RADIOCARBON DATING TEPHRA LAYERS IN BRITAIN AND ICELAND

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ABSTRACT. Layers of volcanic ash, or tephra form widespread chronostratigraphic marker horizons which are important because of their distinctive characteristics and rapid deposition over large areas. Absolute dating of prehistoric layers effectively depends upon ^{14}C analysis. We focus here on Icelandic tephra layers at both proximal and distal sites and consider three strategies to obtain age estimates: 1) the conventional dating of individual profiles; 2) high-precision multisample techniques or "wiggle-matching" using stratigraphic sequences of peat; and 3) a combination of routine analyses from multiple sites. The first approach is illustrated by the dating of a peat profile in Scotland containing tephra from the AD 1510 eruption of Hekla. This produced a ^{14}C age compatible with AD 1510, independently derived by geochemical correlation with historically dated Icelandic deposits. In addition, the *ca.* 2100 BP date for the Glen Garry tephra in Scotland, determined by a series of dates on a peat profile in Caithness, is supported by its stratigraphic position within ^{14}C dated profiles in Sutherland, and may be applied over a very large area of Scotland. More precise dates for individual tephras may be produced by "wiggle-matching", although this approach could be biased by changes in peat-bog stratigraphy close to the position of the tephra fall. As appropriate sites for "wiggle-match" exercises may be found only for a few Icelandic tephras, we also consider the results of a spatial approach to ^{14}C dating tephra layers. We combined dates on peat underlying the same layer at several sites to estimate the age of the tephra: 3826 ± 12 BP for the Hekla-4 tephra and 2879 ± 34 BP for the Hekla-3 tephra. This approach is effective in terms of cost, the need for widespread applicability to Icelandic tephra stratigraphy and the production of ages of a useful resolution. We stress the need for accurate identification of tephra deposits without which the conclusions drawn from subsequent ^{14}C dating will be fundamentally flawed.

INTRODUCTION

Layers of volcanic ash, or tephra, form chronostratigraphic marker horizons of great importance because of their distinctive characteristics, widespread distribution and rapid dispersal. Tephra can be used to define time-parallel marker horizons, or isochrones, particularly valuable in paleoenvironmental studies because deposits at different sites may be correlated with a relative dating precision of years, months or even days (Thórarinsson 1981; Hallsdóttir 1987; Blackford *et al.* 1992; Merkt *et al.* 1993; Edwards *et al.* 1994). Within the historical period, reference to reliable records can provide calendar dates of similar precision (Thórarinsson 1967). In Iceland, since the 16th century, accurate records have been kept, from which dates of eruptions may be determined. Data becomes scarce between the mid-16th century and AD 1430, somewhat uneven for the preceding period of early annals writing and very poor for the centuries immediately following the 9th century Norse settlement (Thórarinsson 1967; Larsen 1984; Ogilvie 1984). If historical records are unavailable to date tephra layers, other techniques such as ^{14}C dating must be employed to estimate the "absolute" age (Kjartansson, Thórarinsson and Einarsson 1964). Where the surface onto which tephra has fallen can be identified, relative dating by reference to the stratigraphic marker formed by the tephra layer may still be precise to days or months, but the quality of an "absolute" age estimate will be determined by the characteristics of the method used. The chronological precision, however, can be optimized by using the best samples from within the area covered by the tephra. Further, the dating uncertainty associated with tephras in southern Iceland can be constrained by their positions in the detailed tephra stratigraphy of the region (Thórarinsson 1967; Larsen 1984; Dugmore 1989). For the Holocene, ^{14}C dating offers the most potential for dating tephra isochrones of unknown age. We consider here several alternative but complementary strategies.

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379

Determining the "Absolute" Age of a Tephra Isochrone

Conventional Dating of a Single Stratigraphic Section

A widely used strategy for dating tephra deposits is to ^{14}C date a vertical sequence at a single site (*e.g.*, Björk *et al.* 1992; Bennett *et al.* 1992). The age of the tephra can be estimated from dates on the organic material coincident with or underlying the deposit, supported by the overall age/depth profile. We dated a shallow peat profile containing a zone of tephra (Fig. 1) at Loch Portain in the Scottish Outer Hebrides. The calibrated age/depth profile produced a range of possible ages for the tephra, but geochemical analysis identified two distinct populations of tephra, one of which can be correlated to Icelandic deposits from the AD 1510 eruption of Hekla (Fig. 2; Dugmore, Larsen and Newton 1995). Historical records firmly place the start of this eruption on 25 July, and as the tephra that fell in Scotland is the silicic portion produced at the beginning of the eruption, it was probably deposited no later than 26 July, 485 yr ago (Thórarinsson 1967). Although a very precise age may be attributed to one of the tephra populations, this precision cannot be applied to a clearly defined level within the stratigraphy because the tephra horizon is diffuse. Taking the probable maximum and minimum rates of accumulation based on the ^{14}C ages, the tephra could be spread through material 125–195 yr old.
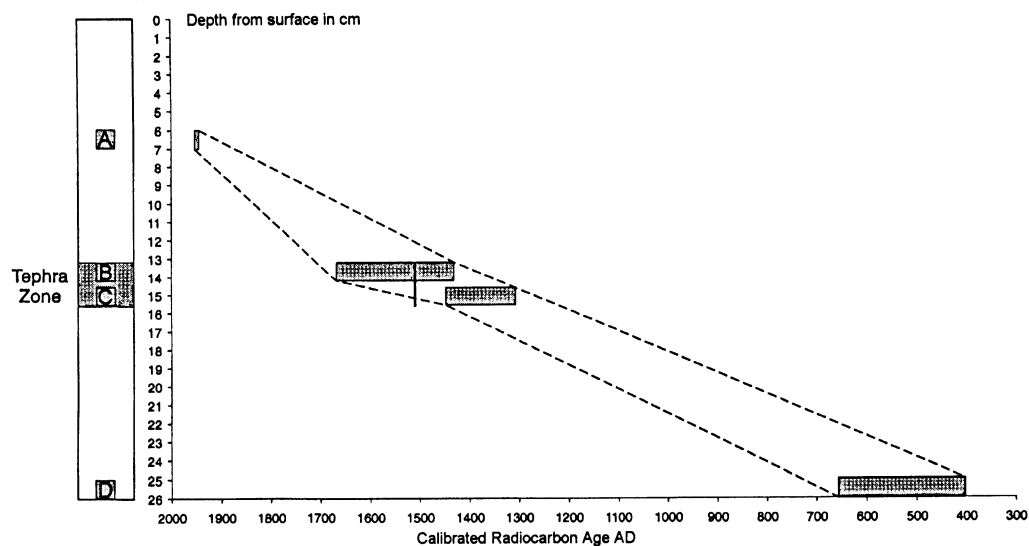

Fig. 1. A ^{14}C-dated profile from Loch Portain, North Uist, Outer Hebrides, Scotland (NGR 950724). The stratigraphic location of four ^{14}C dates and a zone containing a diffuse horizon of very fine-grained tephra is shown in the left column. The date A. Modern; B. 360 ± 70 BP (GU-3010); C. 540 ± 50 BP (GU-3009); D. 1530 ± 70 BP (GU-3008). ▓▓▓ = calibrated ^{14}C ages at 2 σ; – – – = an envelope containing the likely age-depth profile (Stuiver and Reimer 1993). The tephra zone is formed by two distinct populations, one of which is geochemically correlated with Icelandic tephra from the AD 1510 eruption of Hekla (*cf.* Fig. 2). The vertical bar represents the independently derived calendar date, and is consistent with the calibrated ^{14}C ages.

A calendar date of AD 1510 for a component of the tephra zone is compatible with the ^{14}C age/depth profile, but the 350-yr range for the calibrated ^{14}C ages for the tephra zone, is significantly greater than the relative dating precision of the tephra defined by its stratigraphic position. There is clearly room to improve ^{14}C dating to match more closely the relative dating precision possible with distal tephra deposits.
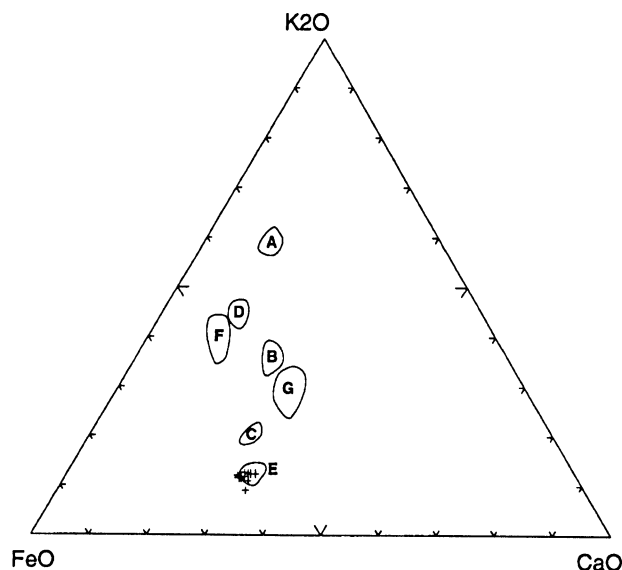
Fig. 2. The geochemical characteristics of seven silicic tephras produced by Icelandic volcanic eruptions in historical times. The fields are defined by data from the electron probe microanalysis of individual grains within tephra layers in Iceland. Analyses were carried out using a Cambridge Instruments Microscan V electron probe. We used a standard Wavelength Dispersive Spectrometry (WDS) method with an accelerating voltage of 20 KV and a beam current of 15 nA. Other operating conditions are described elsewhere (Dugmore *et al.* 1992). A. Landnám tephra of *ca.* AD 900; B. Hekla AD 1104 tephra; C. Hekla tephra AD 1158; D. Öræfajökull tephra AD 1362; E. Hekla tephra AD 1510; F. Eyjafjallajökull AD 1821–1823 tephra; G. Askja tephra AD 1875. **+** = data from a tephra zone 13–16 cm below the surface at Loch Portain, North Uist, in the Outer Hebrides of Scotland (NGR 950724) (data from Dugmore, Larsen and Newton 1995; Larsen *et al.*). The geochemical correlation between the Loch Portain tephra and tephra from the AD 1510 eruption of Hekla in Iceland agrees with the ^{14}C dating of the Scottish profile (*cf.* Fig. 1).

Although limited, the ages of tephra layers based on the routine ^{14}C dating of single profiles provide chronological control useful for a wide range of paleoenvironmental applications. The Glen Garry tephra, found at sites across Scotland, was first dated in Caithness to 2120 ± 60 BP (GU-7017). This is supported by a ^{14}C age of 2010 ± 60 BP (GU-7016) above the tephra and 2220 ± 80 BP (GU-7018) below it. Subsequently, this dating has been further supported by ^{14}C dating on a peat profile containing the Glen Garry tephra at Achany Glen, Sutherland (NGR NC 020583) (M. Smith, written communication). The age attributed to the Glen Garry tephra is, at present, no more precise than other dates routinely determined for Holocene paleoenvironmental studies, but it is noteworthy because it may be applied, and further refined whereever the tephra is identified; currently, this includes >27,000 km^2 of northern Scotland and part of southeastern Iceland (Dugmore and Newton 1992; Dugmore, Larsen and Newton 1995; Larsen, Newton and Dugmore, ms.). Given the large areas covered by Icelandic tephras, both in Iceland and abroad, and the extensive range of applications for tephrochronology in paleoenvironmental studies, precise and accurate ages of tephra layers would be most useful. In proximal areas where tephra form visible layers, the relative dating preci-

sion is frequently to <1 yr because it is possible to identify the surface onto which the tephra fell. [14]C dating will never be able to match such a level of precision, but there is significant room for improvement, especially in the British Isles and Scandinavia, where tephra deposits are fine grained and form invisible horizons. In the British Isles, a clear target is to reduce the gap between the *ca.* 250-yr range for the most probable age of tephras, as determined by routine ^{14}C dating, and the 40- to 80-yr range for the relative dating precision commonly achievable in Holocene blanket peats, based on typical rates of accumulation and the stratigraphic spread of the tephra (Barber 1981; Dugmore and Newton 1992; Pilcher and Hall 1992). One strategy for improving dating precision is the high-precision multisample technique, or "wiggle-matching".

High-Precision Multisample [14]C Dating, or "Wiggle-Matching"

A profile of high-precision ^{14}C dates through rapidly accumulating peats, such as those found in the lowland raised bogs of Northern Ireland, may be matched against the calibration curve to produce very precise age estimates. This strategy has been used by Pilcher, Hall and McCormac (1994, 1995) to produce dates of AD 1088 ± 20 and 860 ± 20 for two tephras in Northern Ireland. In these dates, an uncertainty of <10 yr is attributable to the fit to the calibration curve. The final uncertainty was increased to ±20 to cover possible variation in peat accumulation rates. This provision is needed to produce an age range of AD 1068–1108, which is wide enough to be consistent with the correlation of the younger tephra to the AD 1104 eruption of Hekla on the basis of its geochemical characteristics. It would therefore seem probable that variation in peat accumulation rates introduces some bias to the high-precision multisample age estimates for tephras of historical age.

Similar uncertainties are likely when using [14]C "wiggle-matching" with older tephras, and this provision is included in the dating of 2310 ± 20 BC for a deposit of the Hekla 4 tephra at Sluggan Bog in Northern Ireland (Fig. 3; Hall, Pilcher and McCormac 1994; Pilcher, Hall and McCormac 1994, 1995). However, variation in peat growth around the Hekla 4 tephra may be somewhat greater than that above and below the tephras of historical age considered earlier. A phase of reduced growth lasting 15 yr began at 2350 BC in oaks growing at Garry Bog and sites south of Lough Neagh in Northern Ireland (Baillie and Munro 1988). Although there are no palynological changes around the Hekla 4 tephra at Sluggan Bog comparable with those observed in Caithness, Scotland the tree-ring data show that short-lived but significant environmental changes were occurring at about or just before this time in the lowland raised bogs of Northern Ireland (Figs. 3 and 4; Blackford *et al.* 1992; Hall, Pilcher and McCormac 1994). This raises the possibility that variation in the rate of peat accumulation may occur in close association with some prehistoric tephras, which is significantly greater than that associated with recent deposits. This factor may reduce the high precision potentially achievable by [14]C "wiggle-matching" with peat sequences. As only a restricted number of Icelandic tephras are present in the Irish peats most suitable for "wiggle-matching", alternatives must be used to improve the resolution of the ^{14}C dating of other key tephras.
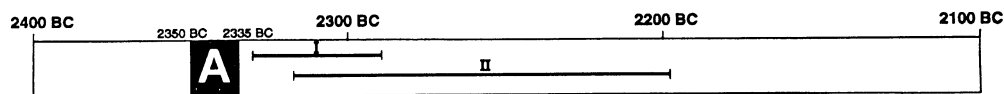

Fig. 3. Calibrated age estimates for the Hekla 4 tephra and the age of a growth downturn in the Irish tree-ring record (Baillie and Munro 1988). "Wiggle matching" has yielded a date of 2310 ± 20 BC for Hekla 4 tephra (Hall, Pilcher and McCormac 1994), shown as age range I. We report a compilation of dates that produced a ^{14}C age of 3832 ± 12 BP or a calibrated age range 2317–2198 BC, which is shown as age range II. Both age ranges are younger than the growth downturn in the tree-ring record that dates to between 2350 and 2335 BC (area A). These data suggest that a short-lived environmental change that significantly affected oak tree growth in areas close to peats bogs occurred before the deposition of the Hekla 4 tephra and could have also affected peat accumulation rates.
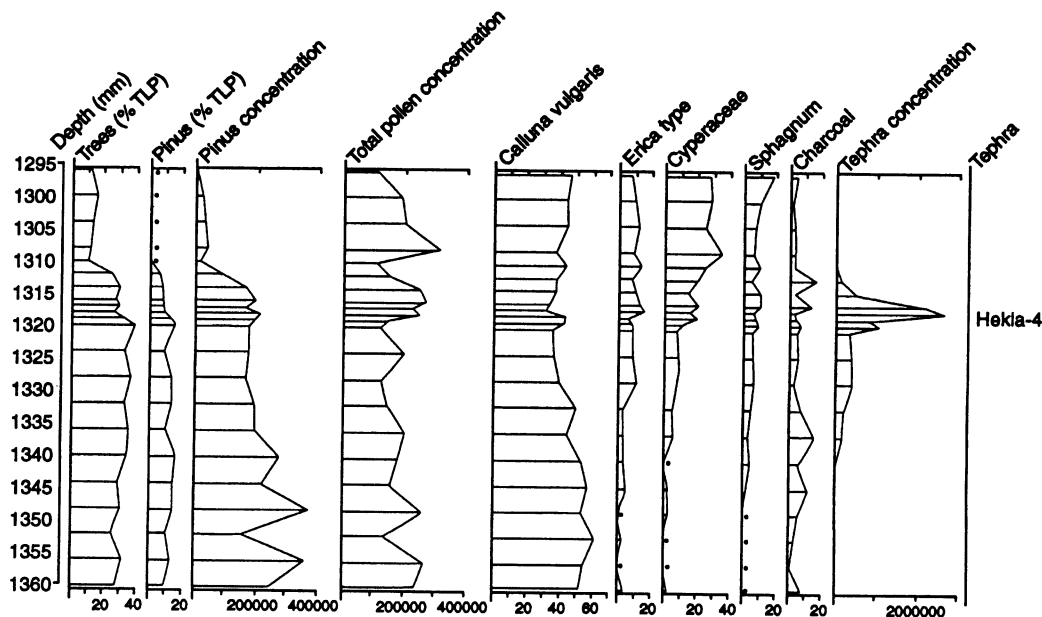
Fig. 4. High-resolution, millimeter-scale pollen, charcoal and tephra data from Loch Leir in Caithness from Blackford *et al.* (1992) show a stratigraphic link between the decline of *Pinus sylvestris* pollen and the deposition of the Hekla 4 tephra. The implication is that significant ecological changes occurred in this area of Scotland at about the time of the deposition of the tephra.

A Spatial Compilation of *14C* Dates

Another approach to improving the precision of 14C ages for tephra layers is to combine separate dates (*e.g.*, Vogel *et al.* 1990). In Icelandic peats, the surface layers covering a tephra fall may be identified, and a more precise 14C age on the deposition of the tephra may be obtained by combining results on chronologically equivalent material from different sites. An advantage to this method is that it may be applied in proximal areas where a tephra layer may be disturbed, effectively ruling out the "wiggle-matching" approach used in Ireland. Any site-specific bias may also be greatly reduced, and dating precision closer to that of the stratigraphic resolution of the tephra isochrone may be achieved with a routine series of 14C dates.

Dating Icelandic tephras in proximal areas is important because they form visible layers in continuous vertical sequences containing up to 80 other tephras (Fig. 5). Detailed mapping of tephra layers in Iceland has produced accurate information about the stratigraphic relation between different tephras (*e.g.*, Thórarinsson 1967; Larsen 1982, 1984; Dugmore 1987). As more dating evidence becomes available, this framework becomes tighter, forming a tephrochronology that is much stronger than simply the sum of the separately dated layers. Whatever the uncertainties about the dating on individual tephras, the sequence of events is known.

Close to the source areas, stratigraphical relations can be used to distinguish clearly between tephras formed by separate eruptions. Different tephras produced by the same volcanic system can have similar geochemical characteristics (Jakobsson 1979; Imsland 1978; Larsen 1981, 1982). Subsequently, the geochemical data may be applied in distal areas where tephra deposits are less numerous and microscopic, and can present significant analytical challenges due to their small grain size, vesicularity and potential instability during electron probe microanalysis (Larsen 1981; Hunt and

Hill 1993). Without rigorous linkage to the source areas, different tephras from the same volcanic system may be identified mistakenly as the product of a single eruption. Effective correlation between tephra studies in proximal and distal areas is essential, particularly if chronological data from one specific area is to be applied throughout the range of the tephra distribution.
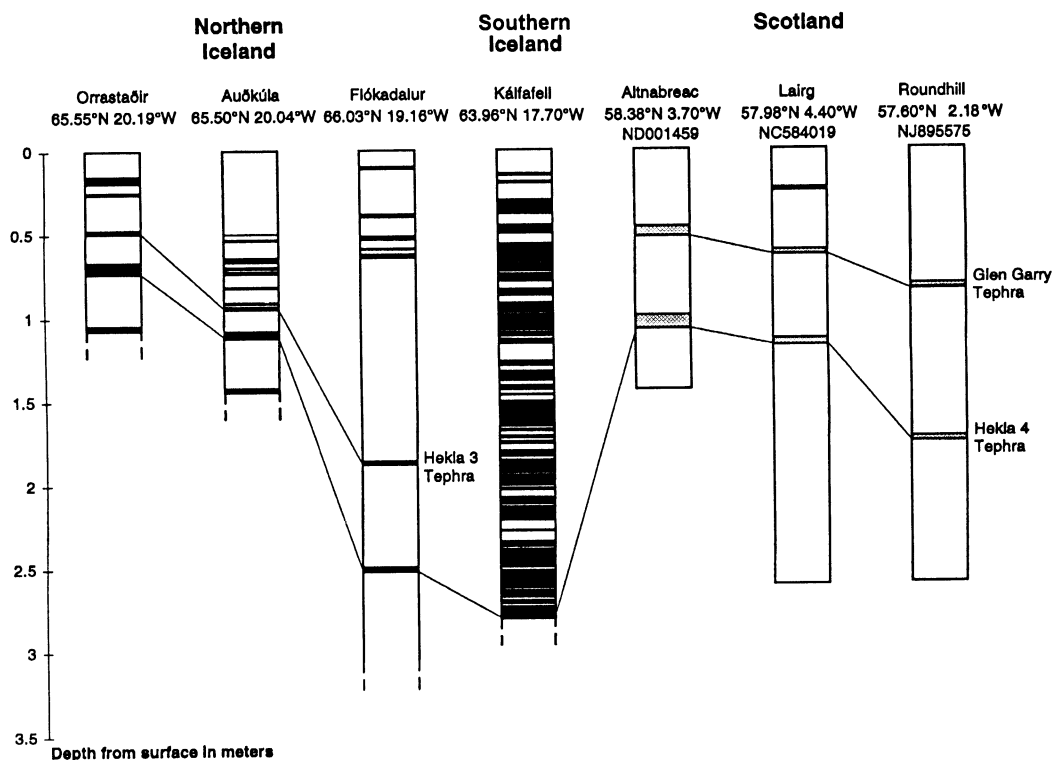

Fig. 5. Stratigraphic sections including the Hekla 3, Glen Garry and Hekla 4 tephras. ▬ = visible tephra layers in Iceland. In Scotland, where the grains of tephra are <150 μm and the mass loading <10 tonnes ha^{-1}, the deposits are invisible (▬). Peak grain abundance occurs over more restricted depths than the distribution of the tephra horizon as a whole (*cf.* Fig. 4). Tephra layers are most abundant in southern Iceland where peat accumulation rates are affected by the frequent mantling of the bog surface with inorganic material. For clarity, the identification of other tephra layers has been omitted.

The Hekla 4 tephra has been identified at many sites in Iceland and the British Isles, seven of which are shown in Figure 5. Geochemical analysis has been used at each site to determine the identity of the tephra permitting accurate correlation between sites 1200 km apart (Fig. 6). Combined ^{14}C dates from 15 profiles at these sites give 3826 ± 12 BP for Hekla 4 (Table 1; Pearson and Stuiver 1993). In Iceland, we took peat samples below the tephra layer because the surface onto which the tephra had fallen was clearly identifiable. In contrast, the overlying peat did not always begin to form immediately after the eruption. In some profiles, tephra layers formed soon after 3800 BP are either missing, or mixed together with a reworked upper part of the Hekla 4 tephra. In Scotland, as the surface onto which the tephra had fallen could not be seen, we used slices of peat that enclosed the level of peak tephra-grain abundance.

Hekla 3 has attracted considerable attention as it erupted at about the same time as several other events, which include a brief and unusual period of growth downturn in the Irish dendrochronolog-

TABLE 1. ¹⁴C ages obtained for peat underlying (0–2 cm) Hekla 4 tephra at Orrastaðir (65.55°N, 20.19°W), Flókadalur (66.03°N, 19.16°W) and Auðkúla (65.50°N, 20.04°W), Iceland, and Altnabreac (58.38°N, 3.70°W), Lairg (57.98°N, 4.40°W) and Roundhill (57.60°N, 2.18°W), Scotland. The tephra stratigraphy for each site is shown in Figure 5. Calibration is after Stuiver and Reimer (1993).

Lab no.	Fraction dated	Site	Age (yr BP)	δ^{13}C (‰)	Cal range BC (2 σ)
Hekla 4 tephra (Iceland)					
GU-7001	Humic acid	Orrastaðir	3890 ± 90	−29.6	2582–2044
GU-7010a	Humic acid	Orrastaðir	3910 ± 80	−29.7	2582–2139
GU-7010b	Humin	Orrastaðir	3680 ± 170	−29.6	2558–1618
GU-3240	Humic acid	Orrastaðir	3850 ± 50	−29.1	2462–2139
GU-3241	Humic acid	Orrastaðir	3790 ± 50	−28.6	2398–2037
GU-3242	Humic acid	Orrastaðir	3790 ± 50	−28.9	2398–2037
GU-3243	Humic acid	Orrastaðir	3820 ± 50	−28.9	2455–2047
GU-4334	Humic acid	Orrastaðir	3820 ± 50	−29.3	2455–2047
GU-4335	Humin	Orrastaðir	3770 ± 50	−29.2	2330–1988
GU-4336	Humic acid	Orrastaðir	3750 ± 50	−29.0	2290–1980
GU-4337	Humin	Orrastaðir	3750 ± 50	−28.9	2290–1980
GU-7011	Humic acid	Auðkúla	4020 ± 80	−28.4	2869–2312
GU-7022	Humic acid	Auðkúla	3820 ± 50	−28.5	2455–2047
GU-7023	Humin	Auðkúla	3910 ± 100	−28.4	2837–2044
GU-7024	Humic acid	Auðkúla	3930 ± 60	−28.6	2573–2203
GU-7025	Humin	Auðkúla	3730 ± 90	−28.6	2453–1884
GU-7051	Humic acid	Auðkúla	3940 ± 50	−28.2	2569–2283
GU-7052	Humin	Auðkúla	3700 ± 360	−28.7	3036–1204
GU-7053	Humic acid	Auðkúla	3760 ± 50	−28.0	2319–1984
GU-7054	Humin	Auðkúla	3740 ± 80	−28.1	2451–1907
GU-7122	Humic acid	Auðkúla	3800 ± 50	−27.9	2451–2041
GU-7123	Humic acid	Auðkúla	3860 ± 50	−27.8	2464–2142
GU-7128	Humic acid	Flókadalur	3880 ± 50	n/a*	2469–2147
GU-7129	Humin	Flókadalur	3890 ± 60	−27.2	2554–2145
GU-7130	Humic acid	Flókadalur	3860 ± 50	−28.8	2464–2142
GU-7131	Humin	Flókadalur	3870 ± 60	−27.0	2476–2139
GU-3017	Humic acid	Kálfafell	3880 ± 70	−27.9	2559–2137
GU-3018	Humic acid	Kálfafell	3840 ± 50	−27.9	2460–2136
Hekla 4 Tephra (UK)					
GU-3012	Humic acid	Altnabreac	3880 ± 70	−28.5	2559–2137
GU-7102	Humic acid	Lairg	3680 ± 50	−29.4	2194–1904
GU-7103	Humin	Lairg	3790 ± 50	−28.9	2398–2037
GU-7104	Humic acid	Lairg	3740 ± 50	−29.5	2286–1975
GU-7105	Humin	Lairg	3890 ± 50	−27.3	2477–2196
GU-3819	Humic acid	Lairg	3870 ± 50	−29.6	2467–2144
GU-3218	Humic acid	Roundhill	3800 ± 100	−28.4	2489–1934

*n/a = not analyzed

ical record, an acidity peak in Greenland ice and putative archaeological change in the British Isles (Burgess 1989; Baillie 1989a,b; but *cf.* Buckland, Dugmore and Edwards, ms.). The Hekla 3 tephra has been dated in six profiles at Flókadalur and Auðkúla in northern Iceland (Fig. 5). The weighted mean for these dates is 2879 ± 34 BP (Table 2).
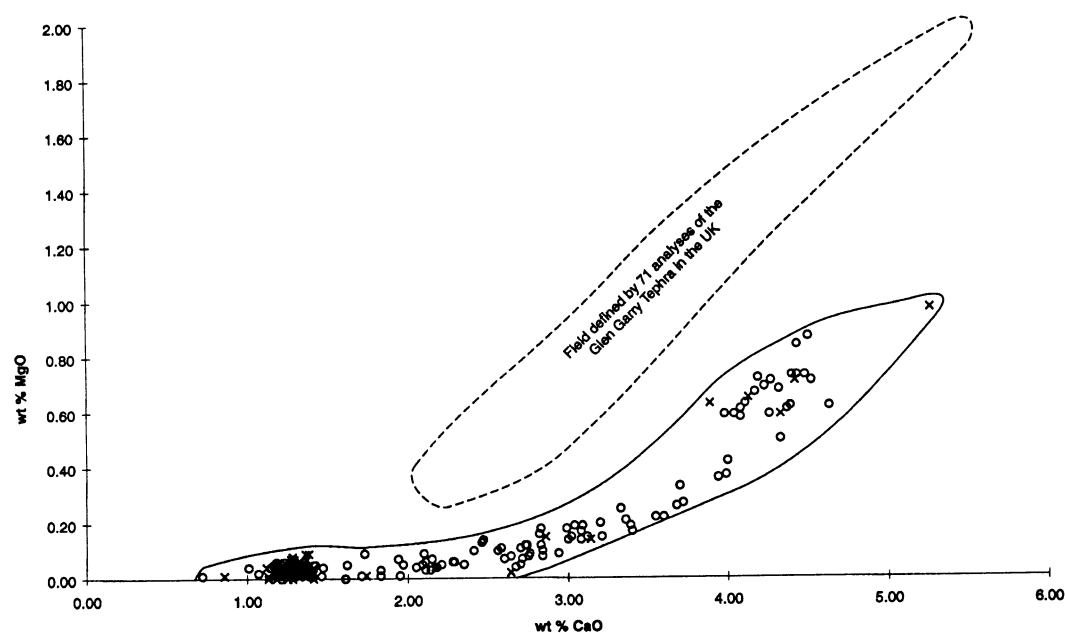

Fig. 6. Geochemical characteristics of the Hekla 4 tephra (———), and Glen Garry tephra (– – –) at the ^{14}C-dated sites considered in this paper (*cf.* Fig. 5). The separation of the two fields illustrates the discrimination of different tephras possible through the use of geochemical analysis. Points within the field for Hekla 4 represent the analyses of individual grains in Iceland (×) and Scotland (o) and illustrate effective correlation between areas up to 1200 km apart (Dugmore *et al.* 1992). The range of values represent changes during the course of the eruption, and show that all of the silicic parts of the tephra present in southern Iceland also occur in Scotland (Larsen and Thórarinsson 1977; Dugmore, Larsen and Newton 1995).

TABLE 2. [14]C ages obtained for peat underlying (0–2 cm) Hekla 3 tephra at Flókadalur (66.03°N, 19.16°W) and Auðkúla (65.50°N, 20.04°W), Iceland. The tephra stratigraphy for both sites is shown in Figure 5. Calibration is after Stuiver and Reimer (1993).

Lab no.	Fraction dated	Site	Age (yr BP)	$\delta^{13}C$ (‰)	Cal range BC (2 σ)
GU-7028	Humic acid	Flókadalur	2960 ± 50	−29.2	1372–1003
GU-7029	Humin	Flókadalur	2840 ± 100	−29.1	1297–805
GU-7030	Humic acid	Auðkúla	2820 ± 50	n/a*	1117–836
GU-7031	Humin	Auðkúla	2810 ± 80	−29.0	1198–807
GU-7032	Humic acid	Auðkúla	3060 ± 50	−28.6	1421–1133
GU-7036	Humic acid	Auðkúla	2910 ± 50	−28.6	1260–925
GU-7037	Humin	Auðkúla	2750 ± 80	−29.2	1113–794
GU-7038	Humic acid	Auðkúla	2800 ± 50	−28.7	1047–826
GU-7039	Humin	Auðkúla	2810 ± 50	−28.9	1113–830

*n/a = not analyzed

These dates offer a precision that narrows the gap between the resolution of the ¹⁴C ages and the precision of stratigraphic correlation possible with tephra layers, and illustrates an approach that can be used with virtually all the Icelandic tephra formed during the postglacial period. ¹⁴C dating tephra layers also allows one to compare groups of results for thematic or spatial categories, and for different peat fractions, types of vegetation and areas as far apart as northern Iceland and the Scottish Highlands (Shore, Cook and Dugmore 1995). The greatest possible precision is always desirable, but as a compromise between the considerations of cost, the need for widespread applicability to Icelandic tephra stratigraphy and the production of absolute dates of a good resolution, the combination of chronologically equivalent dates is an effective approach.

CONCLUSION

1. Effective dates on tephra layers can be determined by ¹⁴C analyses on a single profile, but precision can be significantly increased by combining analyses from several sites.
2. A dating strategy based on multiple analyses of samples of the same age underlying a tephra layer also presents an opportunity to evaluate site-specific factors that may influence ¹⁴C content.
3. High-precision multisample ¹⁴C dating techniques, or "wiggle-matching", can produce particularly accurate and precise age determinations at appropriate sites, but this approach may be applied only to a few Icelandic tephra layers.
4. The correct identification of tephra is critical, and of particular concern with Icelandic material is the possibility that different tephra from the same volcanic system may be mistakenly identified as the product of a single eruption.

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