

Precise dating of the Holmatindur cooling event in eastern Iceland: Evidence for mid-Miocene bipolar glaciation

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Abstract. A succession of basaltic lavas, volcanoclastic sediments, and lignite beds in the Holmatindur region of eastern Iceland provides the means for tying magnetic reversal stratigraphy and a record of major North Atlantic cooling to a precise radiometric timescale. A prominent part of the section is the Holmatindur clastic bed, which is up to 66 m thick and can be traced 80 km along strike. The geological significance of this unit lies in its composition and associated thin lignite seams. The volcanoclastic composition is basaltic (in contrast to the common rhyolitic/dacitic composition of tuff units in the area), and hyaloclastic material is dominant. Hydroexplosive volcanism most likely produced the hyaloclastite, through subglacial eruptions within the paleovolcanic zone. Pollen assemblages from the lignite beds indicate a dramatic climatic deterioration, from subtropical to cool temperate conditions, through these sediments. Feldspar crystals separated from the Holmatindur clastic bed were determined to be from 10.72 (\pm 0.16) Ma, from ^{40}Ar - ^{39}Ar incremental heating experiments. We correlate the Holmatindur cooling event with a relative maximum in benthic foraminiferal $\delta^{18}\text{O}$ (Zone Mi6 of Miller *et al.* [1991]), which has been interpreted as an episode of ice accumulation within the mid-Miocene cooling period, as well as with pulses in ice-rafted debris supplied to deep water sites in the North Atlantic Ocean, a global sea level drop of 70 m, and submarine canyon cutting, all of which occurred within the early part of magnetic anomaly 5 normal (C5n). While strong evidence exists for mid-Miocene ice sheets in Antarctica, northern hemisphere glaciation is thought to have started much later. The Iceland sites studied here demonstrate that significant ice accumulation occurred, albeit intermittently, as early as late middle Miocene time in the North Atlantic Ocean. From radiometric dating of Tertiary lavas that lie below and above the well-established lower boundary C5n, we conclude that the onset of this long normal polarity period occurred at 10.94 (\pm 0.16) Ma. The new data are compatible with the Cande and Kent [1995] interpolated estimate for this boundary (10.95 Ma) but are significantly older, or more precise, than previous direct dating by conventional K-Ar methods.

1. Introduction

The volcanic stratigraphy of eastern Iceland has been built up from eruptions at both fissure systems and central volcanoes. Tertiary volcanic centers grew and died within the paleorift zones, then subsided, moved laterally eastward with the Eurasian plate, and have been exposed by glacial and subaerial erosion. Each succession of strata, roughly 1-3 km in thickness, that formed by central volcanic activity can be divided into alternating sequences of proximal and distal facies lavas. These sequences accumulated either rapidly within volcanic centers as numerous, thin flows or more slowly in distal settings as occasional, larger-volume flows that escaped the topographic confines of the volcanic center. The central facies sections, or Tertiary volcanic centers, produce much more varied lithologies than the fissure-fed sections, exhibiting higher accumulation rates and lavas ranging in composition from basalts to rhyolites. Exposed in the roughly 1 km high cliff section of eastern Iceland are, in

addition to the lava sequences, dike swarms that emanate from fissures and extend laterally into the extinct volcanic centers. Their mode of intrusion is comparable to the recent dike formation associated with the "Kraflafires" of northeastern Iceland during 1973-1978 [e.g., Björnsson *et al.*, 1977; Einarsson and Brandsdóttir, 1980; Helgason and Zentilli, 1985].

The magnetostratigraphy of eastern Iceland is well documented through combined magnetic, stratigraphic, and whole rock K-Ar radiometric dating studies of a 9 km thick section, consisting of over 700 successive lava flows that range in age between 13.6 and 2 Ma [e.g., Watkins and Walker, 1977; Helgason, 1982; Kristjansson *et al.*, 1995]. Several Tertiary tuff horizons serve as excellent regional stratigraphic markers. These tuffs are mostly of acidic composition and formed by repeated explosive activity in volcanic centers, such as the Reydarfjörður and Skessa acid tuffs [e.g., Walker, 1959, 1962; Gibson *et al.*, 1966]. An exception is the Holmatindur clastic bed that is composed almost entirely of basaltic material. This unit is of Miocene age and occurs within a thick sequence of normally magnetized lavas that have been correlated with magnetic anomaly 5 normal (C5n) [Helgason, 1982].

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Within the distal facies of the Holmatindur clastic bed are lignite seams that contain pollen which demonstrate a substantial climatic cooling event [Mudie and Helgason, 1983]. Physical aspects of this volcanic sediment also indicate extremely cold conditions, much like subglacial parts of present Iceland. By correlation with available magnetostratigraphic data, the age of the Holmatindur clastic bed was estimated to be 9.8 Ma [Mudie and Helgason, 1983]. In this paper, we present ^{40}Ar - ^{39}Ar age determinations for thin basaltic crystal tuffs found within the Holmatindur clastic bed and basaltic lava flows that bracket the clastic layers. The ages precisely date one of the earliest major Miocene cooling events in the northern hemisphere and coincidentally provide a new estimate for the time of onset of C5n.

2. Holmatindur Clastic Bed: Stratigraphic and Lithologic Character

2.1. Exposed Cliff Section in Reydarfjörður

In eastern Iceland the Holmatindur sedimentary unit has been traced along strike for up to 80 km and some 15-20 km down dip (Figure 1). The air fall tuff is excellently exposed close to sea level in Reydarfjörður, by the Njörvadalsá river, where it consists of a central or proximal facies sediment. At this locality, the horizon is about 30 m thick and extends from 50 to about 80 m above sea level. On the basis of lithologic characteristics we have divided the unit into 26 beds which range in thickness from a few centimeters to over 10 m. Bed 20 is a 80-100 cm thick crystal-rich (up to 20%) tuff bed, which lies some 22 m above the base. Feldspar

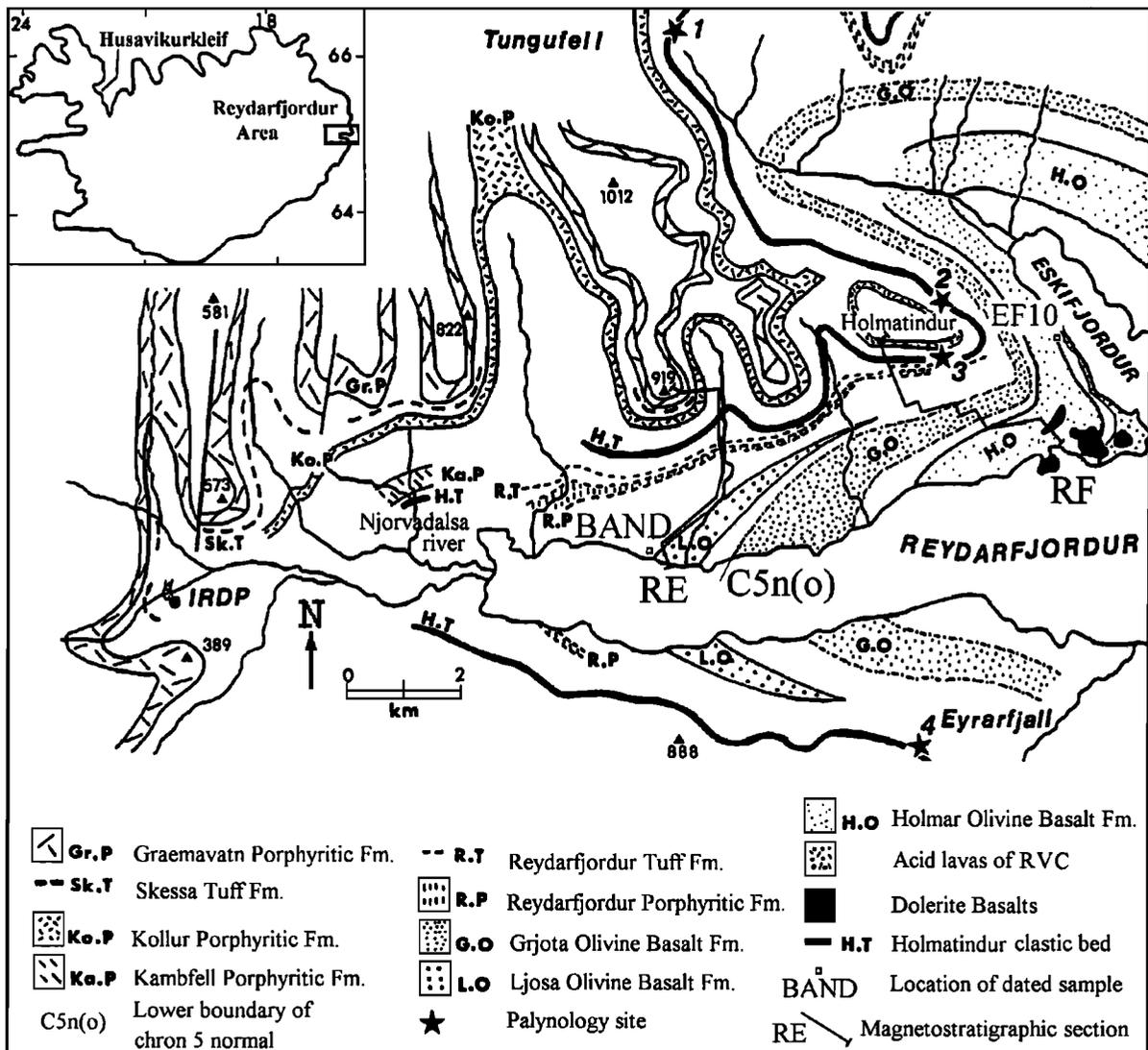


Figure 1. The Reydarfjörður region of eastern Iceland [after Helgason, 1982; Mudie and Helgason, 1983], showing the main division of stratigraphic formations (i.e., basaltic lavas and tuffs) and location of magnetostratigraphic profiles and sample sites. C5n(o) is indicated on the north side of Reydarfjörður, within the Grjota olivine basalt formation. IRDP represents the location of the Iceland Research Drilling Project drill site; RVC is Reydarfjörður volcanic center. The location of the Husavikurkleif sediments in northwestern Iceland is shown in the inset.

crystals (0.2-2 mm in size) were separated from this layer for ^{40}Ar - ^{39}Ar dating. The plagioclase composition, determined from albite twinning, is $\text{An}_{64}\text{-Ab}_{36}$.

Farther updip to the east in the Eyrarfjall section (Figure 1), the unit has distal type characteristics, including thin lignite and laterite beds. Here, the total thickness is about 46 m, extending from 632 to 678 m above sea level. Although thin whitish gray crystal tuff beds are found within this unit, its bulk character (well over 90%) is that of clastic material of basaltic composition. Thus we refer to it as a "basaltic clastic bed" rather than as a "tuff" in order to distinguish it from the well-defined acidic tuffs in eastern Iceland.

2.2. Holmatindur Clastic Bed in the IRDP Borehole

Schmincke et al. [1982] described two relatively thick clastic units in the Iceland Research Drilling Project (IRDP) drill core from Reydarfjörður that *Helgason and Zentilli* [1982] correlated with the Holmatindur clastic bed in the surrounding exposed cliff sections (Figure 1). The units referred to are 58.1 at 344.15-362.25 m (18.10 m thick) and unit 67.1 at 402.33-409.60 m (7.27 m thick). Unit 58.1 is described as a grayish green, largely lapilli-rich tuff of dominantly basic composition. Unit 67.1 is a reddish brown, dominantly epiclastic hyaloclastite of basic composition. In the IRDP borehole, unit 58.1 is one of the thickest clastic units and can be regarded as part of a thick sedimentary episode, of roughly 25 m thickness, because unit 67.1 also forms part of the recognized Holmatindur clastic bed. Units 58.1 and 67.1 are separated by three lava flow units and one dike unit in the IRDP core. Only one clastic unit is thicker, i.e., the Reydarfjörður acid tuff or ignimbrite, at 919.82-950.55 m.

2.3. Origin of the Holmatindur Clastic Bed

Clastic beds of basaltic composition as thick as the Holmatindur are rare in eastern Iceland. They are most likely produced by basaltic volcanism under subaqueous or subglacial conditions. The latter environment is more probable because pollen analysis of lignite beds within the distal facies location of the Holmatindur clastic bed [*Mudie and Helgason*, 1983] indicates a temperature decline of about 10°C, from strongly thermophilic swamp forest to cool-temperate deciduous-boreal forest, then microthermal spruce forest, and, finally, subarctic alder woodland. Thus, during the late middle Miocene, the inland and most elevated parts of Iceland over the active volcanic axis were probably covered by ice, which caused flooding or "jökulhlaups" (glacial bursts) to carry large quantities of hyaloclastite material to the lower (distal) elevations. The lower-lying areas, however, were clearly ice-free based on the absence of tillites or moraine material in the Holmatindur clastic bed. Icelandic jökulhlaups in the late middle Miocene may have produced distinct pulses of basaltic clastic material that may be found in the deep-sea sedimentary record surrounding Iceland. The present study aims at constraining the timing of this event.

3. The ^{40}Ar - ^{39}Ar Radiometric Dating

3.1. Methods

3.1.1. Crystal tuffs within the Holmatindur clastic bed. High-precision radiometric ages were determined from fresh plagioclase feldspar using ^{40}Ar - ^{39}Ar incremental heating

methods. The ~0.5 mm size fraction of separated crystals was ultrasonically cleaned in distilled water, dried and wrapped in Cu-foil, loaded into evacuated quartz vials, and irradiated in a fast neutron flux in the core of the Oregon State University TRIGA experimental reactor for 6 hours at 1 MW power, along with flux monitor standard biotite FCT-3 (27.95 ± 0.2 Ma, adjusted to 520.4 Ma for Mmhb-1 hornblende [*Lanphere et al.*, 1990]). Samples were heated in six increasing temperature steps and Ar isotopic compositions were measured in two separate gas source mass spectrometer systems. The first is an AEI MS-10 instrument, which uses RF induction heating for gas extractions; the second is a MAP 215/50 instrument which uses a thermocouple-controlled, double-vacuum resistance furnace. Sensitivity is about 2 orders of magnitude greater in the second system, so sample size was adjusted (0.5 versus 0.05 g, respectively). Details of analytical procedure and system characteristics are given by *Duncan and Hogan* [1994] and *Mahoney et al.* [1995].

3.1.2. Basaltic lavas in Holmatindur cliff section.

Eight whole rock samples (see Figure 1 for locations) from lavas in the Holmatindur cliff section (profile RF) and adjoining sequences were dated, also by ^{40}Ar - ^{39}Ar incremental heating methods. Lavas in the upper part of the Holmatindur profile are all normally magnetized and have been correlated with C5n, whereas the lower lavas are, except for five lavas, reversely magnetized and lie below the C5n(o) boundary [*Helgason*, 1982]. Dating this section therefore offers an opportunity to determine the age of the onset of C5n. Stratigraphically, the transition from reverse to normal polarity, or the lower C5n boundary, coincides with units RF-47A (N)/RF-47 (R) (Figure 2 and *Helgason* [1982]). Both of these units are defined as part of the Grjota formation of thin olivine basalt lava flows; unit RF-47A represents the top unit of the Grjota formation. Individual lavas are thin, i.e., generally less than 5 m, which suggests rapid accumulation of the Grjota formation. Almost entirely aphyric tholeiite lavas that are much thicker and clearly have distal type lava facies lie above the Grjota formation. These upper lavas, which are normally magnetized, have intercalated sediments and lower accumulation rates. The fact that the transition occurs within the rapidly deposited Grjota lava formation suggests that only a short time elapsed between deposition of units RF-47A and RF-47 at the magnetic polarity transition.

3.2. Results

3.2.1. Holmatindur clastic bed. Data acquired from incremental heating experiments on separated feldspar (sample JH-1, Table 1) show step ages that are indistinguishable over most of the temperature range. These indicate concordant release of ^{40}Ar and ^{39}Ar (see plateau diagram, Figure 3). Our best estimate of crystallization age is the mean of the step ages, weighted by inverse variance. In the first experiment, which was run on the MS-10 system, we derived a plateau age of 11.45 ± 0.66 Ma (not shown in Table 1), and in the second experiment, which was run on the MAP system, a plateau age of 10.62 ± 0.14 Ma was determined. The second is more precise because of greater sensitivity (larger signal) and lower blank (smaller ^{40}Ar atmospheric correction) of the MAP 215/50 system, in spite of the smaller sample size.

We also plotted our data in isotope correlation space ($^{36}\text{Ar}/^{40}\text{Ar}$ versus $^{39}\text{Ar}/^{40}\text{Ar}$) to derive isochron ages as an independent estimate of the age and as a check on the

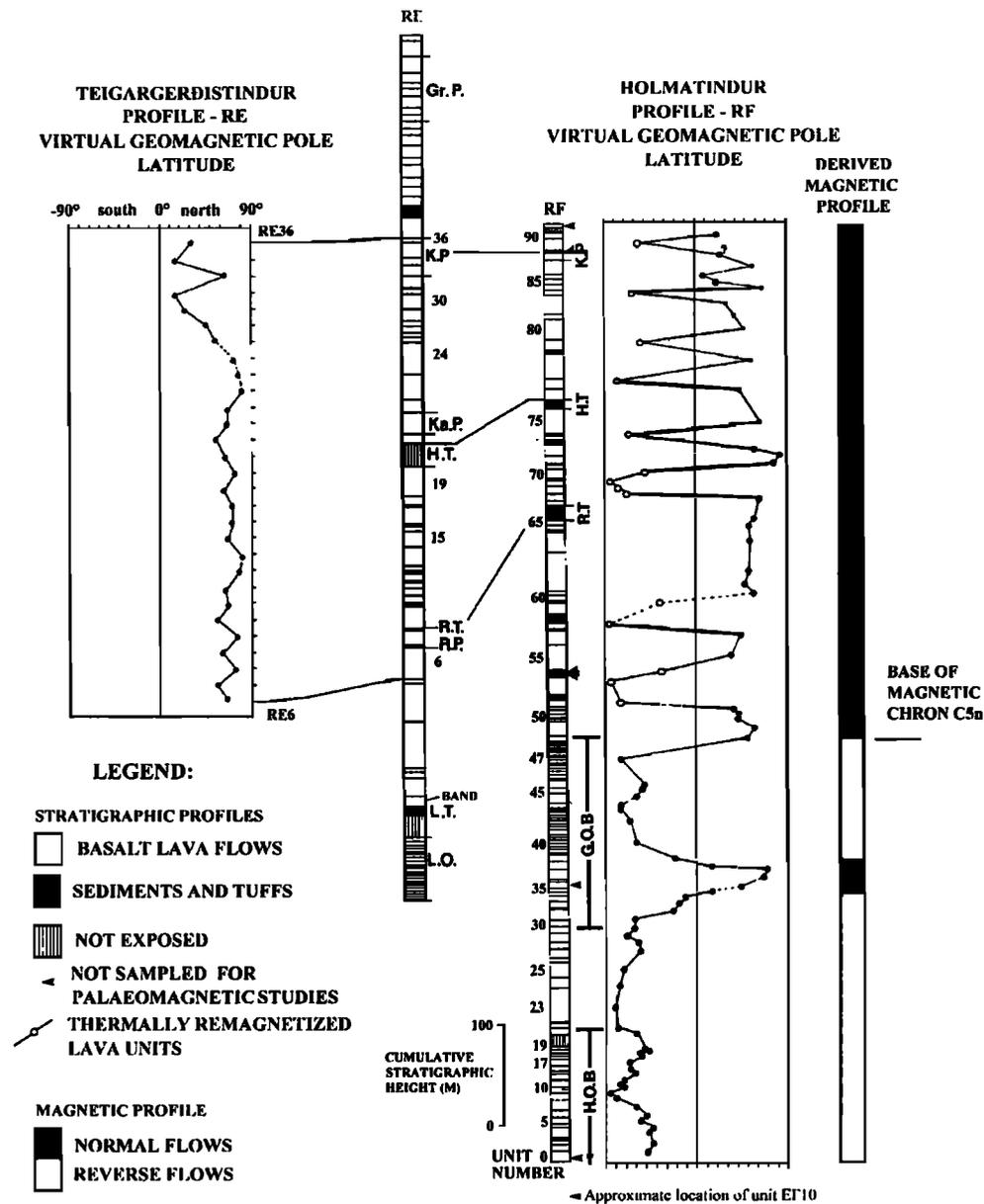


Figure 2. Summary of paleomagnetic data from the RE and RF profiles [after Helgason, 1982]. Apparent reversals within the upper part of the RF profile have been shown to be magnetic overprints due to later dike emplacement (see correlated section in profile RE which is unmodified by dikes). Thus the C5n(o) boundary is placed between lava flows RF-47 and RF-47A. Dated samples come mainly from the RF profile; sample EF-10a lies at its base and BAND is from the RE profile. RVC is Reydarfjörður volcanic center.

assumption of initial atmospheric Ar used in the plateau age calculations. In these diagrams (Figure 3), step compositions define linear arrays whose x intercepts give the time since the feldspar crystallized and whose y intercepts give the initial Ar composition. In both cases, the isochron age matches the plateau age, and intercepts indicate complete equilibration with atmospheric Ar at crystallization.

The weighted mean of plateau ages gives an age of the Holmatindur clastic bed as 10.72 (± 0.16) Ma or late middle Miocene. The age of the boundary between late and middle Miocene has been placed at 11.2 Ma [Berggren *et al.*, 1995]. Thus the Holmatindur clastic bed was formed during early Tortonian time.

3.2.2. Duration of the Holmatindur cooling event. In the IRDP borehole, three lava flow units divide the Holmatindur clastic bed into two parts. In the cliff section at Holmatindur, profile RF, a distal facies location of the Holmatindur clastic bed is divided by four lava flows, i.e., units RF-76 to RF-79. The measured age plotted against cumulative stratigraphic thickness (Figure 4) shows a remarkably linear relation at this location and at several much thicker Icelandic lava sections that cover many millions of years of activity [McDougall *et al.*, 1976, 1984; Watkins and Walker, 1977]. These observations indicate uniform local rates of crustal accretion, from which average eruption rates of one lava flow every 9 to 13 kyr can be calculated for northwest Iceland, and one every 16 kyr for eastern Iceland.

Table 1. The ^{40}Ar - ^{39}Ar Age Determinations for Lavas and Tuffs From the Reydarfjörður Area, Eastern Iceland

Sample	Material	Total Fusion Age, Ma	Plateau Age, Ma	^{39}Ar Percent of Total	Isochron Age, Ma	N	$^{40}\text{Ar}/^{36}\text{Ar}$ Intercept $\pm 1\sigma$	J
<i>Reydarfjörður</i>								
RF-89	basalt	10.5	10.63 \pm 0.16	100	10.67 \pm 0.19	4	296.2 \pm 2.9	0.000503
RF-76	basalt	11.8	11.88 \pm 0.26	79		2		0.001585
RF-75	basalt	10.6	10.55 \pm 0.31	94	11.30 \pm 1.31	5	289.1 \pm 10.9	0.000481
JH-1 ^a	feldspar	10.9	10.62 \pm 0.14	99	10.68 \pm 0.15	4	296.4 \pm 4.0	0.001361
RF-64	basalt	10.8	10.80 \pm 0.19	100	10.85 \pm 0.24	4	300.0 \pm 1.8	0.000456
RF-52	basalt	10.1	10.11 \pm 0.34	60	10.78 \pm 0.88	3	287.0 \pm 8.8	0.000523
BAND	basalt	10.8	10.76 \pm 0.16	87	10.56 \pm 0.15	4	295.8 \pm 1.4	0.001600
RF-43	basalt	11.1	11.11 \pm 0.12	100	10.91 \pm 0.12	4	302.2 \pm 4.0	0.000456
EF-10a	basalt	11.3	11.16 \pm 0.15	82		2		0.001575
<i>Husavikurkleif</i>								
HKHR	basalt	11.6	11.88 \pm 0.71	90	11.20 \pm 0.53	6	299.9 \pm 12.3	0.001448

Sample are those reported by *Helgason* [1982] and *Helgason and Zentilli* [1982]. Ages are reported relative to biotite monitor FCT-3 (27.95 Ma), which is calibrated against hornblende Mmh-1 (520.4 Ma [*Lanphere et al.*, 1990]). Plateau ages are the mean of concordant step ages (N = number of steps), weighted by the inverse of their variances. Calculations use the following decay and reactor interference constants: $\lambda_e = 0.581 \times 10^{-10} \text{ yr}^{-1}$, $\lambda_{\beta} = 4.963 \times 10^{-10} \text{ yr}^{-1}$; $(^{36}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = 0.000264$, $(^{39}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = 0.000673$, $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{Ca}} = 0.01$.

^a Feldspar concentrated from a crystal tuff layer within the Holmatindur clastic bed.

Using these figures and three interlava flow intervals, we estimate the duration of the Holmatindur cooling event as between 30 and 50 kyr.

3.2.3. Dating of the C5n(o) boundary. All of the dated units in eastern Iceland, i.e., eight lavas and one crystal tuff, are stratigraphically close to the C5n(o) boundary, between 460 m above and 430 m below the boundary. The Holmatindur clastic bed is about 310 m above the C5n(o) boundary, and there is good agreement among the age determinations close to the boundary at roughly 10.9 Ma. The lowest unit dated from Holmatindur (flow EF-10a), at 430 m below the C5n(o) boundary, gave a two-step plateau age of 11.26 (\pm 0.15) Ma. Of the two units close to the magnetic boundary, unit RF-52 produced an age that is too young, judging from its stratigraphic position, probably due to ^{40}Ar loss. With reference to the precise dating of feldspar from the Holmatindur clastic bed, it is reasonable to assume that unit RF-52 must be somewhat older than 10.72 Ma. Flow unit RF-76, within the Holmatindur clastic bed, produced a two-step plateau age (11.88 \pm 0.26 Ma) that appears to be erroneously old, perhaps due to Ar recoil effects. A weighted least squares regression of the ages of seven units (omitting RF-52 and RF-76) against stratigraphic height (Figure 4) provides our best estimate of the age of the C5n(o) boundary, which is located between RF-47A and RF-47. This estimate is 10.94 (\pm 0.16) Ma.

Previous estimates of the age of C5n(o) were based on interpolations of regression fits of direct dating of Tertiary lava successions by conventional K-Ar methods against stratigraphic thickness in Iceland. *McDougall et al.* [1976] reported an age of 10.30 (\pm 0.34) Ma (adjusted to modern decay and abundance constants), while *Saemundsson et al.* [1980] proposed an age of 10.47 Ma. In a study of 70 dated lava flows from northwest Iceland, *McDougall et al.* [1984] concluded that the boundary occurred at 11.07 Ma. The effects of ^{40}Ar loss through low-temperature alteration of groundmass to clays are apparent in all of these studies and low-temperature bakeout procedures led to increasingly older estimates for the boundary. Our results appear to confirm, but improve the precision of, the latest estimates based on K-Ar dating. The interpolated age for C5n(o) from *Cande and Kent* [1995], based on a smoothed geomagnetic polarity timescale assembled from a composite of seafloor magnetic profiles and calibrated with several radiometrically

dated tie points, is 10.95 Ma. Reversal boundaries in the Miocene polarity timescale have recently been revised to slightly older ages with high-precision ^{40}Ar - ^{39}Ar dating and astronomical tuning [e.g., *Hilgen et al.*, 1995]. Our

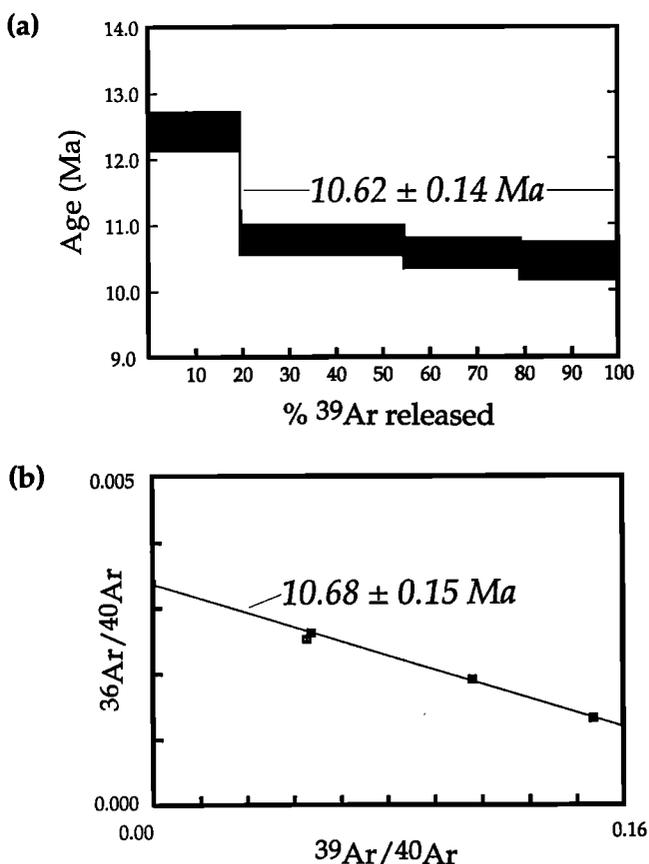


Figure 3. The ^{40}Ar - ^{39}Ar plateau and isochron plots for feldspar separated from the Holmatindur clastic bed, eastern Iceland. (a) The plateau age is calculated as the weighted mean of concordant step ages. (b) The isochron age is calculated from the x intercept of the best fitting line to the plateau step Ar isotopic compositions. The y intercept is atmospheric Ar composition, and the ages determined in both plots are concordant.

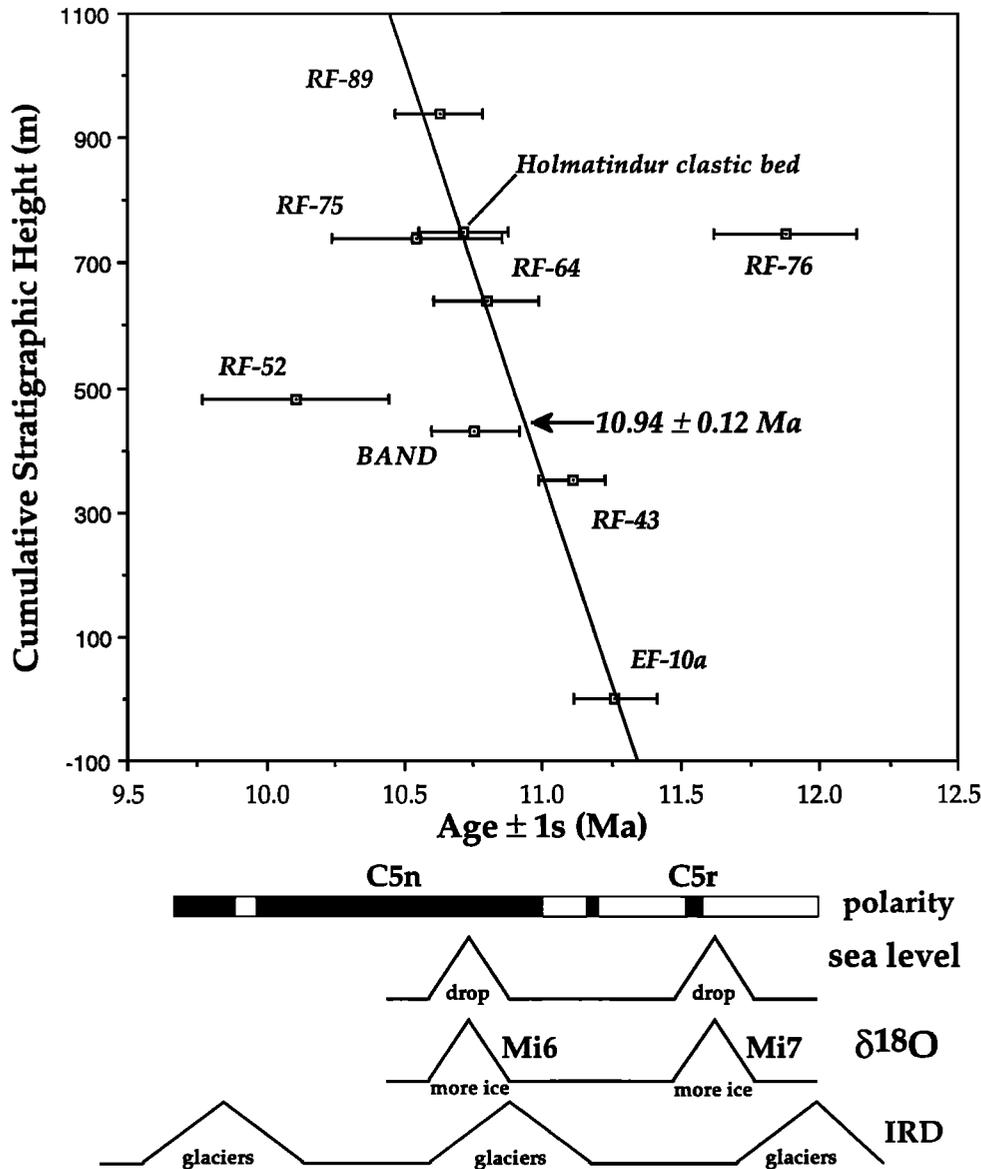


Figure 4. Measured ^{40}Ar - ^{39}Ar plateau ages for lavas and the Holmatindur tuff, eastern Iceland, plotted against cumulative stratigraphic height. The interpolated age of the C5n(o) boundary is derived from the weighted least squares regression (omitting samples RF-52 and RF-76). Comparison of magnetostratigraphy [from Helgason, 1982; Cande and Kent, 1995], eustatic sea level change [from Mountain *et al.*, 1994; Eberli *et al.*, 1997], $\delta^{18}\text{O}$ stratigraphy [from Miller *et al.*, 1991], and the record of North Atlantic ice-rafted debris *Fronval and Jansen* [1998] indicate that the Holmatindur cooling event coincided with a bipolar glaciation in the late middle Miocene, within the lower part of C5n.

dating, although not on actual transitional lava flows, provides the most direct age yet of the C5n(o) boundary.

4. Evidence for the Late Middle Miocene Cooling Event Elsewhere in Iceland

Elsewhere in Iceland, the Holmatindur clastic bed has been correlated with lignite beds on the basis of pollen assemblages, magnetostratigraphy, and radiometric dating. One such location is the Husavikurkleif sediments in Steingrimsfjörður of northwest Iceland. Here, pollen analysis (P. Mudie, personal communication, 1996) indicates a similar cooling from subtropical to cool temperate plant assemblages through the sedimentary section. The magnetostratigraphy of lavas above and below the Husavikurkleif sediments has

been established together with K-Ar dating by *Saemundsson et al.* [1980]. In Steingrimsfjörður the C5n(o) boundary coincides with the Husavikurkleif sediments (although a hiatus may occur in the volcanic section just below the sediments), whereas in Reydarfjörður this boundary is stratigraphically 310 m below the Holmatindur sedimentary horizon. *Saemundsson et al.* [1980] favored an age for the C5n(o) boundary of 11.07 Ma but stated that it might be slightly younger (10.86 Ma), depending on the possible occurrence of anomaly 5 subchrons within the section. We have dated a single low-K, tholeiitic lava flow from the top of the sedimentary section, which produced an imprecise age (11.88 ± 0.71 Ma) that adds very little information (Table 1). In spite of some uncertainty about the details of the Husavikurkleif magnetostratigraphic

interpretation, there is now good agreement for the proposed age of C5n(o) for both eastern and northwestern Iceland, i.e., 10.9 Ma and 10.9 to 11.1 Ma, respectively. This polarity transition immediately precedes a synchronous, late middle Miocene cooling event over much of Iceland that involved at least highland glaciation.

5. Discussion

The age of the Holmatindur clastic bed was previously regarded to be 9.8 Ma [Mudie and Helgason, 1983]. The present results date the clastic bed as considerably older, by about 0.9 m.y. With this new date for the Holmatindur clastic bed, i.e., 10.72 (\pm 0.16) Ma, a far better age estimate exists for a late middle Miocene cooling event that may have affected the northern hemisphere. It is therefore appropriate to compare our results with the available literature on such climatic cooling events. Terrestrial evidence is scarce because of removal of the sedimentary record by much more extensive and younger glacial events; however, it appears clear that glacial ice accumulated both in Iceland [Mudie and Helgason, 1983] and Alaska [Mathews, 1989] at roughly 10 Ma. The exact timing and correlation of this event, other than at the Holmatindur site, is uncertain due to lack of suitable material for dating.

The marine record is much more complete and offers a more robust source of data for correlating the timing and duration of cooling events in the late middle to early late Miocene. The Miocene was a period of transition from the relatively warm and equable climate of the early Eocene to the present glacial-interglacial cycles that have dominated global climates over the last 2.6 m.y. The long-recognized middle Miocene $\delta^{18}\text{O}$ increase recorded in benthic and planktic foraminifera, which represents a major step in the progression toward cold polar climates, was initially interpreted to reflect accumulation of ice on Antarctica [Shackleton and Kennett, 1975], but more recently it is believed to have been caused by both changes in deepwater circulation with attendant cooling bottom water, and ice accumulation [Wright et al., 1992]. Superimposed on this long-term cooling trend are five abrupt cooling events in the mid-late Miocene (events Mi3-7 of Miller et al. [1991]). These cooling events are seen as \sim 0.6‰ increases in $\delta^{18}\text{O}$, which, if interpreted strictly as ice volume changes, represent about 40% of the present Antarctic ice sheet [Shackleton and Kennett, 1975]. Event Mi6 occurs in the mid-early part of C5n and thus correlates closely with the time of the Holmatindur cooling event. The duration of Mi6 is not well resolved but appears to be of order 100-200 kyr.

Ice volume increases near this time are also inferred from \sim 70 m drops in sea level (Figure 4) and erosional surfaces that have been documented at several Atlantic continental margin sites [Miller et al., 1987; Eberli et al., 1997]. The age of Miller et al.'s [1987] m1 surface is estimated from seismic and biostratigraphic data and from ocean drilling to be about 11.5 Ma [Mountain et al., 1994], which correlates well with event Mi7 of Miller et al. [1991]. A sea level event (reflector I) at about 10.5 Ma has been identified by Eberli et al. [1997], which correlates with Mi6 (Figure 4). The evidence from Iceland for glaciation at 10.7 Ma indicates that ice was accumulating in parts of the northern hemisphere as well as in Antarctica at this time. Ice-rafted debris (IRD) has now been identified in mid-to-late Miocene sediment cores at several sites in the North Atlantic Ocean [Fronval and Jansen,

1998; Wolf-Welling et al., 1997]. Pulses of IRD began as early as 14 Ma in the Fram Strait and 12 Ma on the Voring Plateau, with increases at 10.8, 9.8 (Figure 4), and 7 Ma, followed by a major intensification at 4-2.6 Ma. These observations indicate that not only did parts of the North Atlantic region accumulate ice but that glaciers reached the sea during some periods in the mid-to-late Miocene.

6. Conclusions

The stratigraphic succession of lavas, sediments, and organic-rich layers in the Holmatindur region of eastern Iceland provides the means to calibrate magnetic reversal stratigraphy and a record of major North Atlantic Ocean cooling through precise radiometric dating. From ^{40}Ar - ^{39}Ar incremental heating age determinations for lavas that bracket the well-established lower boundary of C5n(o), we conclude that the onset of this prominent, long normal polarity period occurred at 10.94 (\pm 0.16) Ma. This direct dating is compatible with the interpolated estimate of Cande and Kent [1995] but significantly older (or more precise) than previous dating by K-Ar methods.

The cooling event coincides with the Holmatindur clastic bed, a regionally extensive marker unit of basaltic composition that appears to have erupted subglacially. Feldspars from a crystal-rich layer within this thick tuff were dated at 10.72 (\pm 0.16) Ma, providing a precise age for this late middle Miocene cooling event which is recorded globally in marine sedimentary sections as a \sim 70 m drop in sea level, a +0.6‰ excursion in benthic $\delta^{18}\text{O}$ (Mi6 event of Miller et al. [1991]) and as ice-rafted debris at deep-water North Atlantic Ocean sites. The evidence points to accumulation of ice on land, a significant portion of which occurred in the northern hemisphere.

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