Radiocarbon constraints on the history of the western Irish ice sheet prior to the Last Glacial Maximum

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ABSTRACT

Accelerator mass spectrometer ^{14}C dating of in situ monospecific marine microfaunas and reworked shells records high relative sea level on the western coast of Ireland between ca. 40 and 19 cal (calibrated) ka, requiring substantial isostatic loading by the Irish ice sheet (IIS) during that interval. Glacial and marine deposits also record a rapid fluctuation of the IIS margin onto the continental shelf ca. 28 cal ka. Evidence that the coast was not subsequently overridden by the IIS indicates that, at least for this sector of the ice sheet, the ice margin during the Last Glacial Maximum (LGM) was less extensive than the 28 cal ka event. Our data from western Ireland support ^{14}C and ^{36}Cl chronologies from the Irish Sea Basin in identifying an IIS that was as extensive and thick as the LGM IIS for much of the 20 k.y. interval prior to the LGM.

Keywords: Irish ice sheet, last glaciation, relative sea level, ^{14}C dating

INTRODUCTION

Glacial deposits and landforms from the west coast of Ireland have conventionally been interpreted as recording advance of the Irish ice sheet (IIS) during the Last Glacial Maximum (LGM, 19–23 ka; Mix et al., 2001) onto the continental shelf followed by monotonic ice retreat (Synge, 1968; Mitchell et al., 1973; Boulton et al., 1977). New chronological data, however, demonstrate that the IIS was a more dynamic system with several ice-margin fluctuations comparable to the LGM event over the past 45 k.y. (McCabe et al., 1986, 1998, 2005; McCabe and Clark, 1998, 2003; Bowen et al., 2002). For example, at least three advances occurred in the Irish Sea Basin: a maximum advance ca. 37 ^{36}Cl ka, the LGM advance ca. 23 ^{36}Cl ka, and the Killard Point advance ca. 15.5 cal ka (McCabe and Clark, 1998; Bowen et al., 2002). In addition, ^{14}C ages from raised marine deposits record interstadial events associated with substantial isostatic loading and attendant high relative sea level (Clark et al., 2004; McCabe and Clark, 1998; McCabe et al., 2005).

By comparison, the chronology of the western sector of the IIS remains poorly defined. Ice-flow indicators suggest multiple advances of westward flow derived from dispersal centers in central Ireland (Knight et al., 1999; Clark and Meehan, 2001), but none of these are dated. Although existing ^{14}C and ^{36}Cl ages suggest that the glacial and relative sea-level history of the western Irish ice margin may be similar to that from the Irish Sea Basin, most of these ages relate to events since the LGM (McCabe and Clark, 2003; McCabe et al., 2005), and major gaps remain that prevent establishing a firm understanding of the pre-LGM history. Here we present new radiocarbon ages on macrofossil and microfossil shells from glacial and raised marine sediments preserved on the south side of Donegal Bay, western Ireland (Fig. 1; Table 1), that significantly improve and extend our understanding of the glacial and relative sea-level history in western Ireland prior to the LGM.

DESCRIPTION OF STUDY SITES

Sedimentology

We sampled shells for radiocarbon dating from two sites exposed in the lower part of the Glenulra Valley on the south side of Donegal Bay (Fig. 1). On the west side of the valley, at Glenulra Farm, four fossiliferous

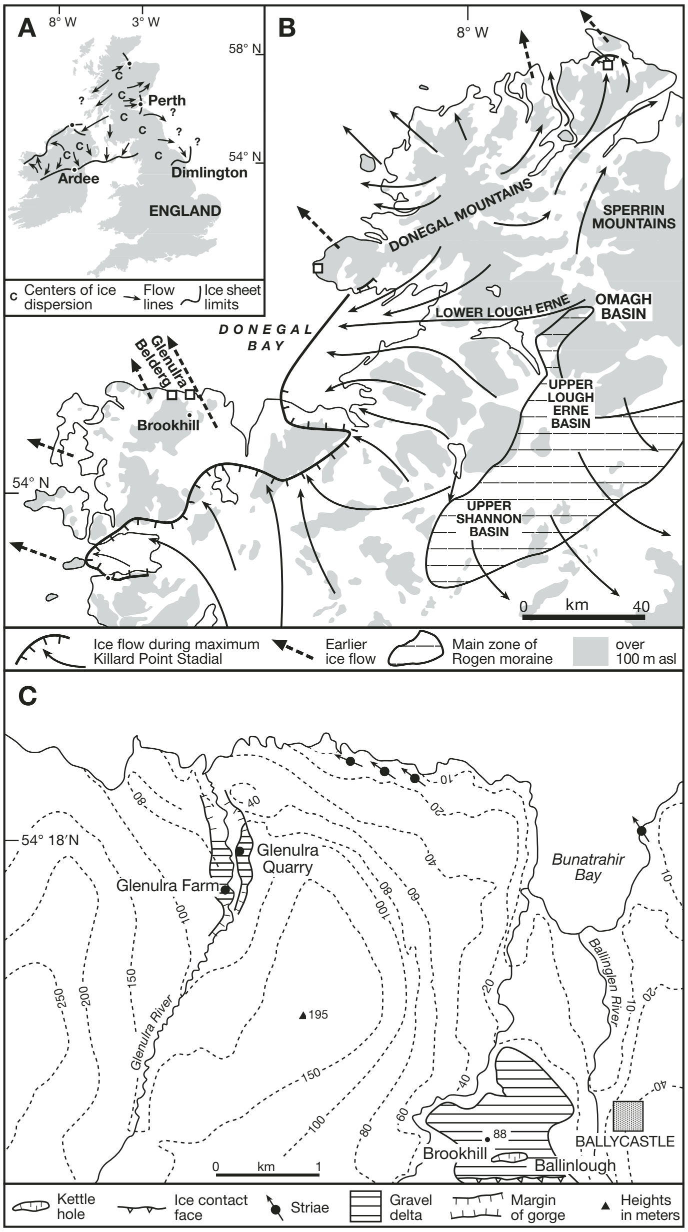

Figure 1. Regional ice-flow direction and location of sites from northwestern Ireland. A: Centers of ice-sheet dispersion, ice-sheet flow lines during Killard Point Stadial in British Isles. B: Ice-sheet flow lines during Killard Point Stadial from northwestern Ireland in relation to sites discussed in text. Note that raised marine and ice-contact deltas at Glenulra and Brookhill are as much as 30 km to west of Killard Point Stadial limits. C: Locations of exposures at Glenulra and Brookhill, north County Mayo, Ireland.

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TABLE 1. RADIOCARBON AGES FROM GLENULRA, IRELAND

Locality, description, comments	Facies	Laboratory number	^{14}C age (yr B.P. ± 1σ)*	Calibrated age (yr B.P. ± 1σ)†
Glenulra Quarry: samples of derived shells of *Arctic islandica* from gravel at base of delta formed during high relative sea level prior to last ice sheet advance.	Gravel	CAMS115272 CAMS115273 CAMS115274	26930 ± 160 24380 ± 120 29660 ± 220	31870 ± 150 28970 ± 150 34850 ± 255
Glenulra Farm: samples of derived shells of *A. islandica* from gravel at top of exposure formed during high relative sea levels prior to last ice sheet advance.	Gravel	CAMS115268 CAMS115267 CAMS115066 CAMS115266	21920 ± 90 33550 ± 340 27200 ± 130 27380 ± 170	26375 ± 115 38440 ± 670 32085 ± 130 32230 ± 155
Glenulra Farm: Monospecific samples of *Elphidium clavatum* in marine mud. Dates high relative sea level following ice sheet advance onto continental shelf.	Mud	AA56702 CAMS111594 CAMS111595 CAMS105068	21130 ± 220 23400 ± 110 23530 ± 110 23740 ± 110	25360 ± 310 27940 ± 145 28075 ± 145 28295 ± 145
Glenulra Farm: samples of derived shells of *A. islandica* from diamict at base of section. Dates high relative sea level before and during a major ice sheet buildup.	Diamict	CAMS105065 CAMS115271 CAMS115269 CAMS105067	23630 ± 90 24630 ± 130 34470 ± 390 39540 ± 490	28180 ± 130 29270 ± 235 39800 ± 625 43890 ± 520

* With 400 yr reservoir age subtraction.
† Calibrated from Fairbanks et al. (2005)

facies are exposed in a river cut (Fig. 2). The lowermost facies comprises locally derived, brecciated slabs of sandstone bedrock. Above this facies is 1.5 m of matrix-supported, overconsolidated massive diamict containing dispersed, glacially beveled, and edge-rounded clasts. Derived shell fragments of *Arctic islandica* are present in both of these units. The diamict facies is overlain by as much as 7 m of laminated mud containing in situ marine microfauna. This facies is overlain by 4 m of low-angle, poorly sorted matrix- to clast-supported pebble and cobble gravel beds. The gravel, which contains derived marine shell fragments, forms a distinct terrace on both sides of the valley at ~80 m above sea level (asl).

A river cut on the east side of the valley at a sand and gravel quarry, 400 m downstream from Glenulra Farm, exposes five facies; only one contains fossils of *A. islandica*. The lowermost facies is a compact diamict similar to that found upstream (Fig. 3). The facies overlying the diamict consists of amalgamated beds of massive, mainly clast-supported disorganized boulder gravel; clast long axes suggest deposition from the south. Derived shell fragments are present throughout the unit. This facies is overlain by massive, laminated, and cross-bedded sands that contain three mud beds as much as 1.5 m thick. A marked erosional contact separates the sand from the overlying pebble gravel foresets that dip consistently at 15° to the northwest. The foresets are truncated by crudely bedded, disorganized boulder gravel. The surface of this sequence forms a terrace at ~80 m asl, which is paired with the terrace across the valley at Glenulra Farm.

A large gravel deposit at least 40 m thick, 3 km southeast of Glenulra, near Ballycastle, has enclosed depressions on its southern surface and steep-ice contact slopes on its southern margin (Fig. 1). McCabe et al. (1986) described three facies in this deposit from an exposure at Brookhill that indicate deposition as a Gilbert delta. The tops of the gravelly foresets are between 74 and 78 m asl.

Radiocarbon Dates

We have obtained 15 accelerator mass spectrometer (AMS) radiocarbon dates from shells contained within each of the fossiliferous units exposed at Glenulra that extend our understanding of glacial and relative sea-level history from the west of Ireland by ~20 k.y. beyond the LGM (Fig. 2; Table 1). Only ages on foraminifera from the marine mud facies at Glenulra Farm are in situ; the remainder are on individual fragments of reworked shells. All ages on foraminifera from the marine mud are on handpicked glossy tests of *E. clavatum* that often had the last aperture intact, and they are in stratigraphic order (Table 1). The ages on reworked shells range from 26,375 ± 115 cal yr B.P. to 43,890 ± 520 cal yr B.P., but because they are reworked, these ages are not necessarily in stratigraphic order. The in situ ages on foraminifera at Glenulra Farm, however, provide a known-age datum against which ages on reworked shells from units above and below must stratigraphically conform. Accordingly, the fact that the ages on the uppermost unit are similar to or older than the ages of the underlying marine mud indicates that the event that caused deposition of this uppermost unit reworked preexisting shells from some location upvalley after deposition of the marine mud. However, the ages on the lowermost unit must be older than the marine mud to conform to the law of superposition. Our four radiocarbon ages follow this rule.

INTERPRETATION

Along the Donegal Bay coast at Glenulra, striae and streamlined bedrock record a northwestward offshore ice advance onto the continental shelf (Fig. 1). The diamict preserved within the Glenulra Valley also suggests an offshore advance. Because this evidence for glaciation is ~20 km west of the limit of the most recent major ice sheet readvance in western Ireland associated with the Killard Point Stadial (ca. 15.5 cal ka) (Fig. 1) (McCabe et al., 1998, 2005), on stratigraphic grounds alone it represents an earlier glacial event.

Because all ice-directional indicators demonstrate that ice flow was offshore, the shells from the diamict cannot be derived from Donegal Bay to the north, but are probably derived from locations to the south of the Glenulra sites. These shells must therefore record an ice sheet situated on the western seaboard of Ireland with attendant isostatic loading sufficient to maintain high relative sea level for much of the ~20 k.y. interval bracketed by our radiocarbon ages. This is consistent with ^{36}Cl dating and records of ice-rafted debris that suggest that several large fluctuations of the IIS occurred between ca. 40 and 25 cal ka (Bowen et al., 2002). We are unable to distinguish from our data whether relative sea level remained continuously above the Glenulra site from 26 to 45 cal ka or fluctuated to lower elevations in response to changes in eustatic level and ice loading. Nevertheless, when compared to the record of eustatic changes, our data indicate that the Donegal Coast was isostatically depressed by 150 m to more than 180 m during much of this interval (Fig. 4).

The youngest ^{14}C age in the lower diamict at Glenulra Farm indicates an ice advance across the site after 28,180 ± 130 cal yr B.P., whereas the oldest ^{14}C age from the overlying marine mud indicates ice retreat before 28,295 ± 145 cal yr B.P. Accordingly, these ages constrain an extremely rapid ice-margin fluctuation. The age of this event indicates that it might correspond to a brief stadial event seen in the Greenland Ice Sheet Project 2 ice core between interstadials 3 and 4 (Grootes et al., 1993; Stuiver and Grootes, 2000) (Fig. 4), although uncertainties in the ice-core chronology and in our reservoir age corrections preclude a firm correlation.

The four AMS ^{14}C ages obtained from the in situ marine microfauna indicate that after the ice margin retreated from the continental shelf, relative sea level remained high (>70 m asl) from 25,360 ± 310 to 28,295 ±

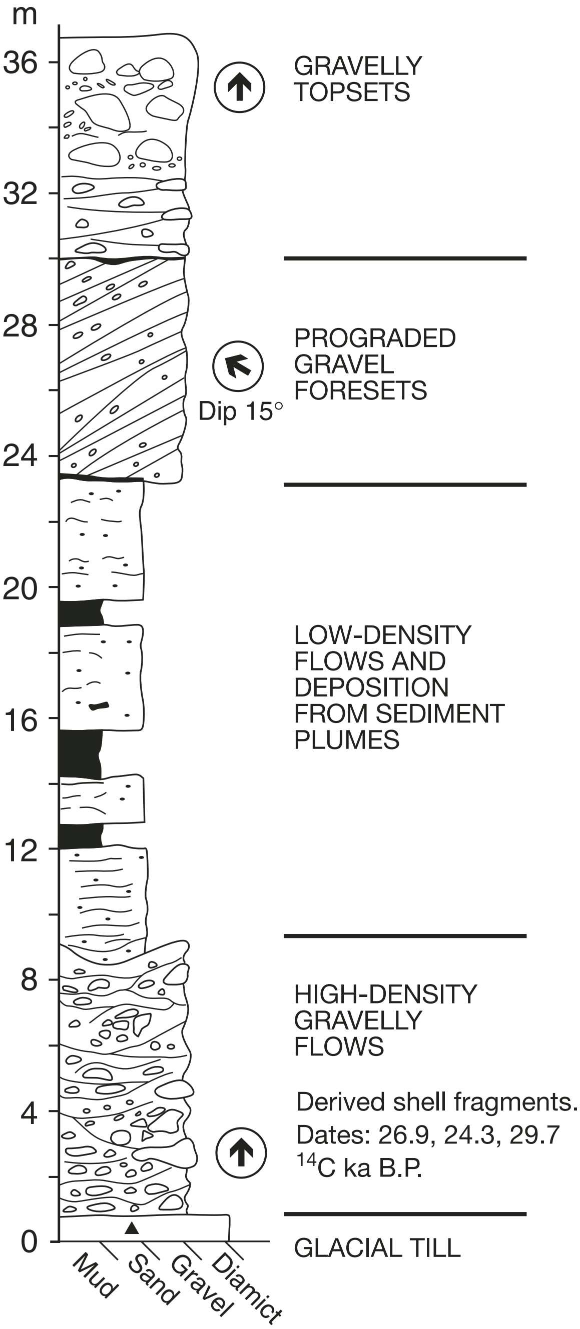

Figure 2. Stratigraphic log and radiocarbon dates from Glenulra Farm, north County Mayo. See Figure 1 for location and regional setting.

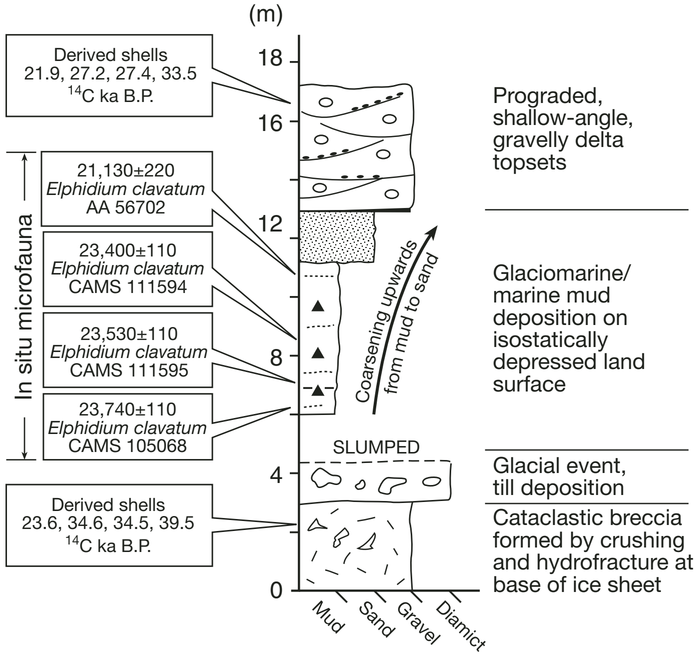

Figure 3. Stratigraphic log and radiocarbon dates from Glenulra Quarry, north County Mayo. See Figure 1 for location and regional setting.

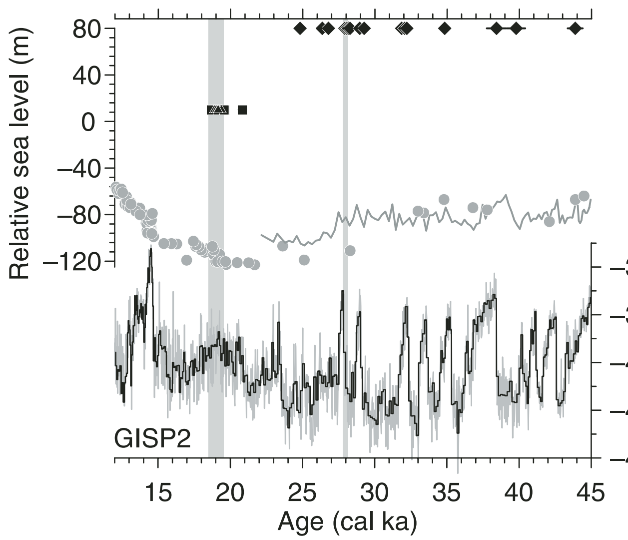

Figure 4. A: Calibrated radiocarbon ages from Ireland constraining relative sea level at Glenulra (diamonds; this paper), Belderg (squares; McCabe et al., 2005), and Kilkeel (triangles; Clark et al., 2004). B: Relative sea-level data from far-field sites (Bard et al., 1993; Chappell et al., 1996; Cutler et al., 2003; Hanebuth et al., 2000; Siddall et al., 2003; Yokoyama et al., 2000). C: $\delta^{18}O$ record from Greenland Ice Sheet Project 2 (GISP2) ice core (Grootes et al., 1993; Stuiver and Grootes, 2000).

145 cal yr B.P (Fig. 2), suggesting the persistence of a thick ice mass over western Ireland throughout that time.

The presence of thick, stratified, coarse-grained facies at Glenulra quarry downvalley from the marine facies at Glenulra Farm suggests that the Glenulra quarry facies were deposited in association with ice retreat from the coast. The lower three facies are subaqueous and record rapidly retreating ice from the immediate area, loss of accommodation space largely by sediment deposition, and progradation of gravelly topsets. The range of sedimentary structures within the lower gravel indicates subaqueous deposition from high-density flows along the valley (Lowe, 1982; Postma et al., 1988). The overlying horizontal sand and mud beds record low-density flows and quiet-water sedimentation from sediment plumes. The third facies, consisting of northward-dipping foresets, records prograding coarser-grained sediment and decreasing water depths. The uppermost facies of boulder gravel was deposited within shallow channels deposited in shallow, high-energy channels. The foresets at this site record sea level at ~74 m asl.

The ice-contact slopes and kettle holes along the southern margin of the Brookhill delta suggest that it was deposited in contact with an ice margin that had withdrawn only a few kilometers from inland of Donegal Bay (McCabe et al., 1986). The gravelly foresets of the delta dip northward and record a water plane infilling Bunatrahir Bay and the Ballinglen Valley to ~78 m asl.

DISCUSSION AND CONCLUSIONS

Bowen et al. (2002) first documented evidence for extensive pre-LGM ice cover over Ireland. In particular, ^{36}Cl ages indicate ice extent ca. 35 ^{36}Cl ka that was similar to or perhaps greater than that associated with the LGM event. Records of ice-rafted debris provide additional temporal constraints that support the near-continuous presence of a marine ice margin off the western Scotland coast since at least 45 cal ka (Knutz et al., 2001). Our new ^{14}C ages confirm the presence of extensive ice for ~20 k.y. prior to the LGM. Moreover, our evidence for an ice advance over the Glenulra site ca. 28 cal ka, as well as the evidence that Glenulra was never overridden again, indicates that at least for this sector of the ice sheet, the LGM margin was less extensive than the 28 cal ka event.

Although the western LGM margin was less extensive than the earlier advance, two lines of evidence suggest that it remained in Donegal Bay during the LGM. First, the presence of marine muds recording high relative sea level at Glenulra Farm requires ice loading until at least 25,650 ± 330 cal yr B.P. Second, fossiliferous glaciomarine muds at the Belderg and Fiddauntawnanoneen sites ~5 km west of Glenulra (Fig. 1) have ^{14}C ages that range from 18,740 ± 180 to 20,840 ± 310 cal ka B.P. (Fig. 4) (McCabe et al., 2005). In this case, the marine sediments only constrain relative sea level to be at least 10 m asl, whereas the Glenulra record suggests that it never exceeded the 80 m deltas there. Accordingly, because these muds were deposited during the LGM, when eustatic sea level was ~130 m lower than present (Yokoyama et al., 2000) (Fig. 4), isostatic depression was at least 140 m but not more than 210 m. The existing sea-level data thus indicate significant isostatic depression of the south coast of Donegal Bay for much of the interval between ca. 40 cal ka until at least 19 cal ka, with little difference between pre-LGM and LGM ice loading.

The best constraints from ^{36}Cl ages for extensive pre-LGM ice come from sites bordering the Irish Sea (Bowen et al., 2002). Although no evidence of pre-LGM high relative sea level has yet been identified from this region, the evidence for extensive pre-LGM ice suggests that substantial loading must have occurred. This is supported by raised marine deposits along the Irish Sea coast that record high relative sea level associated with the northward retreat from the LGM margin (Eyles and McCabe, 1989) and subsequent readvance during the Killard Point Stadial (McCabe and Clark, 1998; McCabe et al., 2005). The marine limit following retreat of the LGM ice in the Irish Sea, for example, suggests isostatic loading of ~160 m (Clark et al., 2004), broadly similar to that documented here for western Ireland.

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