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Evidence for high-frequency late Glacial to mid-Holocene (16,800 to 5500 cal yr B.P.) climate variability from oxygen isotope values of Lough Inchiquin, Ireland

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Abstract

A 7.6-m core recovered from Lough Inchiquin, western Ireland provides evidence for rapid and long-term climate change from the Late Glacial period to the Mid-Holocene. We determined percentage of carbonate, total organic matter, mineralogy, and $\delta^{18}O_{calcite}$ values to provide the first high-resolution record of climate variability for this period in Ireland. Following deglaciation, rapid climate amelioration preceded large increases in GISP2 $\delta^{18}O_{ice}$ values by ~2300 yr. The Oldest Dryas (15,100 to 14,500 cal yr B.P.) Late Glacial event is documented in this record as a decrease in $\delta^{18}O_{calcite}$ values. Brief warming at ~12,700 cal yr B.P. was followed by characteristic Younger Dryas cold and dry climate conditions. A rapid increase in $\delta^{18}O_{calcite}$ values at ~10,500 cal yr B.P. marked the onset of Boreal warming in western Ireland. The 8200 cal yr B.P. event is represented by a brief cooling in our record. Prior to general warming, a larger and previously undescribed climate anomaly between 7300 and 6700 cal yr B.P. is characterized by low $\delta^{18}O_{calcite}$ values with high-frequency variability.

Keywords: Oxygen isotopes; Lake sediment; Ireland; Late Glacial; Holocene; Atmospheric circulation; Climate change

Introduction

Lacustrine calcite (marl) has long been established as a reliable climate proxy (e.g., Leng and Marshall, 2004). Paleoclimate reconstructions from lake cores in the northeastern United States have demonstrated that oxygen isotope values of lacustrine sediment are controlled by variation in the position of the circumpolar vortex (CPV) through the Holocene (Kirby et al., 2002). The CPV defines a cyclonic band of fast-moving air over the midlatitudes and at the core of the CPV is the Polar Front Jet Stream. The Polar Front separates cold and dry air to the north from warm and moist air to the south. Therefore, as the distribution of Earth's heat budget changes over time, the shape and latitude of the Polar Front fluctuates, resulting in climate variability (Kirby et al., 2002).

We expand this record of atmospheric circulation change across the Atlantic Ocean by developing a high-resolution lacustrine sediment record in western Ireland. Ireland has a temperate maritime climate moderated by proximity to the Atlantic Ocean (Jordan, 1997) and the influence of the Gulf Stream (Kiely et al., 1998) that reduces seasonal variation in temperature and elevates temperatures relative to other landmasses at similar latitudes. Ireland is in a particularly sensitive location about which the CPV changes position frequently. The position and shape of the CPV are significant factors in controlling advection of air masses and consequently, moisture to a given region. Decadal-scale climate variation in Western Europe is dominated by the North Atlantic Oscillation (NAO), which also plays a significant role in forcing the weather of North America and Asia (e.g., Hurrell, 1995). Thus, climate records from lake sediment in western Ireland are ideal for reconstruction of circulation mechanisms that affect large

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regions of the Northern Hemisphere. To this end, we present the first high-resolution oxygen isotope study of a marl lake, Lough Inchiquin, in County Clare western Ireland.

This study centers on a stable oxygen isotope record recovered at 5–50 yr resolution from a sediment core obtained at Lough Inchiquin. Isotope data provide an archive of Irish paleoclimate from 16,800 to 5500 cal yr B.P that indicate highly variable climate through the Late Glacial and early to mid-Holocene periods. Variations in $\delta^{18}O_{calcite}$ values are likely forced by fluctuations in the size, strength, and position of the Polar Front as well as other mechanisms discussed herein. It is our hope that this study provides a baseline for future studies of natural climate variability in Ireland's past and projections of anthropogenic forcing in the future.

Background and study site

Lough Inchiquin is located in the Burren of County Clare, an area unique in its climatological, ecological, and archaeological significance to Ireland (Drew and Magee, 1994). Bedrock is dominated by Lower Carboniferous (Visean) limestone (Moles and Moles, 2002). Many of the lakes in this area generate marl sediment that consists of between 60 to 95 wt. % calcite. Several climate records have been reconstructed from this region at Lough Gortlecka, Rinn Na Mona, and Lough Goller (Watts, 1985). However, these studies are principally pollen records with age control limited to a few dates. Furthermore, complications with pollen records arise due to variations in the origin (regional or remote) of taxa and timing of vegetation changes lagging behind climate perturbations (Leng and Marshall, 2004).

Lough Inchiquin lies ~20 km inland of the Atlantic Ocean (Fig. 1) and 2 km northwest of the town of Corrofin. Temperature and dissolved oxygen measurements of this lake indicate that thermal stratification is generally established by June and isothermal conditions return by mid-October (Allott, 1986). Despite strong winds, the lake develops a thermocline with a warm epilimnion and a cool hypolimnion (Allott, 1986). Lough Inchiquin has an area of 110 ha, averages 10.8 m depth and is a maximum of 28 m. Clifden Hill shelters the lake from prevailing southwesterly winds (Allott, 1986). The River Fergus drains into Lough Inchiquin from the north and exits to the south. Drew (1988) determined the catchment of the River Fergus just north of Lough Inchiquin to be 115 km^2 based on the river flow (3.9 $m^3\ s^{-1}$) measured from 1984 to 1988 and regional precipitation input (34 $l\ s^{-1}\ km^{-2}$). The influx of groundwater into Lough Inchiquin provides a significant portion of the lake water and the residence time of groundwater in the River Fergus catchment is extremely short due to the karstic nature of the region (Drew, 1988). The residence time of Lough Inchiquin is ~1 month (Irvine et al., 2001) making this lake ideal for high-resolution climate studies.

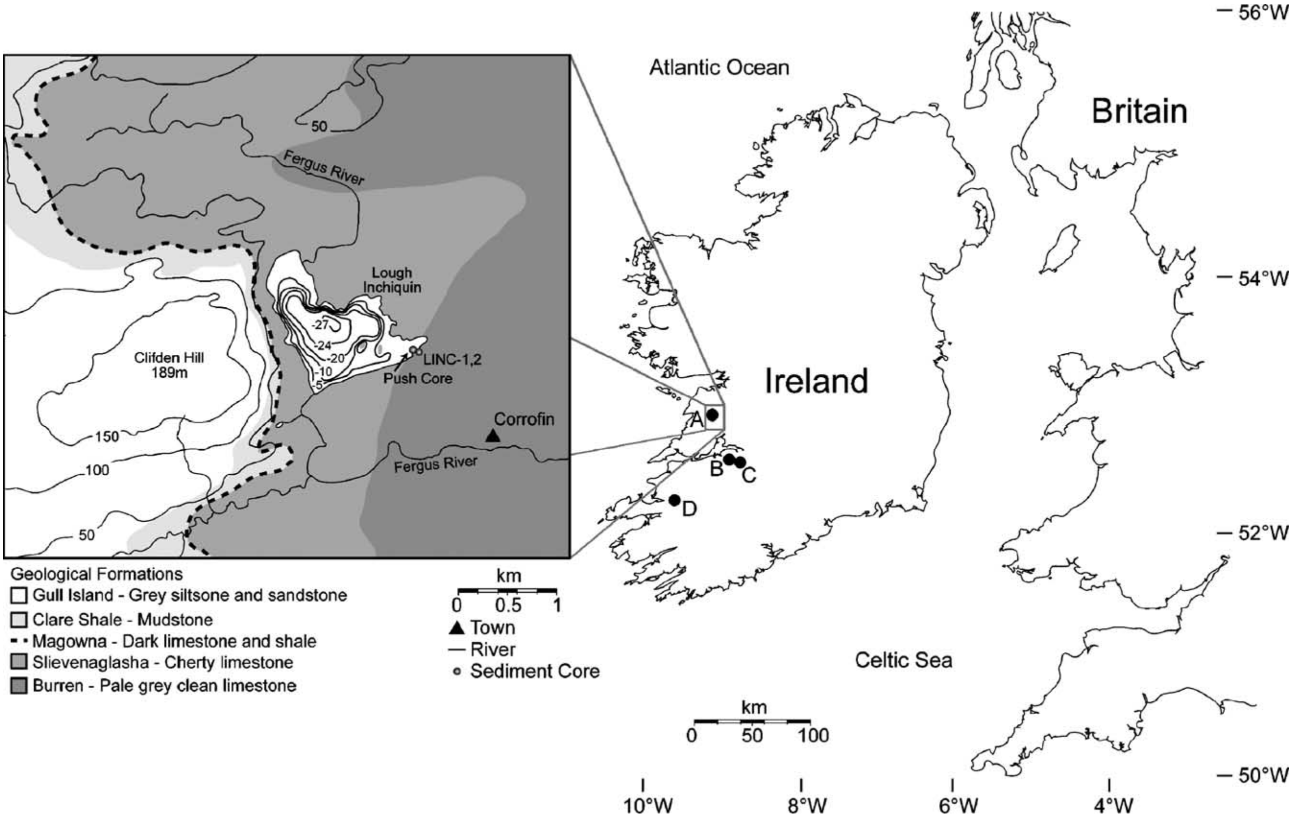

Figure 1. Geography of Ireland with location of the study lake, Lough Inchiquin (A) and other sites mentioned in text: Tory Hill (B), Red Bog/Lough Gur (C), and Crag Cave (D). Inset map shows the local surface hydrology, local geology (MacDermot et al., 2003), and bathymetry of Lough Inchiquin (Allott, N., personal communication, 2004).

Stable isotope values of surface waters have previously been determined in Ireland to evaluate which lakes are most appropriate for development of sediment-based paleoclimate records (Diefendorf and Patterson, 2005). The distribution of surface water isotope values in the Burren is complicated by surface and subsurface drainage as well as lakes with variable residence times that display $\delta^{18}O_{\text{lake water}}$ values ranging between −4.1 and −6.1‰ VSMOW. Hydrologic variables include differences in residence time, catchment size, input of groundwater, and total surface area of the lake (Diefendorf and Patterson, 2005). In 2002, Lough Inchiquin had a $\delta^{18}O_{\text{lake water}}$ of −5.9‰ VSMOW and a $\delta D_{\text{lake water}}$ of −37‰ VSMOW, suggesting that evaporation may be lower than other Burren lakes that have more positive isotope values.

Methods

A 7.6-m-long core (LINC-1) was recovered in June 2002 from the southeastern shoreline of Lough Inchiquin (W09°04′44″, N52°57′03″; Irish Grid number IR: 27750 89570) using a Livingstone square-rod piston coring device. A second core was retrieved (LINC-2) 2 m to the south and was archived. A push core, LINC PC-1, was recovered from the lake ~15 m NW of the LINC-1 coring site. LINC-1 was opened, split, described, and sub-sampled for loss on ignition (LOI) determinations at the Botany Department, National University of Ireland in Galway and at the Saskatchewan Isotope Laboratory. LOI sampling was conducted at 5-cm spacing for total wt. % organic matter (TOM) and total carbonate (TC; converted to wt. % calcite) by combustion at 550°C and 1000°C, respectively (Dean, 1974).

The core was sampled at 2-mm intervals for ostracod, organic matter, and cellulose isotope analyses. Samples for $\delta^{18}O$ analyses were collected (0.5 mm thick) from the base of each 2-mm segment (n = 3005). Several samples were analyzed to determine mineralogy of the core using X-ray diffraction (XRD). Samples from marl-rich sections contained calcite with no aragonite or dolomite. Samples from the clay sections were primarily quartz, clay minerals, and some calcite except the sample from 7.42 m that contains dolomite as well. Local bedrock consists of Visean marine calcite.

Primary age control was established by dating of bulk aquatic macrofossils, bulk calcite, and organics from LINC-1 and LINC PC-1. Samples were dated using AMS ^{14}C at the University of Arizona (Table 1, Fig. 2). Radiocarbon dates on LINC-1 bulk calcite and macrofossil components are influenced by the hard-water effect, which we quantified by comparing contemporaneous wood and carbonate macrofossils. These samples have a difference of 1575 ^{14}C years which is used to correct LINC-1 macrofossil dates. The scarcity of terrestrial macrofossils at Lough Inchiquin precludes development of an age model based solely on terrestrial macrofossils or a model with variable hard-water corrections. Therefore, although we assume a constant hard-water effect through time we are cognizant that the effect may actually be variable (see below). Our correction is thus a best estimate based on information available at this time. Macrofossil dates as well as the uppermost organic sample were calibrated to calendar years (cal yr B.P.) using CALIB 4.3 (Stuiver et al., 1998a,b) after the hard-water correction. Our age model (Fig. 2) is based on linear interpolation between calibrated ages.

Table 1
Radiocarbon dates for Late Glacial to mid-Holocene sediments at Lough Inchiquin, western Ireland

Core	Depth (m)	Uncorrected radiocarbon date ^{14}C yr B.P. (±1σ)	Lab. code	Corrected radiocarbon date^{a} ^{14}C yr B.P.	Calibrated age range (1σ)^{b} cal yr B.P.	Calibrated age range (2σ)^{b} cal yr B.P.	Material	$\delta^{13}C$‰ VPDB
LINC-1	0.15	3960 ± 60	AA54025		4350–4450	4240–4530	Peat	−26.8
	1.15–1.20	7860 ± 70	AA54026				Organic	−40.7
	1.50	8131 ± 35	AA56893b				Bulk Calcite	−6.4
	1.50	6850 ± 50	AA56893	5280	6070–6110	5930–6180	Bulk Macrofossil	−9.9
	2.60	8422 ± 34	AA56894b				Bulk Calcite	−7.3
	2.60	6100 ± 170	AA56894				Bulk Macrofossil	−10.2
	3.55	8896 ± 49	AA56889b				Bulk Calcite	−7.4
	3.55	8355 ± 44	AA56889	6781	7608–7662	7569–7683	Bulk Macrofossil	−9.9
	3.55	8550 ± 70	AA54027				Organic	−32.9
	4.90–5.00	10,160 ± 120	AA54028				Organic	−41.3
	4.97	10,081 ± 48	AA56890b				Bulk Calcite	−6.1
	4.97	9000 ± 120	AA56890	7430	8160–8360	8000–8410	Bulk Macrofossil	−9.5
	6.25	11,380 ± 60	AA56897	9810	11,170–11240	11,090–11310	Bulk Macrofossil	−1.4
	6.70	11,780 ± 60	AA56892	10200	11,690–11980	11,630–12340	Bulk Macrofossil	−1.2
	7.45	15,040 ± 90	AA56896	13470	15,930–16420	15,600–16790	Bulk Macrofossil	+2.4
LINC PC-1	0.13	7258 ± 42^{c}	AA56891		8008–8058	7974–8165	Wood	−28.2
	0.13	8830 ± 90^{c}	AA56898				Bulk Macrofossil	−10.3

All radiocarbon samples were determined at the University of Arizona AMS facility.

[a] Corrected radiocarbon age was determined by subtracting 1575 ^{14}C yr from uncorrected radiocarbon ages.

[b] Calibrated age range is determined from corrected radiocarbon age except in the case of the peat sample (0.15 m) which is not affected by the hard-water effect. Ages are calibrated using Calib 4.3 (Stuiver et al., 1998a,b).

[c] Radiocarbon ages used for determination of hard-water effect of 1575 ^{14}C yr.

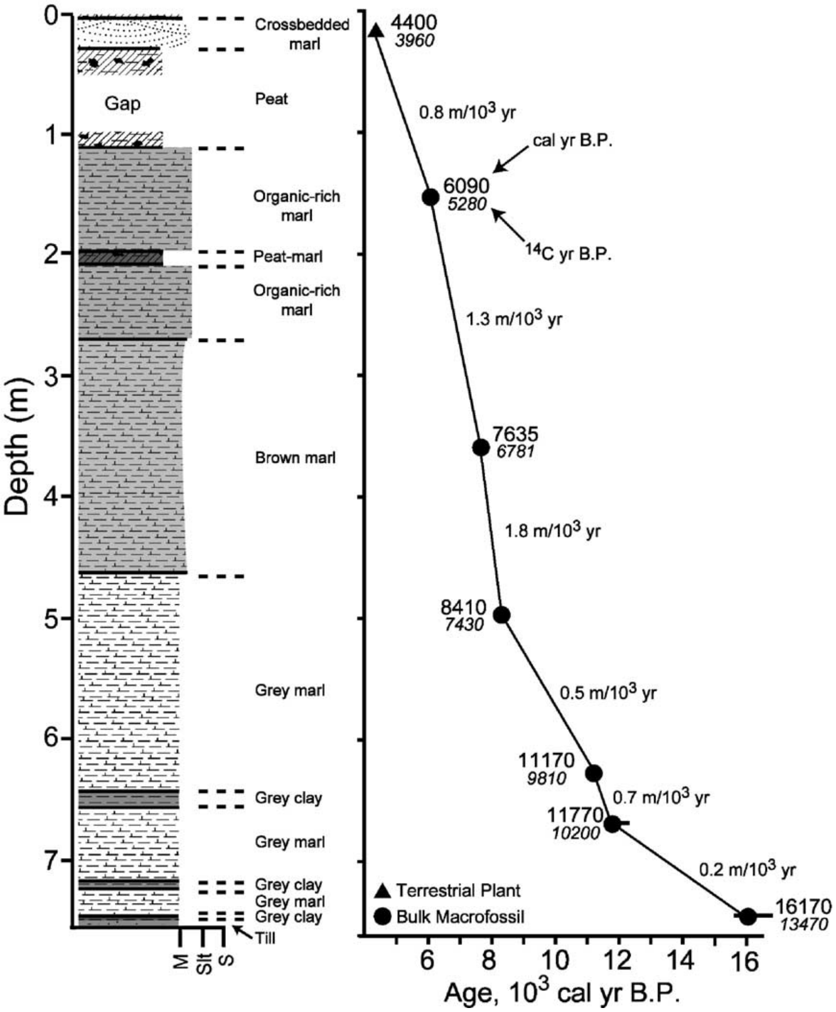

Figure 2. Lithology and age model for Lough Inchiquin sediment core based on calibrated radiocarbon ages (see Table 1). Sedimentation rate is based on the accumulation rate in meters per thousand years and is determined from the age model. The 2σ calibrated age range is generally smaller than the black circles. Grey bars represent the 2σ calibrated age range when the error exceeds the circles.

The age model yields an age of initial sedimentation at Lough Inchiquin of 16,750 cal yr B.P., in agreement with the deglaciation chronology in the region (Bowen et al., 2002; McCabe et al., 1998). This age also corresponds to the initial accumulation of late-glacial sediments at Tory Hill (O'Connell et al., 1999). It is possible that the stratigraphically lowest date is offset by a larger hard-water effect as $\delta^{13}C_{calcite}$ values at this depth are ~2.5‰ VPDB, similar to the bedrock $\delta^{13}C_{calcite}$ of 3.2‰ VPDB. This suggests that calcite at this depth is derived primarily from Paleozoic bedrock carbon, which is devoid of ^{14}C. Therefore, our age estimate could be up to 1900 years too old based on wiggle matching $\delta^{18}O_{calcite}$ values with the GISP2 $\delta^{18}O_{ice}$ record. This would result in younger ages below 6.7 m and a new basal age of 14,480 cal yr B.P. However, the age model yields an age of the clay-rich sediments and decreasing $\delta^{18}O_{calcite}$ values between 7.19 and 7.25 m of 14,635 and 14,990 cal yr B.P. respectively, contemporaneous with accepted dates of the Oldest Dryas event (Stuiver et al., 1995).

The age model yields an age for the end of the clay layer at 6.4 m of 11,300 cal yr B.P. This age is similar to the end of the Younger Dryas at Tory Hill of 11,450 cal yr B.P. (O'Connell et al., 1999) further validating our age model. In addition to the age model, this 20-cm-thick clay layer is the uppermost clay deposit at this lake and is stratigraphically similar to other Late-glacial to Holocene sequences in Ireland (Watts, 1985, and references within). The age model around the 8200-yr event (discussed in detail later) is likely correct in terms of the hard-water effect because the hard-water effect was determined from a piece of wood in LINC PC-1 with an age of 7975–8165 cal yr B.P.

Macrofaunal and microfaunal components were separated by stereomicroscope under 30× magnification to limit isotope analyses to fine-grained sediment. $\delta^{18}O$ analyses were conducted in the Saskatchewan Isotope Laboratory at the University of Saskatchewan. Samples were roasted in-vacuo at 200°C for 1 h to remove volatile organic material and water that may influence isotope values. Samples were analyzed by a Finnigan Kiel-III carbonate preparation device directly coupled to a Thermo-Finnigan MAT 253 gas ratio mass spectrometer. Thirty- to 50-microgram samples were reacted with 103% anhydrous phosphoric acid for 3 min at 70°C. Samples were corrected for ^{17}O contribution, acid/water fractionation, and temperature fractionation. Values are reported in standard delta per mille (‰) notation relative to the VPDB standard using NBS-19, NBS-18, as well as internal standards. Precision is ±0.16‰ for δ^{18}O determined on NBS-19 (n = 58, 1σ).

Results

The LINC-1 core is shown in Figure 2 and is dominantly composed of marl with as much as 94% TC. The base of the core is composed of glacial material and is overlain by alternating sequences of clay and marl. The marl is capped with peat and an interbedded peat-marl-sand layer. The gap in the upper 1 m of the core is the result of the high compressibility of peat during the coring process as well as a large piece of wood in the core. Differential compressibility of marl, peat, and wood preclude accurate removal of compression from the upper 1 m of sediment and consequently the isotope data from this section has been omitted.

TC is relatively constant throughout the core at values >90% except for several large anomalies (Fig. 3). TC decreases to ~55% at 16,600 cal yr B.P. followed by a rapid increase to 80% by 16,160 cal yr B.P. Another decrease in TC occurs at 15,000 cal yr B.P. The largest excursion in TC begins at 11,700 cal yr B.P. decreasing to ~5% and returning to high values by 11,300 cal yr B.P. Several notable decreases also occur at 9010, 8260, 7820, 6860, and 6540 cal yr B.P. Values decrease beginning at 5840 cal yr B.P. correlated with increasing TOM that may be attributed to changes in the lake level.

$\delta^{18}O_{calcite}$ values in LINC-1 (Fig. 3) display significant variability (up to 2.0‰). A rapid ~2‰ increase at the base of the core is followed by lower amplitude variation with a slightly decreasing first-order trend to ~10,500 cal yr B.P. Large negative excursions occur before and after a complete loss of TC between 11,400 and 11,600 cal yr B.P. A transition from low values to higher values occurs at 10,500 cal yr B.P. This is followed by high-frequency, albeit low-amplitude, variability with a decreasing asymmetric first-order trend to 8400 cal yr B.P. A transition to more negative values at ~7500 cal yr B.P. occurs followed by a first-order trend towards more positive values.

Discussion

Oxygen isotopes

$\delta^{18}O_{calcite}$ values of lacustrine sediment are interpreted to reflect changes in water/air temperature and/or $\delta^{18}O_{lake\ water}$. In turn, $\delta^{18}O_{lake\ water}$ values vary with changing $\delta^{18}O_{precipitation}$ values that are regulated by condensation temperature, rainout effect, evaporation, relative humidity, water vapor source changes, and changes in seasonal distribution of precipitation. If we assume that temperature is the primary control, then increasing $\delta^{18}O_{calcite}$ values reflect decreasing lake temperatures. For example, $\delta^{18}O_{calcite}$ values from Lough Inchiquin record high-frequency variability on the order of 2‰ that would translate to ~8°C (~4°C/1‰; Kim and O'Neil, 1997) variation in summer temperatures. Because the modern annual

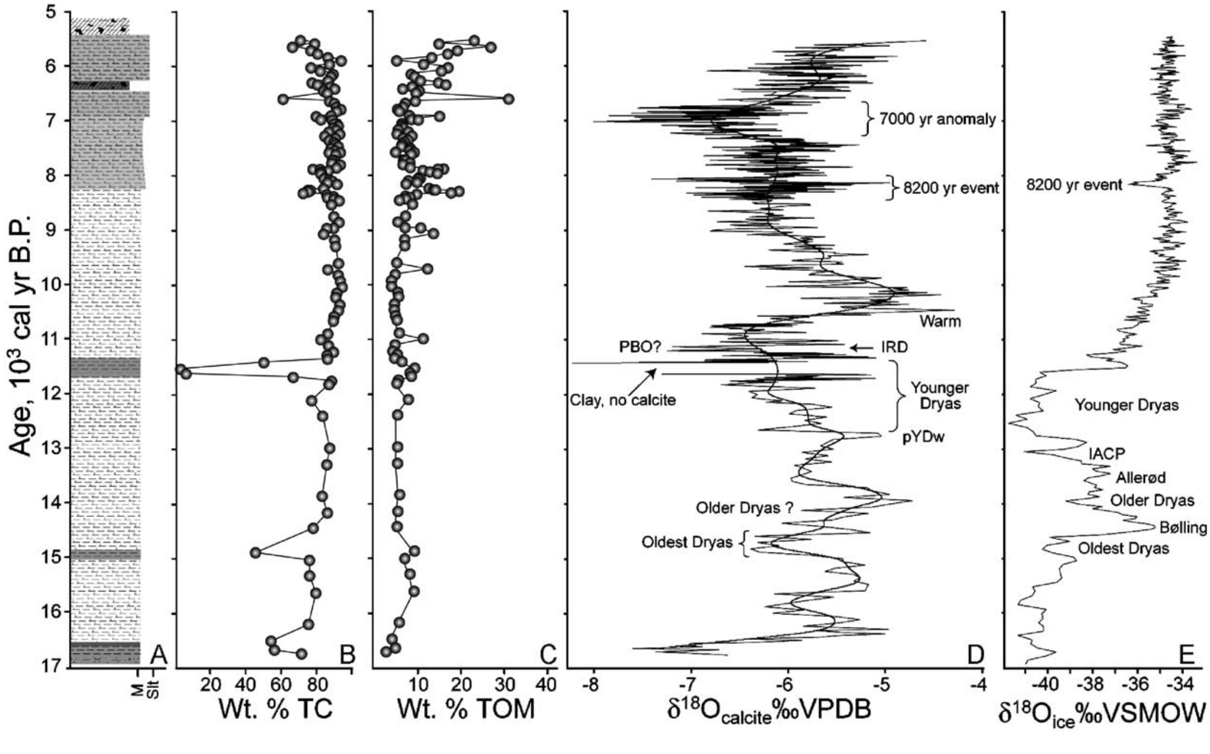

Figure 3. Lithology (A), weight percent total calcite (B), weight percent total organic matter (C), $\delta^{18}O_{calcite}$ values vs. age in cal yr B.P. with significant climate events labeled in brackets and a 50-year moving average in grey illustrating first order trends, and the GISP2 $\delta^{18}O_{ice}$ record with associated climate events for comparison (Stuiver et al., 1995). Ice-rafted debris from Bond et al. (1997) is labeled as IRD. High values indicate higher temperatures and low values are interpreted as lower temperatures resulting from Rayleigh distillation/atmospheric temperature relationships that force $\delta^{18}O_{precipitation}$ values.

temperature range in western Ireland is only 16°C (MET, 2003), a change of 8°C in summer temperatures is unrealistic. Therefore, temperature cannot be the only control on variability. Rather, we hypothesize that the predominant control on $\delta^{18}O_{calcite}$ values is variation in $\delta^{18}O_{precipitation}$ values that are forced by changes in atmospheric circulation and air temperature. This approach has been used in multiple lake studies (e.g., Leng and Marshall, 2004). Other researchers in Ireland have reported a positive correlation between $\delta^{18}O_{calcite}$ and air temperature such that $\delta^{18}O_{calcite}/\delta T = 0.33‰/°C$ (Ahlberg et al., 1996).

Late glacial climate change

The last glacial maximum (Pleniglacial) occurred at ~22,000 cal yr B.P. following Heinrich event 2 and was terminated by rapid deglaciation after ~17,400 cal yr B.P. in Ireland and the British Isles (Bowen et al., 2002). However, the nature and timing of the termination of the Pleniglacial in western Ireland is not entirely understood because most climate records are either inadequately dated or do not extend far enough into the past (O'Connell et al., 1999). At Tory Hill (Site B, Fig. 1), Co. Limerick, 53 km south of Lough Inchiquin, a pollen record suggests that at 16,800 cal yr B.P., average temperatures likely did not exceed 5°C (O'Connell et al., 1999). The termination of the Pleniglacial period was recorded at Lough Inchiquin as characteristic dark grey gravely clays (Watts, 1985) following the disappearance of the Midlandian ice sheet (O'Connell, 1999). $\delta^{18}O_{calcite}$ values at the base of the core are −7.6‰ reflecting low $\delta^{18}O_{precipitation}$ values associated with cold atmospheric temperatures and/or snow melt. These low values may be attributed to a detrital calcite component ($\delta^{18}O_{bedrock} = -10.8‰$) mixed with the autochthonous calcite.

The early climate amelioration peaks at 16,300 cal yr B.P., about ~2300 yr earlier than the GISP2 core (Fig. 3; Stuiver et al., 1995). We attribute the warming to a northerly advance of the Gulf Stream. However, climate was not stable as $\delta^{18}O_{calcite}$ values decrease from 16,400 to 15,600 cal yr B.P. followed by another amelioration.

The Oldest Dryas period is recognized at Lough Inchiquin as a distinctive decrease in TC and an increase in clay. The timing of the onset of this event is similar to that observed in Greenland ice core between 15,070 and 14,670 cal yr B.P. (Stuiver et al., 1995). The climate anomaly at this time is also apparent in the $\delta^{18}O_{calcite}$ record as a ~1‰ decrease in values suggesting a decrease in temperature. Increased TC and $\delta^{18}O_{calcite}$ values by ~14,600 cal yr B.P. suggest warming characteristic of the Bølling period. Proxy records suggest that the Bølling was as warm as today (e.g., O'Connell et al., 1999). Fluctuations in $\delta^{18}O_{calcite}$ values suggest that this period was unstable and it is possible that the excursion at ~14,100 cal yr B.P. is the Older Dryas event that is identified in Greenland (Stuiver et al., 1995).

Highest $\delta^{18}O_{calcite}$ values during the Late Glacial period occurred between 14,100 and 13,900 cal yr B.P., suggesting that this may have been the warmest period of the Late Glacial. $\delta^{18}O_{calcite}$ values and a chironomid record from Hawes Water in northwest England suggest a regional warming 14,100 GRIP yr ago (Jones et al., 2002). $\delta^{18}O_{calcite}$ values suggest that temperatures increased until 13,700 cal yr B.P. as a rapid decrease in $\delta^{18}O_{calcite}$ occurs. $\delta^{18}O_{ice}$ values suggest the Allerød period in Greenland (14,000–12,900 cal yr B.P.) was characterized by lower temperatures than the Bølling period (Stuiver et al., 1995). However, our record shows higher values early in the Allerød compared to the Bølling.

Following the end of the Allerød, a warming period is suggested by an increase in $\delta^{18}O_{calcite}$ at 12,750 cal yr B.P. O'Connell et al. (1999) report evidence for a regional warming of unknown magnitude. This period was informally deemed the pre-Younger Dryas warming (pYDw) by O'Connell et al. (1999). Our $\delta^{18}O_{calcite}$ values for the pYDw are nearly as high as those of the early Allerød, correlative with a record from Lough Gur, Red Bog (Ahlberg et al., 1996) and at Tory Hill (O'Connell et al., 1999). Lehman and Keigwin (1992) suggest that this period represents a short lived increase in North Atlantic sea surface temperatures at 11,300 ^{14}C yr B.P. Increasing temperatures documented by marine molluscs indicate increased equatorial heat transport facilitated by North Atlantic surface circulation (Peacock, 1989) thereby explaining the increase in $\delta^{18}O_{calcite}$ values in western Ireland.

The Younger Dryas (YD) is manifested in our record as a decrease from the high pYDw $\delta^{18}O_{calcite}$ values at 12,640 cal yr B.P. as well as a small (<10%) decrease in TC. The YD is documented by multiple proxies in records across Europe and North America (e.g., Alley et al., 1993; Jones et al., 2002). The YD is widely thought to have resulted from shutdown of the Atlantic oceanic conveyor-belt by meltwater leading to a decrease in surface water salinity and density where North Atlantic Deep Water forms (Broecker et al., 1989). The North Atlantic oceanic conveyor belt transports enormous amounts of heat to the atmosphere at mid and high latitudes (Broecker et al., 1985). During the YD, there was a re-advance of polar waters in the North Atlantic as far south as 53°N (Ruddiman et al., 1977), while summer sea surface temperatures derived from foraminifera record ocean temperatures decreasing by 10°C off the coast of Ireland (Duplessy et al., 1996).

The onset of the YD is characterized by a large decrease in $\delta^{18}O_{calcite}$ values punctuated by several increases that suggest it was a stepwise process (Alley, 2000). TC values record a slight decrease at this time. O'Connell et al. (1999) characterized the early YD as a period of high winter precipitation that may be masked by detrital carbonates supplied by increased solifluxion. However, we believe that a detrital signal is unlikely because the limestone bedrock is Visean (Carboniferous) with $\delta^{18}O_{calcite}$ values between ~−3 to −8‰ (Bruckschen et al., 1999) and we determined bedrock $\delta^{18}O_{calcite}$ values at Lough Inchiquin to be −11.4‰. It is likely that higher $\delta^{18}O_{calcite}$ values in the early part of the YD reflect a regional climate signal and Ahlberg et al. (2001) suggested this may be accounted for by dominantly Westerly winds during this time generating higher $\delta^{18}O_{calcite}$ values from oceanic derived precipitation. Westerly winds are also supported by studies of dune formation elsewhere in Europe as well as climate models (Isarin et al., 1997).

Our YD data are similar to the GISP2 data in that $\delta^{18}O$ values are lower than the Bølling and Allerød periods. However, Lough Inchiquin displays continually decreasing values. The largest anomaly in our record occurs at 11,750 cal yr B.P. with a significant increase in values just prior to the largest decrease in TC. The most severe climate deterioration in Ireland during the YD appears much later than other records and was noted by O'Connell et al. (1999) as well. Elevated $\delta^{18}O_{calcite}$ values prior to and just after the clay layer in our record may be evidence for increased residence time of the lake resulting in increased $\delta^{18}O_{lake\ water}$ values possibly suggesting decreased precipitation. Further evidence for climatic instability from 11,800 to 11,500 cal yr B.P. may be explained by persistent changes in the position of the oceanic front separating sea water covered by ice from relatively warm water (Ebbesen and Hald, 2004).

The Holocene

Following the end of the YD at Lough Inchiquin, $\delta^{18}O_{calcite}$ values remain low. High-frequency variability may be associated with changes in meltwater supply to the North Atlantic that forced changes in oceanic and atmospheric circulation (Andrews et al., 1991). The PreBoreal Oscillation (11,335 cal yr B.P.) caused by melt water pulses from Lake Agassiz that persisted until 10,750 cal yr B.P. (Fisher et al., 2002) likely forced rapid changes in $\delta^{18}O_{calcite}$ values at Lough Inchiquin. The PreBoreal Oscillation led to increases in pack ice on the North Atlantic Ocean that lowered surface temperatures, increased albedo, and likely forced changes in ocean circulation (Fisher et al., 2002). Ice-rafted debris (IRD) in the form of hematite-stained grains and Icelandic glass in an oceanic core recovered near western Ireland indicates that sea ice may have reached as far south as the Irish coast (Bond et al., 1997; Fisher et al., 2002) at 11,100 cal yr B.P. (Fig. 2 in Bond et al., 1997) again suggesting a decrease in sea surface temperatures. This resulted in the Polar Front advancing southward with the development of pack ice that further decreased atmospheric temperatures causing a decrease in $\delta^{18}O_{precipitation}$, resulting in a period of lower $\delta^{18}O_{calcite}$ values after the YD.

A stepwise increase in $\delta^{18}O_{calcite}$ that begins at ~10,800 cal yr B.P. is not present in the Greenland ice records (Stuiver et al., 1995). As there are no apparent changes in TC and TOM, it is likely that this increase results from changes in the Polar Front related to the decrease of the pack ice. As the Polar Front moved to more northerly latitudes, a rapid increase in atmospheric temperature resulted in higher $\delta^{18}O_{precipitation}$ values. Maximum $\delta^{18}O_{calcite}$ values are reached at this time suggesting that this was the warmest period in our record and marks the end of Late Glacial type environments in Ireland. This warm period is coincident with the Holocene hypsithermal, Holocene Climatic Optimum, in North America (Pielou, 1991) and Europe (Kalis et al., 2003).

High-frequency, low amplitude variation around 8200 cal yr B.P. is likely related to the "8.2 ka cold event" (8400 to 8000 cal yr B.P.) identified in Greenland ice cores (Alley et al., 1997) and elsewhere in Europe (e.g., McDermott et al., 2001; Magny and Bégeot, 2004). An increase in TOM and a decrease in TC suggest that cooling was initiated at 8400 cal yr B.P. at Lough Inchiquin. These events are correlative with the catastrophic drainage of Lake Agassiz through Hudson's Bay at 8400 cal yr B.P. (Barber et al., 1999; Teller et al., 2002) that resulted in cold, dry, and windy conditions adjacent to the North Atlantic (Alley et al., 1997). This event is observed in multiple climate proxies across Europe (e.g., McDermott et al., 2001; Magny and Bégeot, 2004; Veski et al., 2004) and North America (Guiles-Ellis et al., 2004). The 8200 cal yr B.P. event in our record is not as prominent as is observed in other records (Stuiver et al., 1995; McDermott et al., 2001). Cold, dry, and windy conditions in the North Atlantic at this time (Alley et al., 1997) as well as decreased precipitation in western Ireland (McDermott et al., 2001; Baldini et al., 2002) likely suggest increased residence time at Lough Inchiquin resulting in higher $\delta^{18}O_{lake\ water}$ values. $\delta^{18}O_{calcite}$ values may likewise be conflated during this period because $\delta^{18}O_{calcite}$ values predominantly reflect low lake water temperatures. High-frequency variation at Lough Inchiquin is likely explained by rapid changes in the latitudinal position of the Polar Front. Magny and Bégeot (2004) found evidence for a perturbation in atmospheric circulation (e.g., Alley et al., 1997; Renssen et al., 2001; Tinner and Lotter, 2001) that suggests a southerly displacement of the Polar Front as well as changes in the position of cyclone tracks in Western Europe (Renssen et al., 2001).

At ~7300 cal yr B.P. the largest perturbation in Holocene climate at Lough Inchiquin is observed as a negative excursion in $\delta^{18}O_{calcite}$ that persisted until ~6700 cal yr B.P. This anomaly has not been documented, to our knowledge, elsewhere in Ireland or in the GISP2 record. However, a similar climate excursion is present in a North American sediment record from Seneca Lake, New York (Guiles-Ellis et al., 2004). Because TC and TOM are only slightly affected during this time, perhaps temperatures did not change considerably. Therefore, this period of low $\delta^{18}O_{calcite}$ values likely represents a period of increased winter precipitation (low $\delta^{18}O_{precipitation}$ values) that would decrease $\delta^{18}O_{lake\ water}$ values associated with changes in atmospheric circulation. For this to be the case, hydrologic residence time has to increase by decreasing summer precipitation and lower summer evaporation. High lake levels between 7550 and 7250 cal yr B.P. in Europe (Magny and Bégeot, 2004) may corroborate our interpretation of the isotope data in suggesting an increase in precipitation and residence time. Further investigation of other proxy records in western Ireland are likely needed to characterize this event more rigorously.

Conclusion

$\delta^{18}O_{calcite}$ values and LOI data recovered from a core at Lough Inchiquin provides an archive of western Ireland paleoclimate between ~16,800 and 5500 cal yr B.P. Ireland is particularly sensitive to climate variability because it is located in the eastern Atlantic Ocean where minor changes in ocean and atmospheric circulation have a significant effect on the $\delta^{18}O_{precipitation}$ and therefore the $\delta^{18}O_{calcite}$ values. $\delta^{18}O_{calcite}$ values provide proxy evidence for changes in these variables. Based on this information, the climate of Ireland was highly variable through the Late Glacial and early to mid Holocene. Several previously unidentified climate anomalies in western Ireland were identified in our study at 10,800 and 7100 cal yr B.P. Following the Younger Dryas event, $\delta^{18}O_{calcite}$ values recover strongly, followed by decreasing values and then show an asymmetric increase in values. Increased winter precipitation between 7300 and 6700 cal yr B.P. is possibly responsible for the significant decrease in $\delta^{18}O_{calcite}$ values. This is the first high-resolution climate record for western Ireland that extends back to ~16,800 cal yr B.P. and provides evidence for rapid climate change in western Ireland during the Late Glacial and the early Holocene.

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