 1963; Winkler, 1863). A radiometric age obtained from a lava flow immediately north of Kaldakvísl, underlying Bárðarson's sandstone units c, d, e, and marine unit 2 ("The *Tapes* horizon") yielded 4.30 ± 0.17 Ma (Albertsson, 1976, 1978). Albertsson considered this to be a minimum age. The age model for the Tjörnes sequence was revised by Verhoeven et al. (2011), who, based on the absence of Miocene dinoflagellate species in the Tjörnes beds, suggested a post-Miocene age for the base of the Tjörnes beds, although an uppermost Miocene age could not be excluded.

6.3.2 *The Héðinshöfði Graben*

The Héðinshöfði Formation is exposed within a graben structure on Héðinshöfði Peninsula (cf. Eiríksson et al., 2020c). A basal lava flow was radiometrically dated to 4.0 ± 0.8 Ma by Aronson and Sæmundsson (1975). Another K/Ar date from a monolithic basalt agglomerate higher up in the sequence yielded an age of 2.6 ± 0.2 Ma. Aronson and Sæmundsson (1975) correlated part of the Héðinshöfði sequence with the lowest part of the Breiðavík Group ("Furuvík beds") on the basis of radiometric ages, paleomagnetic data, and sedimentary facies. The basal flow date is similar to the date published by Albertsson (1976) for a lava flow in the Grænhöfði tectonic block north of the river Kaldakvísl, and the overlying lava and sediments in Héðinshöfði are considered to belong to the Barmur Group and the Höskuldsvík Group.

6.3.3 *The Eyvík Graben*

A second graben structure dissecting the Kaldakvísl lava basement is located at Eyvík (cf. Eiríksson et al., 2020c). Neither radiometric dates nor paleomagnetic data are available for the rocks at this locality. A species list of marine fossils collected in the Eyvík graben sediments was published by Emilsson (1929). The species correspond to the *Serripes* Zone of the Barmur Group north of the river Kaldakvísl. The age estimate for this specific unit, the Eyvík Formation, is based on correlation of the basal lavas with the Kaldakvísl lavas and of the fossiliferous sediments with the *Serripes* Zone. The relative age is considered younger than the altered Kaldakvísl lavas to the south and to the north. The sediments indicate rugged terrain and development of lacustrine and marine basins, as well as local sediment sources. The development of the graben is considered analogous to the Héðinshöfði basin and related to transform movement along the southern margin of the Tjörnes Fracture Zone (cf. Eiríksson et al., 2020a).

6.3.4 *The Kaldakvísl Locality and the Age of the Tapes Zone*

Since Bárðarson's pioneering work on the Tjörnes stratigraphy, the base of the sedimentary sequence traditionally called the Tjörnes beds has been defined at the lignite unit A just south of the mouth of the river Kaldakvísl (Fig. 6.1; Bárðarson, 1925). However, later observations and mapping have shown that the locality is distorted by faults and a straightforward correlation across the river is not possible.

The northern limit of the exposed Kaldakvísl lava zone rocks crops out along the coastline just south of the Kaldakvísl river mouth and is marked by a fault zone. The dates published by Aronson and Sæmundsson (1975) are based on samples at this northern limit, collected along the rivers Kaldakvísl and Tunguá (Fig. 6.1). The contact with the traditional Tjörnes beds is not exposed to the south of the faults at Kaldakvísl.

In the light of our new investigation of the Kaldakvísl river mouth locality, and a new definition of lithostratigraphic units, the sequence across the Kaldakvísl and Tunguá rivers cannot be regarded as a continuous sequence of strata. Instead, we have to regard the lithological record in blocks separated by faults as separate units, which cannot be correlated lithostratigraphically across the faults. This is because the faults result from horizontal relative offsets of the blocks (cf. Eiríksson et al., 2020c). The amount of lateral displacement is unknown and may amount to several kilometres or even tens of kilometres (cf. Eiríksson et al., 2020a). However, the fossil record in these blocks places them within the *Tapes Zone*.

In Bárðarson's original stratigraphy of the Pliocene Tjörnes beds, his zones included not only marine sediments but also several units of lignites and sandstones without marine molluscs. The oldest biozone of the Barmur Group, the *Tapes Zone*, is no exception. The base of the *Tapes Zone* contains terrestrial units and a lava flow succeeded by marine fossiliferous pebbly sandstone. These terrestrial sedimentary units are therefore somewhat older than estimates of the age of the first marine deposits based on faunal evidence.

The most recently published age model for the Tjörnes sequence places the base of the marine part of the Tjörnes beds (within the *Tapes Zone*) somewhat arbitrarily at 5 Ma (Verhoeven et al., 2011: Fig. 3), but, as mentioned, the authors concluded that a terminal Miocene age could not be excluded. The Miocene-Pliocene boundary is currently defined at 5.33 Ma (Cohen et al., 2013). According to new stratigraphic and mapping data (Eiríksson et al., 2020c), the youngest radiometric date from lava flows stratigraphically below the *Tapes Zone* is 6.14 ± 0.27 (Albertsson, 1976). The lava flow which underlies the *Tapes Zone* sediments in Grænhöfði is now lithostratigraphically placed within that zone (see discussion below). With the available dating results, it is not possible to give a precise date for the base of the Barmur Group. It seems most appropriate to work with a date above the youngest Kaldakvísl lava zone K/Ar date and below the Miocene-Pliocene boundary, and we propose an estimated age of 5.85 ± 0.5 Ma (Fig. 6.4). This age is simply an average of the Miocene-Pliocene boundary age and the K/Ar date (including error limit) from the lava flow beneath the lowest terrestrial units of the *Tapes Zone* with the error representing the range of these two ages. A terminal Miocene age is consid-

ered compatible with the occurrence of Miocene to Pliocene foraminiferal species in the *Tapes* Zone.

6.3.5 Tectonic Fault Blocks at the Base of the Barmur Group: The Lynghöfði – Kaldakvísl – Grænhöfði Area

Three lithostratigraphical formations have been introduced here for the sedimentary and volcanic sequences at the base of the Barmur Group (cf. Eiríksson et al., 2020c). The Lynghöfði Formation (Fig. 6.2) lies just south of the mouth of the river Kaldakvísl and is currently accessible in an excavation adjacent to a hydroelectric power station at the river mouth. The Oddi Formation is defined for the rocks above the Kaldakvísl lava zone in the tongue defined by the bifurcation of the rivers Kaldakvísl and Tunguá (Fig. 6.1). North of the river mouth of Kaldakvísl, the Grænhöfði Formation crops out in the hill Grænhöfði rising from the beach level. Rocks of that formation have also been penetrated by a borehole located at the top of the hill.

An outcrop of the traditional Tjörnes beds is located immediately south of the mouth of the river Kaldakvísl in the Lynghöfði hill (cf. Eiríksson et al., 2020c). The sequence starts with terrestrial sediments (Bárðarson's unit A), followed by marine unit 1, "The *Mytilus* deposit at Kaldakvísl". Unit 1 has been included in the lowest mollusc biozone of the Tjörnes beds, the *Tapes* Zone, in all previous studies. The Lynghöfði Formation is therefore not older than the base of that zone, which is estimated at 5.85 ± 0.5 Ma. The outcrop is isolated and bordered by faults. The sequence of strata does not correspond to the adjacent outcrops in the Syðrihóll hill east of the confluence of the Kaldakvísl and Tunguá rivers (Fig. 6.1), nor to outcrops north of the Kaldakvísl river mouth.

Both the north and south sides of the confluence hill (Syðrihóll) between Kaldakvísl and Tunguá expose basement basalts followed by terrestrial sediments, two lava flows separated again by terrestrial sediments (Tunguá Member, cf. Eiríksson et al. 2020c), and, finally marine sandstone (Syðrihóll Member). The dates published by Aronson and Sæmundsson (1975) are from the basement basalts between Tunguá and Kaldakvísl (Oddi, cf. Fig. 6.1 and location map in Eiríksson et al., 2020c). Albertsson (1976, 1978) dated two flows beneath the sediments in Syðrihóll. The uppermost of these yielded an age of 6.14 ± 0.27 , and the marine fossils in the Syðrihóll Member are consistent with the *Tapes* Zone. The Oddi Formation is therefore considered to be younger than 5.85 ± 0.5 Ma, and to correspond in age to the *Tapes* Zone of the Barmur Group (Figs. 6.2 and 6.4). There is no obvious lithological correlation with the section containing units A and 1 south of Kaldakvísl. A minor rotated block with south-east dipping sediments is located at the foot of the confluence hill at Oddatá, exposing both a marine and terrestrial marine unit (cf. Eiríksson et al., 2020c).

The coastal section in Grænhöfði starts with two lava flows (the upper one was dated to 4.30 ± 0.17 Ma by Albertsson (1976, 1978)) followed by a thin, discontinu-

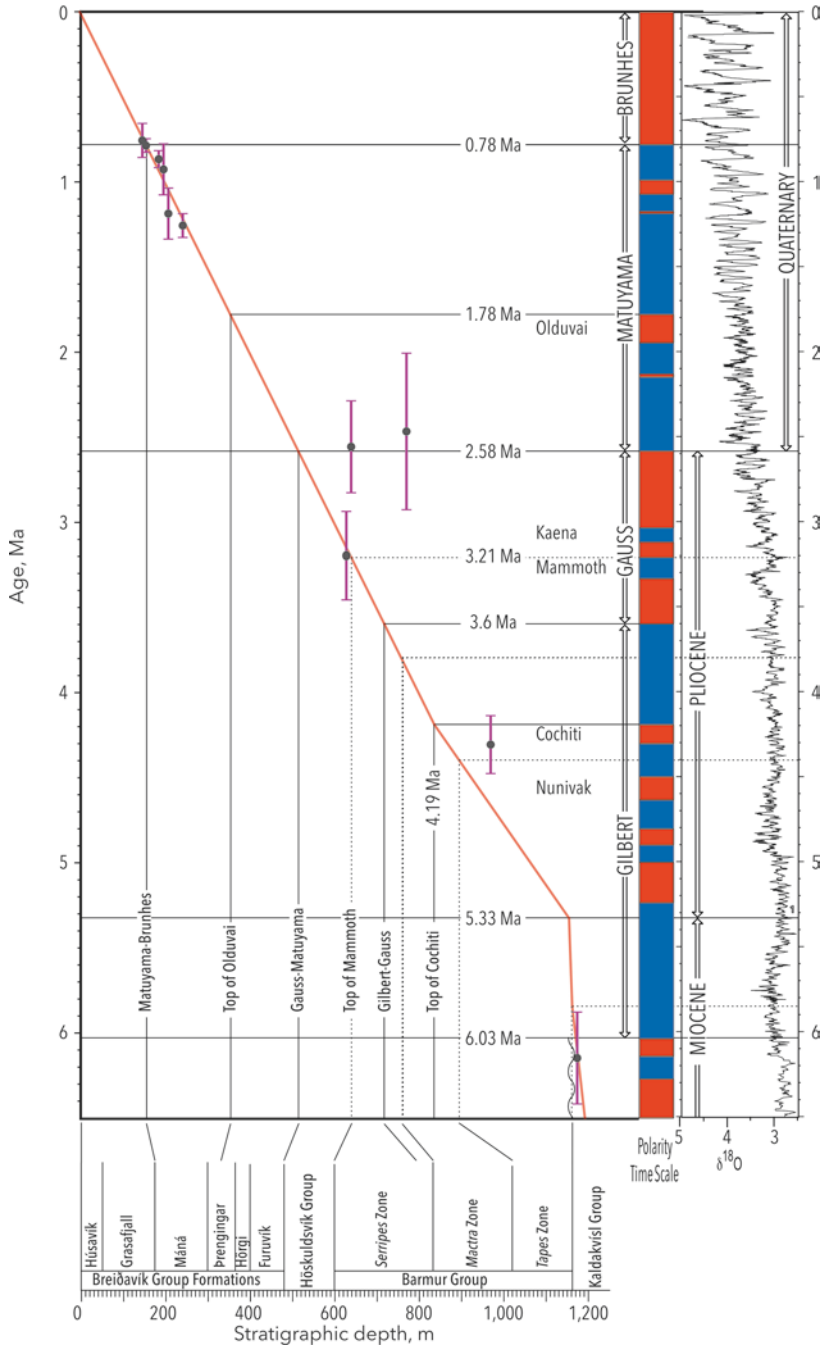


Fig. 6.4 A revised age model for the Tjörnes sequence. Radiometric dates are shown with blue circles and purple error bars. The red age model line is a simplification and does not show hiatus

ous pebbly conglomerate and then by Bárðarson's units c, d, e, and 2. These fossiliferous sediments belong to the *Tapes* Zone. With respect to the estimated age of the base of the *Tapes* Zone, the lavas at the base of Grænhöfði fall within the *Tapes* Zone.

A borehole core was drilled from the top of the Grænhöfði hill, penetrating the sediments down to the lava flows, and below that additionally 50 m of lava flows and red sedimentary beds (cf. Eiríksson et al., 2020c). One layer of sandstone and conglomerate was penetrated (Richter, 2001, 2002), and the base of the *Tapes* Zone in the core section is tentatively placed at the base of this 4 m thick conglomerate.

6.3.6 *Sedimentary Sequence Between Egilsgjóta and Skeifá, Below the Skeifá Basalts*

The Grænhöfði lavas and overlying sediments are terminated northward by a fault just south of Egilsgjóta (Fig. 6.1). The fault planes at Egilsgjóta display sub-horizontal slickensides, indicating lateral relative movement of the blocks on either side. It is not possible to correlate the sediments across the faults based on lithostratigraphy. The faults mark the northern margin of exposed lava flows in the Barmur coastal section (cf. Eiríksson et al., 2020c).

The faults at Egilsgjóta are considered to represent major right-lateral faults cutting across the Tjörnes sequence. Bárðarson's (1925) units d, 3, B, and 4 are exposed immediately north of Egilsgjóta, and the sequence continues with north-west dipping units along the coast towards the top of the Barmur Group in Höskuldsvík (Fig. 6.1). The most conspicuous lignite seam of the Tjörnes sequence, Bárðarson's unit F, crops out in the coastal section at the Skeifá waterfall, and has been mapped eastward along the Skeifá river valley towards the so-called Skeifá basalts. These volcanic units, which are partly in the form of pillow lavas, have been placed within the *Serripes* Zone by several workers in the area (Einarsson et al., 1967; Strauch, 1963). Numerous north-south trending faults across the Skeifá valley delineate a graben structure, with an aggregate eastward downthrow of at least 300 m. The graben structure trends northward to the Breiðavík Bay. The geomagnetic polarity of the Skeifá basalts is reverse and was originally determined by Doell (1972). The Skeifá basalts do not crop out in the coastal sections. Either their emplacement was fairly localized, or they have been eroded away shortly after deposition in the area exposed in coastal sections of the Tjörnes Peninsula.



Fig. 6.4 (continued) except at the base of the Barmur Group, see discussion in text. Lithostratigraphic units are shown with a stratigraphic depth scale at the base of the diagram (cf. Eiríksson et al., 2020b; Eiríksson et al., 2020c). The benthic marine isotope stack LR04 (Lisiecki & Raymo, 2005) forms a reference section for world average $\delta^{18}\text{O}$ variability, which reflects temperature, global ice volume, and sea-level changes. The high value peaks correspond to increased global ice volume (glacial) stages. The geomagnetic polarity time scale is based on Ogg and Smith (2004)

The boundary between the *Mactra* and *Serripes* Zones lies between Bárðarson's units 12 and 13 in the coastal section (in Strauch's more detailed subdivision of Bárðarson's units, the lowest unit of the *Serripes* Zone is numbered 13/1, Strauch, 1963). Kristjánsson (2004) studied the paleomagnetic properties of the uppermost part of the *Mactra* Zone in the coastal section at Tungukambur, as well as the *Serripes* Zone both in the Tungukambur coastal section and in the inland Skeifá basalt locality (cf. location map in Eiríksson, Símonarson, & Knudsen, this volume). Unfortunately, his assumed stratigraphic position of samples assumed to be taken from Bárðarson's (1925) units 11 and 14 are inverted, the error being caused by a misunderstanding caused by the inverted numbering system of samples SA-1-9. Normal polarity was obtained for both the top of the *Mactra* Zone and the lowest *Serripes* Zone beds in the coastal section. On the other hand, Kristjánsson confirmed reversed polarity for the Skeifá basalts and determined reversed polarity *Serripes* Zone sediments below. The appearance of the species *Macoma obliqua* and *Serripes groenlandicus* within the reversed polarity sedimentary sequence below the Skeifá basalts is considered to mark the change from the *Mactra* Zone to the *Serripes* Zone (Strauch, 1963). This reversed polarity interval was found to be underlain by normal polarity sediments also belonging to the *Mactra* Zone. The reversed polarity interval of sedimentation and lava emplacement is completely missing in the coastal section at the mouth of the river Hallbjarnarstaðaá, amounting to more than 75 m in stratigraphic thickness preserved in the inland outcrop of the Skeifá river valley. Out of two attempts to determine the radiometric age of the Skeifá basalts, one was incomplete and the other yielded 2.46 ± 0.46 Ma, which was considered a minimum age by Albertsson (1976). In a study of the paleomagnetic properties of the Tjörnes sequence, Gladenkov and Gurari (1976) reported a level of reversed polarity just below the F lignite, and a lower one around Bárðarson's unit C lignite. They also confirmed reversed polarity at the Skeifá basalts, and a reversed polarity level higher up in the *Serripes* Zone sediments.

The sediments north of Egilsgjóta up to the *Mactra-Serripes* boundary in the coastal section belong to the *Tapes* and *Mactra* mollusc Zones. These mollusc zones have traditionally been assigned to the Pliocene (cf. Eiríksson & Símonarson, 2020).

In summary, new mapping results presented by Eiríksson et al., (2020c) show that the sequence at the base of the Tjörnes beds is not straightforward and conformable, being separated tectonically by faults and probably originating from geographically widely separated parts of the sedimentary basin. These new results show that the relative age of, for example Bárðarson's units 1, 2, and 3 cannot be determined from field relations. However, all these units, in separate tectonic blocks, were sampled by Verhoeven et al. (2011), and the arguments for a Pliocene age or a terminal Miocene age apply to all these units. Secondly, a considerable hiatus must be assumed to be present in the coastal section at Hallbjarnarstaðaá (Fig. 6.1), where the top of the *Mactra* Zone and the lowest part of the *Serripes* Zone are missing.

6.3.7 *The Sequence of Strata Along the Coastline from the Skeifá Valley up to Höskuldsvík*

Geological mapping of lignite unit F from coastal outcrops at the Skeifá waterfall towards Hallbjarnarstaðaá river (Fig. 6.1) has confirmed the overall sequence established by Bárðarson (1925). At the coastal section, the uppermost *Maetra* Zone rocks (Bárðarson's units 11 and 12) display normal polarity, followed by normal polarity *Serripes* Zone rocks (Bárðarson's units 13 to H). Units I to 25 represent, according to Kristjánsson (2004), a reversed polarity interval, but these sediments are capped by a normal polarity subaerial lava flow in Höskuldsvík. The lava is structurally conformable with the underlying sediments and there is no indication of an erosional contact. On the contrary, the basal part of the lava is brecciated with inclusions of the underlying sediment, which has evidently been soft at the time of lava emplacement. This uppermost unit of the Tjörnes beds (unit 25) displays an upwards coarsening, regressional sequence.

Based on highest occurrence (HO) levels for several species of dinoflagellates within the *Serripes* Zone, and a new interpretation of the paleomagnetic data, Verhoeven et al. (2011) concluded that the top of the *Serripes* Zone could be dated to c. 4.0 Ma, and the boundary between the *Maetra* Zone and the *Serripes* Zone was placed at c. 4.5 Ma. They stated that "Reworking of the species from the *Maetra* sediments however appears unlikely. The basin was at the time not subjected to uplift and it is not very likely that wave currents alone caused a reworking of *Maetra* sediments." With regard to the improved mapping control of the lithological units of the Barmur Group (traditional Tjörnes beds), the statement above can no longer be accepted. Direct evidence is now available of considerable erosion amounting to removal of at least 75 m thickness of *Serripes* Zone sediments and extending well down into the *Maetra* Zone sediments. Palynological samples from the lowest part of the *Serripes* Zone in the coastal section show considerable content of redeposited pollen grains, especially in Bárðarson's unit 15, but also in unit 14 (Akhmetiev et al., 1978). A significant gap in the coastal section has thus been demonstrated (Eiríksson et al., 2020c). A sizeable body of sediment has been eroded and resuspended, and subsequently redeposited at a later stage than indicated by the microfossils derived from the original deposits. In the present age model, the reversed polarity sediments in Höskuldsvík are correlated to the Mammoth subchron of the Gauss geomagnetic chron (Fig. 6.4), having been deposited during the interval 3.2–3.3 Ma. The boundary between the Barmur Group and the overlying Höskuldsvík Group is therefore, considered to date from c. 3.2 Ma.

6.4 The Höskuldsvík Group

The Barmur Group of primarily sedimentary rocks is overlain in the coastal section along the west coast of Tjörnes Peninsula by subaerial basaltic lava flows (Fig. 6.2).

The sequence was surveyed by Einarsson et al. (1967), who described the unit as follows: “The Tjörnes beds are overlain by a thick lava flow of normal remanent magnetism exposed at Höskuldsvík ... then by a pair of lava flows of rather obliquely reversed magnetism followed by a clearly reversed flow, and in turn by a thicker sequence of normally magnetized flows exposed at Hvalvík” (p. 317). In the coastal section at Furuvík, the uppermost lava flow of the Höskuldsvík Group is discontinuous as evidenced by a parallel erosional unconformity at the interface with the Breiðavík Group rocks above. The boundary is only exposed in the coastal section. Strike and dip measurements at the sole of the uppermost lava flow yielded $40^{\circ}/10^{\circ}\text{W}$. Lava flows in the lowest formation of the Breiðavík Group reveal strike and dip of $40^{\circ}/8^{\circ}\text{W}$, indicating a structural continuity across the boundary between the two uppermost major units of the Tjörnes sequence. Two radiometric ages from the Höskuldsvík Group were reported by Albertsson (1976). A single date from the “Höskuldsvík basalt” yielded an age of 2.55 ± 0.27 Ma, but an isochron estimate based on three determinations from the reversed polarity “Hvalvík basalt” yielded an age of 3.19 ± 0.26 Ma, which was considered anomalous by Albertsson, with respect to the younger age of the Höskuldsvík lava below. In retrospect, one could just as well claim that the young Höskuldsvík lava age was anomalous, representing a minimum age in line with the general conclusion by K/Ar scientists dealing with Tjörnes samples. The 3.19 ± 0.26 age of the reversed polarity flows in Hvalvík is consistent with an age at or close to the Kaena subchron of the Gauss chron (Fig. 6.4). The age model presented by Verhoeven et al. (2011) assumes a large hiatus at the top of the Barmur Group. A major hiatus is not borne out by field relations and was based on the assumption that dinoflagellate cysts in the *Serripes* Zone had not been reworked from older deposits leading to the conclusion that the *Serripes* Zone was much older than previous studies had indicated.

6.5 The Breiðavík Group

The Breiðavík Group is the youngest major lithostratigraphic unit of the Tjörnes sequence comprising the entire upper part of the Tjörnes sequence from the lowest diamictite bed up to and including the present soil cover (Eiríksson et al., 2020a). The Breiðavík Group (Fig. 6.3) is characterized by sheets of diamictite which occur throughout, but lithologies range from basaltic lava flows, volcanic tuffs, and subglacial/aquatic eruptives to mudrocks, sandstones, conglomerates, and diamictites. All except the very youngest of the Breiðavík Group rocks are lithified and form very hard rocks.

6.5.1 *Quaternary Sequence from the Matuyama Chron*

The Breiðavík Group contains a remarkably detailed history of Upper Cainozoic glaciations in North Iceland. The lower part of the Breiðavík Group displays distinct cyclicity, where a bed of lodgement tillite is typically followed by kame conglomerates and glacio-lacustrine mudrocks and then by marine sediments with an interglacial mollusc fauna indicating glacial retreat. These sediments interfinger with and are replaced in the vertical sense by fluvial sediments and lava flows indicating regression and ice-free conditions. The upper part of the Breiðavík Group was formed during a phase of increasing tectonic uplift on Tjörnes, and deposition took place in mostly terrestrial environments.

There are several lines of evidence supporting a Quaternary age for the Breiðavík Group. Marine fossils in the Breiðavík Group were originally considered compatible with a Pliocene age, but later discoveries of arctic mollusc species, as well as microfossils, have supported Quaternary age of the group. Mollusc species indicating extremely cold conditions have been identified in the lower part of the Breiðavík Group (Áskelsson, 1935; Eiríksson, 1981; Símonarson & Eiríksson, 2008; Vilhjálmsson, 1985). Integration of foraminifera, mollusc, and sedimentological data has also demonstrated glacial-interglacial cyclicity in the Breiðavík Group (Eiríksson et al., 1992). Based on dinoflagellate cysts, Verhoeven et al. (2011) proposed an Early Pleistocene age older than the Olduvai subchron (possibly c. 2.0 Ma) for the Hörgi Formation (Breiðavík Group), corresponding well with the age estimate of Símonarson and Eiríksson (2008). Recent radiometric dates and paleomagnetic data, as well as improved mapping of the lithostratigraphy and tectonic structure, have contributed significantly to the age constraints of the Breiðavík Group (Camps et al., 2011; Eiríksson et al., 1990).

A compilation of Quaternary glacial events in the volcanic succession of Iceland (Eiríksson, 2008) shows that glaciation of high relief mountainous areas and volcanic centres had already started in Iceland at 7 Ma. The frequency of preserved glacial events after the first regional expansion of local highland glaciers close to the Gauss-Matuyama chron boundary exceeds one event per 100,000 years. These amounted to massive glacial events covering most of Iceland, and each event was separated by ice-free conditions. Comparison with other parts of the stratigraphic succession in Iceland indicates that the Tjörnes glaciation record, being located at sea level distant from the highland glaciation areas in Southeast Iceland, starts at the time when the first regional ice-sheet expansions began, that is close to the Gauss-Matuyama chron boundary.

New data on the magnetic properties of the sediments in Breiðavík and Furuvík were presented by Eiríksson et al. (1990), who reviewed the age estimates for the Upper Tjörnes sequence and supported the suggestion of Einarsson et al. (1967) that the reversely magnetized lower part of the overlying Breiðavík Group accumulated during the Matuyama epoch. According to the preferred age model of Eiríksson et al. (1990), the polarity reversal from normal to reverse at the base of the Breiðavík Group in Furuvík is correlated with the Gauss-Matuyama boundary (2.58 Ma, cf.

Ogg & Smith, 2004). Normal polarity flows belonging to the Furugerði and Miðnef Members (Fig. 6.3) could then correspond to Réunion, and another, higher normal polarity interval was considered to correspond to the Olduvai chron by Eiríksson et al. (1992).

The correlation of the geomagnetic reversal at the base of the Breiðavík Group has implications for the age estimates of the units below. The reverse magnetized Höskuldsvík Group lava in Hvalvík should most probably be correlated with the Kaena event, and the reversed interval immediately below the Höskuldsvík Group would correspond to the Mammoth subchron (Fig. 6.4). The Skeifá pillow lavas and the reversed interval of sediments immediately below these lavas would correspond to the uppermost Gilbert chron (3.596–4.187 Ma, cf. Ogg & Smith, 2004). The mollusc fauna changes within this reversed interval of sediments with the appearance of species neither found in the *Maetra* nor the *Tapes* Zones. This would place the *Maetra-Serripes* boundary within the uppermost Gilbert chron, tentatively estimated at 3.8–3.9 Ma. The normal polarity interval below may have been deposited during the Cochiti chron (4.187–4.3 Ma).

In the age model presented by Verhoeven et al. (2011), a considerable time gap of 600 kyr up to c. 900 kyr was assumed to separate the Furuvík Formation from the Hörgi Formation. Referring to Einarsson's observations and interpretation, the angular unconformity observed between the Furuvík Formation and the mainly reversely polarized Hörgi Formation (Einarsson, 1958) was taken to represent an hiatus that likely included the Gauss-Matuyama boundary. The Hörgi Formation is estimated to be c. 2.0 Ma based on dinoflagellate cysts and the normally magnetized upper part of the Hörgi Formation could be correlated with the Réunion subchron (2.128–2.148 Ma).

The strike changes from 40° to 90° and the dip from 8°NW to 2°N at the base of Hörgi Formation within the Breiðavík Group, changing to a northwesterly strike and a dip of 4°NE above the Hörgi Formation. Reworked clasts from the Pliocene Tjörnes beds occur in the lower part of the Breiðavík Group sediments above the Hörgi unconformity (Bárðarson, 1925) indicating local uplift and erosion of Pliocene units.

Einarsson (1957a, 1957b, 1958, 1963, 1965) investigated the structure of Tjörnes and used paleomagnetic measurements to map lava units. He identified the angular unconformity beneath the sediments in Breiðavík (Einarsson, 1957a, 1958). In his diaries from 1941 Línal (1964) had noted that the lava flows, which cover the Breiðavík beds in the eastern part of Breiðavík and the lava flows above a tillite covering older lava flows in Búrfell (Fig. 6.1), were rather similar in appearance, and suggested that they belonged to the same stratigraphical horizon. Such a correlation requires either considerable faults north of Búrfell or an unconformity across the more steeply dipping units beneath the Hörgi Formation. Einarsson concluded that "somewhere between Höskuldsvík and the marine Breiðavík there is a large unconformity. It probably lies at the base of the Breiðavík sediments" (Einarsson, 1958: p. 7). His conclusion was based on the fact that the reversed polarity lavas in Voladalstorfa (Fig. 6.1), covering the sediments in Breiðavík, can be

traced almost continuously to Búrfell. The unconformity apparently cuts across all older units of the Tjörnes sequence.

Although the angular unconformity described above almost certainly represents an hiatus within the Breiðavík Group, the hiatus may not be very long. This is because the sediments and lava flows exposed in Breiðavík were deposited in an active, partly submarine north-south trending graben valley, a continuation of the graben cutting across the river Skeifá further south on Tjörnes Peninsula. The lowest unit in Breiðavík, the Hörgi Formation (Fig. 6.3) is seen both within the Breiðavík graben structure and resting on more steeply dipping lava flows, but the Hörgi Formation is capped by a lava flow, remnants of which are preserved at the Hörgi locality. This volcanic unit has probably shielded the sediments from subsequent erosion. The change in strike and dip may be partly associated with dislocation at faults similar to such changes further south on the peninsula.

6.5.2 *Matuyama-Brunhes Transition in the Tjörnes Sequence*

The rock sequence above the sediments in Breiðavík is dominated by volcanic rocks. Einarsson (1958) reported a reverse to normal polarity reversal within the sequence of lava flows. Lava flows from the lower, reverse part (Dimmidalur Member, Fig. 6.3; Eiríksson et al., 2020a) have been dated by Albertsson (1976, 1978) at 0.75 ± 0.1 Ma (uppermost reverse flow in the coastal section at Engidalsgjá, Fig. 6.1) and at 1.25 ± 0.07 Ma (a weighted mean of four samples from flows at the Torfhóll section in Breiðavík, Torfhóll Member). The Engidalsgjá section was sampled by Doell (1972), who confirmed the presence of the geomagnetic transition. The reversed polarity lava units at Engidalsgjá and Torfhóll have been mapped southward to sections in Grasafjall and Búrfell, and belong to the Dimmidalur Member (Eiríksson, 1985). A detailed study of the Matuyama-Brunhes transition in sections in central Tjörnes was carried out by Kristjánsson et al. (1988). Reversed polarity was confirmed for the Dimmidalur lava units, and in a stratigraphically higher lava belonging to the Búrfellsá Member. In all the four sections studied by Kristjánsson et al. (1988), a group of transitional remanence occurred above the reversed polarity units, corresponding to the Miðlækur Member (Eiríksson, 1985). It was suggested that the transition might be related to the Matuyama-Brunhes transition, and the results underlined that excursions in the magnetic field, recorded in volcanics, could be used for stratigraphic correlation over distances up to 10 km or more.

The central Tjörnes sections were revisited by Camps et al. (2011), who made a detailed study of the intermediate directions reported by Kristjánsson et al. (1988). They confirmed the presence of the transitional units in all the sampled sections, which were in the central southern part of Tjörnes Peninsula (Fig. 6.1). Camps et al. (2011) published several $^{40}\text{Ar}/^{39}\text{Ar}$ dates from the normal, transitional, and reversed polarity flows in the sections, obtaining an average age of 0.78 ± 0.04 Ma for the

normal flows, 0.862 ± 0.051 Ma for the transitional ones, while the basal reverse flows ranged from 0.917 ± 0.15 and 1.182 ± 0.15 Ma. They correlated the transitional interval with the Kamikatsura event which has a weighted average age of 0.9004 ± 0.004 Ma (although a correlation with the Takatsugi event which has an age of 0.850 ± 0.03 Ma was not ruled out). The normal polarity lavas above were considered to have been emplaced either during the lowest part of the Brunhes chron, or, more probably, during the Brunhes-Matuyama reversal. The transitional polarity lavas belong to the Miðlækur Member of the Grasafjall Formation in the Tjörnes lithostratigraphic framework (Fig. 6.3), and the reversed polarity flows below belong to the Búrfellsá and Dimmidalur Members of the Máná Formation. The lava flows from the Brunhes-Matuyama transition belong to the Skeiðsöxl Member of the Grasafjöll Formation, and predate the subglacial volcano Búrfell Mountain, which is assigned to the Bangastaðir Member of the Grasafjöll Formation (cf. Eiríksson et al., 2020a).

6.6 A New Age Model for the Tjörnes Sequence. Discussion

A new model of the chronology of the Tjörnes sequence is shown in Fig. 6.4. The age model is based on a variety of data and will undoubtedly be improved in the future by new dating techniques and additional data, for example on paleomagnetism and micropaleontology. Absolute dates have been used whenever possible, taking into account that the volcanic rocks on Tjörnes have proved to be poor dating material due to low potassium content and geothermal alteration, except for the uppermost part of the sequence (Matuyama-Brunhes boundary and younger). Generally, this adds uncertainty to the analytical dating errors, and in many cases the respective authors report the radiometric ages as minimum ages. Secondly, the age model is based on Paleomagnetic work on volcanic rocks and sediments, initiated by Hospers (1953) who also measured sediment samples, and continued by Einarsson (1957a, 1957b, 1958), with an important milestone published by Einarsson et al. (1967).

Lava flows at and around the Matuyama-Brunhes chron boundary were studied by Kristjánsson et al. (1988). Paleomagnetic data for the sediments of the Breiðavík Group added considerable detail to the magnetic stratigraphy (Eiríksson et al., 1990), and Paleomagnetic data for the uppermost part of the Barmur Group (upper *Maetra* and *Serripes* Zones) were published by Kristjánsson (2004). Recent dates from the uppermost Matuyama chron and the boundary interval up to the Brunhes chron (Camps et al., 2011) improve the correlation of that part of the sequence to an absolute time scale. Finally, biostratigraphic data based on dinocysts (Verhoeven et al., 2011) play an important part in the new age model.

The backbone of the model presented in Fig. 6.4 is the Paleomagnetic time scale (Ogg & Smith, 2004). A stratigraphic depth scale is represented on the x-axis, giving an almost straight line from zero age back to the uppermost Miocene. We present the actual stratigraphy on a separate x-axis, where the actual stratigraphic positions of a few marker horizons and boundaries are connected to the linear accumulation scale.

Considering that parts of the accumulation history involved virtually instantaneous emplacement of great thicknesses of lava flows and given that the sedimentary sequence reflects numerous transgressions and regressions in a near-shore environment, the deviations between the linear model and the actual stratigraphic column are not excessive and not surprising. The steep portion of the age model curve in the uppermost Miocene is interpreted as an hiatus associated with a transgression and reduction of local volcanism towards the end of the Miocene.

The base of the Barmur Group is considered to be of terminal Miocene age, in accordance with the age model published by Verhoeven et al. (2011). This is compatible with Miocene to Pliocene benthic foraminiferal forms in the basal units of the Barmur Group (cf. Knudsen et al., 2020). In Fig. 6.3 the base is arbitrarily depicted at 5.85 ± 0.5 Ma. No fossil evidence is available from the Héðinshöfði Formation, the age of which is entirely based on K/Ar dates, and the Eyvík Formation mollusc fauna indicates that the marine unit there may correspond biostratigraphically to the *Serripes* Zone (cf. Eiríksson et al., 2020c).

There are three fault blocks exposing Barmur Group sediments at the Kaldakvísl locality. About 100 m to the south of the river mouth, north-west dipping lava flows with interbedded redbeds form the bedrock up to 37 m asl, followed by till (Eiríksson et al., 2020c). The contact with the sediments of the Lynghöfði Formation (Fig. 6.2), which are visible immediately south of Kaldakvísl river, is not exposed and it is assumed that there is a major fault separating the Kaldakvísl Group rocks from the Lynghöfði Barmur Group sediment-bearing fault block. No radiometric dates are available from the lava flows cropping out in the coastal section south of Kaldakvísl River. The marine fauna of the Lynghöfði Group (Kvíslarkambur Member, Fig. 6.2) corresponds to the lowest biozone of the Barmur Group, the *Tapes* Zone.

Exposures of the second fault block containing sediments are found in the Syðrihöll confluence hill between the rivers Kaldakvísl and Tunguá (Fig. 6.2; Eiríksson et al., 2020c). Three K/Ar dates are available from lava flows below the sediments (Albertsson, 1976). Two determinations of a lower flow yielded 7.86 ± 0.34 Ma and 8.74 ± 0.34 Ma (weighted mean apparent age of 8.29 ± 0.36 Ma), and an upper flow yielded 6.14 ± 0.27 Ma. The sediments above with intercalated thin lava flows include marine units which are consistent with the *Tapes* Zone (cf. Eiríksson et al., 2020c). With respect to the uppermost K/Ar date, the Barmur Group sediments in the confluence hill are younger than 6.14 ± 0.27 Ma.

The third fault block forms the hill Grænhöfði north of Kaldakvísl River (Fig. 6.1). The section in Grænhöfði starts with two lava flows, separated by a fine-grained, red sediment layer. Both lava flows display normal polarity (Hospers, 1953). The upper lava flow was K/Ar dated by Albertsson (1976) and yielded an age of 4.30 ± 0.17 Ma. The lava flow is overlain by sediments belonging to the *Tapes* Zone. Borehole results from Grænhöfði (Richter, 2001, 2002) show that downcore from the two lavas visible at the coast, c. 7 m of lava (possibly more than one flow unit) were penetrated, and below that 4.5 m of brown and red sandstone and conglomerate, resting on an erosional surface. Subsequently, further 22 m of lava flows with red interbed(s) were penetrated. The Grænhöfði sequence shows some similarities with the Tunguá-Kaldakvísl confluence hill sequence, where a continuous sequence of lava flows with intercalated redbeds is succeeded by a reddish con-

glomerate and brown sandstone, followed by thin lava flows and then by lignite bearing sandstones and marine sandstones. In Grænhöfði, the base of the Barmur Group is placed at the erosional surface followed by red and brown sandstone and conglomerate in the borehole section (cf. Eiríksson et al., 2020c). The lowermost Barmur Group sediments in Grænhöfði are thus older than 4.30 ± 0.17 Ma.

According to Hospers (1953), the sediments above the normal polarity flows in Grænhöfði display reversed polarity, changing to normal polarity again about 150 m higher in the Tjörnes beds. The exact level of the samples is not known, but the reversed polarity interval might be consistent with the Gilbert polarity chron, with the underlying lava flow dating from a normal polarity subchron within the Gilbert chron.

The upper part of the age model in Fig. 6.4 is based on a correlation of Paleomagnetic data down to the uppermost lithostratigraphic units containing *Maetra* Zone fossils to an absolute time scale (Ogg & Smith, 2004). The revision of the Verhoeven et al. (2011) age model is discussed above, and the uppermost part is supported by K/Ar and Ar/Ar dates. The new age model indicates an approximate age of 4.4 Ma for the *Tapes-Maetra* Zone boundary, and approximately 3.8 Ma for the *Maetra-Serripes* Zone boundary.

Paleotemperature estimates for the Tjörnes beds were published by Buchardt and Símonarson (2003). Their result shows sea-water temperatures above 10 °C for the upper *Tapes* and the lower *Maetra* Zones. A marked cooling is shown within the *Maetra* Zone interval, reversing to about 10 °C at the *Maetra-Serripes* boundary. Another distinct cooling trend with a temperature drop of 5 °C is seen within the *Serripes* Zone, reversing towards warmer in the upper part.

Because Iceland is an island in the North Atlantic, with a highly oceanic climate, paleotemperatures derived from the geological records in Iceland can be tested against the paleoclimate data from the ocean. In the global benthic isotope stack (Lisiecki & Raymo, 2005; Zachos et al., 2001), the terminal Miocene is a period with very light isotopes interpreted as a warm ocean with concurrent low ice volumes. Sea level is expected to be high. This may well coincide with the initial marine transgression in Tjörnes. After 5 Ma the isotopes indicate slight cooling followed by a warming trend setting in at c. 4.5 Ma. This level is maintained in the long term until c. 3 Ma. However, the interval from c. 4.3 to 4.0 Ma displays a cooling trend (concurrent with the deposition of the *Maetra* Zone sediments), and a sharper one is seen in the global isotope stack from 3.5 to 3.3 Ma (middle to upper *Serripes* Zone sediments). This supports the new age model presented here, which also places the first indications of glaciation extending beyond the coastline in the Tjörnes sequence at the Gauss-Matuyama polarity reversal at start of the Quaternary.

6.7 Conclusions

A revised age model for the Tjörnes sequence has been constructed. The revision is based on new stratigraphic work and is primarily based on published physical measurements of paleomagnetism and radiometric dates. The main deviation from recently published age models concerns the upper Pliocene, affecting the timing of the boundaries of the Barmur Group *Serripes*, *Maetra*, and *Tapes* mollusc biozones.

Recent dating results and Paleomagnetic data support and add some detail to previous age models for the Breiðavík Group, which represents the Quaternary part of the Tjörnes sequence, especially around the Matuyama-Brunhes boundary at 0.78 Ma. According to the revised age model, the first glaciation of the region took place close to the Gauss-Matuyama boundary at 2.58 Ma.

The oldest major lithostratigraphic unit on Tjörnes Peninsula, the Kaldakvísl Lava Group, is entirely of Miocene age, based on several published K/Ar dates. The Tjörnes sequence sediments exposed on the west coast of Tjörnes began to accumulate towards the end of the Miocene in a subsiding basin, the Tjörnes Basin, within the Tjörnes Fracture Zone (TFZ). Very low accumulation rate is indicated in the initial phase of subsidence and the lithological record reflects reduced volcanic activity in an alluvial environment. Hiati in the record are likely, especially at levels of transgression indicated by conglomerate beds. Sporadic lava flows show evidence of deep weathering.

Marine transgression took place early in the Pliocene or possibly during the terminal Miocene according to dinoflagellate cyst analyses. Sediments and lava flows belonging to the lowest Barmur Group biozone, the *Tapes* Zone, are exposed in several tectonic blocks separated by right-lateral transform faults associated with the TFZ. Correlation between the blocks is based on the fossil content but not on lithological units. Tentatively, it is assumed that the age of the blocks belonging to the *Tapes* Zone increases southward along the coastline, but better dating control is needed before this can be confirmed. A shallow-marine to coastal environment is indicated by alternating transgressions and regressions within this oldest part of the Barmur Group. One lava flow within the Grænhöfði Formation (Fig. 6.2) has previously been K/Ar dated, yielding a minimum age of 4.30 ± 0.17 Ma (Albertsson, 1976, 1978). Preferred correlation of the Paleomagnetic record of the upper part of the Barmur Group with an absolute time scale indicates that units with *Maetra* Zone fossils extend at least as far down as the Cochiti subchron of the Gilbert chron, that is 4.3 Ma. An interval of reversed polarity around the base of the *Maetra* Zone, more than 150 m lower in the stratigraphy, has been reported, and the upper boundary of the uppermost lithological unit of the *Tapes* Zone is thus considered older than the lower boundary of the Cochiti subchron of the Gilbert chron, that is 4.3 Ma. The boundary between the *Tapes* and *Maetra* Zones is arbitrarily estimated at 4.4 Ma, which is simply the average of the upper and lower boundaries of the reversed polarity subchron below the Cochiti subchron. The estimate is considered compatible with published data.

The base of the lithological units containing the uppermost biozone of the Barmur Group, the *Serripes* Zone, lies within a reversed polarity interval documented in both sediments and lava flows, followed by normal polarity sediments and, at the top of the Barmur Group, reversed polarity. In the present age model the lower reversed polarity interval is correlated with the uppermost Gilbert chron, and the upper one with the Mammoth subchron of the Gauss chron. This brackets the *Serripes* Zone within the time interval 3.8 to 3.2 Ma. The lower boundary may lie within the interval 4.2 to 3.6 Ma, the boundaries of the uppermost Gilbert reversed polarity subchron.

The Höskulsvík Group spans the interval 3.2 to 2.6 Ma according to the revised age model. The lowest lithostratigraphic unit of the group, a lava flow, is resting conformable with the underlying *Serripes* Zone sediments, and the intricate contact at the base of the lava shows that it flowed across a soft substrate. The large hiatus proposed by Verhoeven et al. (2011) at this boundary is not supported by the revised age model presented here.

The Breiðavík Group spans the interval from the Gauss-Matuyama boundary up to the present date. Within the Group, strike and dip change from a north-west dipping lowest part to north to north-east dipping upper part, and finally, to horizontal attitude. The changes are considered related to an eastward shift subsidence within the Tjörnes Basin, and to the uplift of central to eastern Tjörnes Peninsula related to the northward propagation of the Öxarfjörður spreading axis immediately east of Tjörnes. The Breiðavík Group is characterized by glacial sediments, and at least 14 erosional unconformities have been identified.

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