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Younger Dryas Deglaciation Of Scotland Driven By Warming Summers

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The Younger Dryas stadial (YDS; ~12,900-11,600 yr ago) in the Northern Hemisphere is classically defined by abrupt cooling and renewed glacialiation during the last glacial-interglacial transition. While this event involved a global reorganization of atmospheric and oceanic circulation (Denton GH, Alley RB, Comer GC, Broecker WS (2005) The role of seasonality in abrupt climate change. Quat. Sci. Rev. 24: 1159-1182), the magnitude, seasonality, and geographical footprint of YDS cooling remain unresolved and pose a challenge to our understanding of abrupt climate change. Here, we present a deglacial chronology from Scotland, immediately downwind of the North Atlantic Ocean, indicating that the Scottish ice cap disintegrated during the first half of the YDS. We suggest that stratification of the North Atlantic Ocean resulted in amplified seasonality that, paradoxically, stimulated a severe wintertime climate ice while promoting warming summers through solar heating of the mixed layer. This latter process drove deglaciation of downwind landmasses to completion well before the end of the YDS.

Younger Dryas | Scotland | Deglaciation | Seasonality

Introduction
Determining the causes of abrupt climate change remains an outstanding question of paleoclimatology, the answer to which involves resolving the timing, magnitude, and geographic extent of past abrupt climate events. The YDS is widely considered the canonical example of abrupt climate change. Mean-annual temperatures in the circum-North Atlantic returned to near-full glacial values for ~1300 years, before rising 5-10°C within a few years to decades (2, 3). This dramatic cooling has been correlated with renewed glaciation throughout the Northern Hemisphere, particularly in the circum-North Atlantic. In Europe, for instance, the YDS has been assumed to be synonymous with the most extensive glacier advances of the late glacial (4-8). The extreme temperatures of the stadial have been attributed to stratification of the North Atlantic water column and shutdown of MOC (9), in addition to the spread of wintertime sea ice and shifting westerly airflow (10). However, while the North Atlantic remains a key player in hypotheses for the YDS, recent developments are redefining our view of the event's full manifestation. Mean-annual temperatures recorded in the Greenland ice cores were skewed towards strong wintertime cooling, due to the effect of expanded North Atlantic winter sea ice (1). Conversely, summer atmospheric temperatures, which dominate glacier mass balance, probably were milder than previously thought (1, 11-13). Thus, the North Atlantic may have exhibited the hallmarks of a "continental climate" during the YDS, which, if true, has important implications regarding the role of highly seasonal North Atlantic stadial events in facilitating, rather than stalling, recession of adjacent ice masses. We address this problem by presenting a chronology of glacial activity immediately downwind of the North Atlantic in Scotland.

Glaciers are sensitive to small changes in climate, particularly temperature and precipitation. In Western Europe, where climate is dominated by the ameliorating effect of the North Atlantic Current, glaciers are highly responsive to upwind surface temperatures (Text S1) and past glacier behavior would have been dominated by North Atlantic sea-surface conditions. Thus, the Scottish glacial record is ideal for reconstructing late-glacial variability in North Atlantic temperature (Fig. 1). The last glacier resurgence in Scotland – the "Loch Lomond Advance" (LLA) – culminated in a ~9500 km² ice cap centered over Rannoch Moor (Fig. 24) and surrounded by smaller ice fields and cirque glaciers. The ice cap was drained via calving tidewater glaciers along its western margin and land-terminating glaciers along its eastern margin. Well-preserved moraines indicate that subsequent deglaciation was characterized by progressive, active retreat rather than rapid downwasting (14, 15). In contrast to the wealth of information constraining the physical characteristics of the LLA, few data exist resolving the precise age of the event and there remains considerable uncertainty as to when the advance began or when glaciers reached their maximum extent (16-18). Nevertheless, the LLA traditionally is correlated with the YDS and assumed to have culminated near the end of the stadial (5).

To derive an independent chronology of glacier recession downwind of the North Atlantic, we mapped and dated glacial deposits in the western sector of Rannoch Moor (56.636°N, 4.7732°W), located at the former centre of the LLA ice cap, to reconstruct the final stages of ice-cap retreat. End moraines of up to 5 m relief define the northward recession of an active ice front across the moor (~300 m elevation), whereas chaotic mounds located on broad uplands (~400 m elevation) near the moor's center indicate final stagnation of remnant ice (Fig. 2B). Previous investigations into the deglacial chronology of the site

Significance
Resolving the full manifestation of past abrupt climate change is key to understanding the processes driving and propagating these events. As a principal component of global heat transport, the North Atlantic Ocean also is susceptible to rapid disruptions of meridional overturning circulation and, thus, widely invoked as a cause of abrupt climate variability in the Northern Hemisphere. We assess the impact of one such North Atlantic cold event – the Younger Dryas Stadial – on an adjacent ice mass and show that, rather than instigating a return to glacial conditions, this abrupt climate event was characterized by deglaciation. We suggest this pattern indicates summertime warming during the Younger Dryas, potentially as a function of enhanced seasonality in the North Atlantic.
invoked ice-free conditions at Rannoch Moor – and consequently throughout Scotland – as early as 12,400 ± 330 cal yr (sample SRR-1074 [Ref. 19], Table S1.) and no later than 12,150 ± 300 cal yr (sample BIRM-S88 [Ref. 19], Table S1.). This scenario conflicts with the canonical view that glaciers in Scotland collapsed in response to rapid warming at the end of the YDS (as reviewed in Ref. 18), suggesting instead that deglaciation was underway early in the stadial.

To address this discrepancy, we collected thirteen sediment cores from moraine-dammed bogs on Rannoch Moor (Fig. 2B, Fig. S1-S3) and extracted organic material for 14C dating from sediments immediately overlying the LLA till. Our independent radiocarbon-based chronology is underpinned by 20 basal ages derived from these water-lain post-glacial sediments. Samples consisted primarily of terrestrial plant macrofossils (see Materials and Methods, Fig. S4) that most likely were dislodged from adjacent land surfaces (e.g., by slope processes, wind, rain, etc.) and incorporated into nearby drainage, before being deposited along with reworked minerogenic sediments in topographic basins. Thus, terrestrial plant remains in these earliest post-glacial deposits typically do not reflect growth position. There is no evidence (e.g., till, disturbance of sediments) in our cores for ice overriding subsequent to deposition of the LLA till. Moreover, the near-perfect preservation of the plant remains (Fig. S4) argues against these macrofossils having been glacially worked from the pre-LLA landscape. Thus, the earliest organics in our cores represent the onset of postglacial plant colonization of Rannoch Moor and provide a minimum limit on the age of complete deglaciation of the LLA ice cap.

Results and Discussion

Radiocarbon ages are shown in Figure 3 and are given in Table S1. Ages from the lowermost macrofossils in each core range from 9140 ± 180 to 10,550 ± 65 14C yr, corresponding to 10,320 ± 270 to 12,480 ± 100 cal yr (Table S1). This non-normal distribution is characteristic of minimum-limiting datasets and confirms that the basal ages do not represent a single event (deglaciation) but
samples OS-99977, OS-99978, OS-89841, and OS-89842, all from δ¹⁸O record (43) and YDS (blue shading) are presented by this dataset as 12,371 cal yr (Table 1, Fig. S7). Further interpretation is reinforced by the tight agreement between our data and existing minimum-limiting ages from Rannoch Moor (19, 21, 22) (Fig. 3, Table S1).

Both ‘earliest’ and ‘conservative’ scenarios indicate that Rannoch Moor was deglaciated by mid-YDS time (Fig. 4) and, therefore, that the extensive ~500 km² LLA ice cap was gone from the landscape at least 500 years prior to the end of the stadial. These findings conflict with the prevailing view that glaciers in Scotland advanced and maintained maximum positions throughout much of the YDS, posing the question: What drove deglaciation during a period of apparently severe North Atlantic cold? Furthermore, if the YDS was characterized by deglaciation, then when did the YD itself occur?

We consider two possible resolutions to the paradox of deglaciation during the YDS. First, declining precipitation over Scotland due to gradually increasing North Atlantic sea-ice extent has been invoked to explain the reported shrinkage of glaciers in the latter half of the YDS (16). However, this course of events conflicts with recent data depicting rapid, widespread imposition of winter sea-ice cover at the onset of the YDS (10), rather than progressive expansion throughout the stadial. Furthermore, considering the gradual active retreat of LLA glaciers indicated by the geomorphic record, our chronology suggests that deglaciation during the YDS was driven by a combination of factors.

A third and broader-scale approach assesses the cumulative probability of all eighteen basal ages. Since the non-normal distribution of this dataset precludes taking the mean as a close minimum age for plant colonization (Text S3), we use the 90% confidence interval to identify the earliest probable age represented by this dataset as 12,371 cal yr (Table 1, Fig. S7). Furthermore, although 40% of the cumulative-probability curve lies <11.6 ka, this distribution reflects the inclusion of basal ages that are considerably younger than the onset of plant growth. Thus, we argue that, for this analysis of all basal data, the 90% value constrains most closely the age of deglaciation.

While there are several ways to establish the most representative age for deglaciation using a minimum-limiting dataset such as ours, we note that, regardless of approach, the outcome does not change our conclusions. As shown in Table 1, the difference between the earliest probable age (12,580 cal yr) and our most conservative estimate (12,262 ± 85 cal yr) is <400 years, reflecting the consistency among our oldest basal ages. Furthermore, because these ages represent the first vegetation to colonize Rannoch Moor following deglaciation, they constitute a minimum-limiting age for final disappearance of the LL A ice cap. Our chronology indicates that deglaciation of Rannoch Moor was complete as early as ~12,580 cal yr, but no later than ~12,200 cal yr. For comparison, the GISP2 δ¹⁸O record (S6) and YDS (blue shading) are shown.
in a new SST record from the northeastern North Atlantic, which shows higher summer temperatures during stadial periods (e.g., Heinrich stadials 1 and 2) than during interstadials on account of amplified seasonality (29).

The effects of stratification-driven summertime warming may have been exacerbated by amplified seasonal shifts of the boreal westerlies. Although the jet stream likely was stronger and more zonal across the North Atlantic during YDS winters on account of expanded sea-ice (10), retreat of the sea-ice edge during spring and summer to a position north of Norway (30) could have facilitated a more meridional trajectory of the summertime jet, resulting in incursions of warmer subtropical air masses to Scotland. Additionally, YDS warming of the mid-latitude North Atlantic that arose as a consequence of curtailed MOC (31) would have enhanced warming of subtropical air masses, potentially stimulating summertime melting of downwelling European glaciers. Concurrently, increasing solar radiation due to maximum summer insolation, combined with rising atmospheric CO₂ concentrations (32), could have dominated seasonal warming and glacier recession during the YDS.

Regarding the timing of the LLA, our chronology provides a firm minimum constraint for the event and shows deglaciation of Rannoch Moor — and thus Scotland — was complete by at least ~12,200 yr ago. While this scenario is supported by earlier radiocarbon studies (19, 21, 22, 33), it is difficult to reconcile with the paradigm of the LLA being driven by YDS cooling, since that would require the accumulation and collapse of a major ice cap within as little as 400 years. Indeed, one recent assessment places the onset of the YDS closer to 12.7 Ka (10), further shortening the window of time available for a stadial-driven late-glacial advance. Such rapid build-up and decay of the ice cap is consistent with an earlier interpretation of the Scottish record rather than sudden stagnation (14, 15), and with recent modeled assessment places the onset of the YDS closer to 12.7 Ka (10), since that would require the accumulation and collapse of a minimum seasonal shift of the boreal

28: 147-169.


Table 1. Radiocarbon and calibrated age determinations for the minimum deglaciation-age scenarios. Age determinations are shown in black, while the relative distributions of previously published ages (19, 22) are shown in red. 14C ages are highlighted in red. 14C ages from stratigraphic levels are shown in black.