Chapter 2

Evidence for Synchronous Global Climatic Events: Cosmogenic Exposure Ages of Glaciations

Don J. Easterbrook *, John Gosse †, Cody Sherard ‡, Ed Evenson ** and Robert Finkel ††

* Department of Geology, Western Washington University, Bellingham, WA 98225, USA,
† Dalhousie University, Halifax, Nova Scotia, Canada B3H 4R2, ‡ Department of Geology, Western Washington University, Bellingham, WA 98225, USA, ** Earth and Environmental Sciences Department, Bethlehem, PA 18015, USA, †† Lawrence Livermore National Laboratory, Livermore, CA 94550

Chapter Outline

1. Introduction 53
2. Late Pleistocene Climate Oscillations Recorded by Glaciers 54
   2.1. Sawtooth Mts. Moraine Sequences 56
   2.2. Global LGM Moraines 66
   2.3. Global Younger Dryas Moraines 72
3. Conclusions 83
   Acknowledgments 83

1. INTRODUCTION

Why is knowledge of short-term sensitivity of glaciers to climatic/oceanic changes important? Despite three decades of research on abrupt climate changes, such as the Younger Dryas (YD) event, the geological community is only now arriving at a consensus about its global extent, but has not established an unequivocal cause or a mechanism of global glacial response to rapid climate changes. At present, although Greenland ice cores have allowed the development of highly precise $^{18}$O curves, we cannot adequately explain the cause of abrupt onset and ending of global climatic reversals. In view of present global warming, understanding the cause of climate change is critically...
important to human populations—the initiation and cessation of the YD ice age were both completed within a human generation.

Whether or not large magnitude but short-term fluctuations of late Pleistocene ice sheets and alpine glaciers were synchronous globally is still being debated, although evidence is compelling that the YD was a global climatic event. Some researchers continue to argue that the YD did not affect western North America and that alpine glaciers and ice sheets were out of phase at the last glacial maxima (LGM). Others argue that YD cooling did not affect the Southern Hemisphere. At the root of these debates is a lack of precise time control on discrete regional climatic events, incomplete understanding of the causal mechanisms of abrupt climatic change, problems linked to uncertainties of some of the dating methods when comparing chronologies, stratigraphic complexities, and too few dates at critical localities.

2. LATE PLEISTOCENE CLIMATE OSCILLATIONS RECORDED BY GLACIERS

In addition to the evidence for abrupt, late Pleistocene, climatic changes in ice cores, late Pleistocene climate changes have also been recorded in alpine moraines, which are useful indicators of climate change because they record temporal fluctuations in ice volume. However, they do not necessarily record every climate change because: (1) moraines only mark an ice-marginal position for a particular maximum, so if a subsequent advance is greater, the earlier evidence is obliterated; (2) not all glaciers form moraines during a particular glacial maximum because the glacier margin may not have been stable long enough at a single ice-marginal position to build a significant moraine; (3) glaciological conditions may force glacier advance or retreat out of phase with expected climate change; and (4) glaciers respond to changes in both temperature and precipitation that may induce a complicated moraine record out of phase with global temperature change. Thus, at any single site, these factors may complicate climatic inferences. However, when a consistent pattern emerges over wide regions, the likelihood that all would have been the result of non-climatic influences is much diminished. Thus, well-dated ice-marginal fluctuations can reveal useful information regarding the timing of major paleoclimate reversals and whether or not the effects of some late Pleistocene climate events were felt globally or only in some regions.

Establishing detailed chronologies of glacier fluctuations is limited by stratigraphic context relating the dated material to the climate record and the accuracy of the dating method. Dating of moraines has been accomplished directly using terrestrial in situ cosmogenic nuclide (TCN) dating or $^{14}$C dating of incorporated organic material and indirectly by $^{14}$C dating of associated sediments. Measurements of $^{10}$Be, $^{26}$Al, $^{36}$Cl, and $^{3}$He from boulders give
exposure ages with approximately 1–8% random error (1 s), but uncertainties in
the TCN production rates and other systematic errors of these isotope systems
diminish the obtainable accuracy. However, identifying the 1,300–1,500-year
span of the YD is well within the precision of TCN dating (e.g., Gosse et al.,
1995a,b; Ivy-Ochs et al., 1999; Gosse and Phillips, 2001). Likewise, although
the internal error of $^{14}$C dating is about ±1% (1 s), uncertainty in the $\delta^{14}$C
calibration curve at about the time of the YD decreases the total accuracy. One
might therefore argue that neither dating method provides sufficient accuracy to
distinguish events within the YD. However, identifying multiple YD or other
late Pleistocene events does not depend on the ability to distinguish double YD
moraines solely on the basis of TCN and $^{14}$C dating. If both moraines of a YD
doublet fall within the age range of the YD event, the existence of two moraines
will show that the YD at that site consisted of more than one event. A consistent
pattern of double YD moraines at many sites indicates that the double moraines
are not due to some local glaciological effect. TCN and $^{14}$C dating methods
provide the necessary level of precision for this purpose.

In this paper, morphologic and chronologic evidence is presented that the
YD climatic oscillation that affected glaciers in the western U.S. consisted of
two phases, and glaciers in the Swiss Alps, Scandinavia, and New Zealand
recorded double YD moraines, suggesting that glaciers in both hemispheres
reacted sensitively and virtually simultaneously (Easterbrook, 1994a, 2002,
2003a,b; Easterbrook et al., 2004). Evidence is also presented for the syn-
chronicity of late Pleistocene oscillations of the Cordilleran and Scandinavian
ice sheets, which were also in phase with alpine glacier fluctuations. Not all
post-LGM cirque moraines are YD and not every cirque contains double YD
moraines. In some places, pre-YD (probably Intra-Allerød Cold Period)
moraines have also been documented and some YD localities have single or
multiple moraines. However, enough double YD moraines exist to show a two-
fold YD climate change.

This paper is not intended as an in-depth review of the Younger
Dryas—rather it presents evidence that glaciers in both hemispheres advanced
twice during the YD, and the timing is matched in the GISP2 core. This
suggests that climate was globally connected during the late Pleistocene and
implies that climate connections are via means other than oceanic-atmospheric
teleconnections. Mercer (1982) suggested that glaciations in the Northern and
Southern Hemispheres were synchronous and YD moraines have been found in
many areas. Our contribution is the suggestion that two global YD advances
must mean that glaciers were so sensitive to global climate change that such
changes could not have been initiated in one region and then propagated via the
oceans globally without introducing significant time lags in the glacial response
in different hemispheres.

The essential point of this paper is that such sensitive, global, climate
responses cannot be adequately explained by the North Atlantic deep current
hypothesis. Our objective is to introduce and provide support for the proposed
climatic significance of the widely occurring twin-moraine YD records. We establish a new YD twin-moraine record in the western USA by providing geochronological constraints on late Pleistocene glacial dynamics which ended with the YD readvances. Then we compare this chronology with that of previously dated twin-moraine records. Much discussion has centered around whether or not glaciers in western North America advanced and retreated synchronously or reacted progressively in accordance to theoretical hypotheses related to secondary effects generated by the Laurentide Ice Sheet, calling for progressive westward transgression of glacial climates in the west and asynchronicity of glacial events (Gillespie and Molnar, 1995). Others have suggested an absence of Younger Dryas glacial advances in the western U.S. or asynchroniety of post-LGM events. The data in this paper address these significant questions.

2.1. Sawtooth Mts. Moraine Sequences

2.1.1. Geologic Setting
More than 50 peaks in the Sawtooth Range rise above 10,000 ft (3,300 m), making it among the highest mountain ranges in the northern Rocky Mts. of Idaho. Most of the range consists of granitic rocks of the Idaho batholith, including both Cretaceous and Eocene phases and all of the moraines studied consist largely of granitic material. The contact between the Cretaceous and Eocene granitic rocks occurs in the headwaters of the Redfish Lake drainage so both rock types occur on moraines in the area. The Eocene granite tends to yield much larger erratics than the Cretaceous granite and does not appear to weather as rapidly. All of the moraines in the Redfish Lake area are mantled with large erratics (several meters high) of Eocene granite. Moraines in the valleys south of Redfish Lake consist mostly of Cretaceous granite and erratics are generally considerably smaller. Large erratic boulders suitable for cosmogenic dating are abundant in the Redfish Lake area but are rare on moraines in the southern part of the range. The very large erratics at Redfish Lake may also reflect jointing characteristics of the Eocene granite, allowing big, joint-bounded blocks to be quarried by glaciers.

The Sawtooth Range of central Idaho (Fig. 1) was deeply affected by late Pleistocene alpine glaciation. Valley glaciers from the high mountains extended out onto the piedmont area of the Stanley Basin where they constructed groups of massive moraines that cut across one another in successive glacial advances. These moraines provide an exceptional opportunity for establishing the glacial chronology of this part of the Rocky Mts.

2.1.2. Glacial Geomorphology
The last glacial maximum (LGM) is represented by large, massive moraines rising 330 m above their bases on the valley floors in more than a dozen drainages (Fig. 1). At Redfish Lake, glacial advances emerged from the
mountains and left moraines at nearly right angles to the mountain front (Figs. 1, 2). Massive late Pinedale moraines cut across the older moraines and extend 10 km across the Stanley Basin, temporarily blocking the Salmon River. During its retreat, this glacier built at least two dozen recessional moraines. Four cirques at progressively higher elevations above Redfish Lake contain moraines that record Younger Dryas, successively-rising, equilibrium line altitudes (ELAs).

The moraine record in the Sawtooth Range and Stanley Basin was first studied in detail by Williams (1961), who established relative moraine chronology based on morphology and relative weathering. He mapped several crosscutting morainal systems, which he called Bull Lake 1, Bull Lake 2, and Pinedale, and established a relative chronology, but had no numerical dates. Breckenridge et al. (1988) discussed moraines and lake sediments in the Stanley Basin.

**FIGURE 1** DEM of the Sawtooth Range and Stanley Basin. Moraines 300 m high extend from the mountains well into the basin (Image by L.R. Stanford, IGS).
Thackray et al. (2004) mapped moraines at Alturas, Pettit, and Yellowbelly Lakes, and Hell Roaring valleys south of Redfish Lake. They recognized two morainal groups, each consisting of several lateral and end moraines, which they distinguished on the basis of soil characteristics and moraine morphometry and concluded that the outer moraines were at least 10 ka older than the inner moraines. Our $^{10}$Be dates on these moraines indicate that all of these moraines are late Pinedale and confirm that the prominent cirque moraines indeed fall within the YD chron.

2.1.3. Methods
Samples were collected using a diamond—blade saw to extract uniformly thick (2 cm) specimens from the center of the top of each boulder, minimizing the effects of neutron loss (Masarik and Weiler, 2003) and edge effects (Gosse and Phillips, 2001), and reducing variability in thickness measurements. None of the sampled boulders had peaked or significantly (>12°) dipping surfaces. Only boulders greater than 1.5 m high (except one) situated on moraine crests were sampled in order to minimize the possibility of significant snow burial or post-depositional exhumation.

**FIGURE 2** Morainal groups and $^{10}$Be ages in the Redfish Lake area (Image by L.R. Stanford, IGS).
All samples were cleaned of lichen and soil, crushed, ground, and dry sieved. Following Kohl and Nishiizumi (1992), ca. 300 g of the 250–500 μm fraction was leached in 4 l of deionized water with 140 ml of HF acid and 50 ml of HNO₃ acid in ultrasonic tanks for 50 h, during which the grains were rinsed and solution replaced two times. After confirming that greater than 35% of the original quartz mass was dissolved, quartz purity was verified using Al concentrations determined with Quant-EM strips (all samples had <100 mg/ml Al). To achieve a sufficient AMS current for BeO and a $^{10}\text{Be}/^{9}\text{Be}$ above $5 \times 10^{-13}$, 0.2 mg of $^{10}\text{Be}$ carrier was added to approximately 15–40 g of each dried sample in a 500 ml Teflon digestion vessel. The mixture was dissolved in 20 h in a solution of HF (540 ml), HClO₄ (13 ml) and Aqua Regia (50 ml), then evaporated and reduced to a chloride. The Be carrier is a 985 mg/ml solution from a BeCl₃ prepared by J. Klein (U. Pennsylvania) using a beryl crystal collected deep within the Homestake Gold mine in South Dakota, USA (long-term average $^{10}\text{Be}/^{9}\text{Be}$ is $4 \times 10^{-15}$). The Be carrier concentration has been re-measured regularly with ICP-MS, AA, and ICP.OES and found to be within 3% of this value. Be was isolated using ion chromatography (10 ml and 17 ml of anion and cation Biorad® resins) and controlled precipitations with ultrapure ammonia gas, with final ignition to BeO in a furnace. The $^{10}\text{Be}/^{9}\text{Be}$ measurements at CAMS-LLNL against KNSTD3110 Be standard yielded precisions of 1.1–2.9%, and most blank corrections were less than 2%; one $^{10}\text{Be}/^{9}\text{Be}$ process blank had a high ratio ($29 \times 10^{-15}$) which caused a 5% adjustment to the measured ratio of sample ID-RL-04-024. Isobaric boron interference corrections were low (<1%).

Following data reduction, the concentrations were corrected for snow cover (0–3% based on boulder height and assumed snow depth of 2 m at 2 g cm$^{-3}$ density for 4 months per year, Gosse and Phillips, 2001), tree cover (0–2% in an open pine forest, Plug et al., 2007), and topographic shielding (<2%; Gosse and Phillips, 2001). No correction for boulder erosion has been made as our sampling strategy was devised to minimize this effect. However, it is possible that erosion may have decreased the apparent ages of LGM and pre-LGM boulders by a few percent. Additional details including $^{10}\text{Be}$ concentrations and AMS error are provided in Sherard (2006). The ages have been calculated using the $^{10}\text{Be}$ online CRONUS-CALCULATOR v. 2.2 (Balco et al., 2008). The ages reported in the text are the average of the three time-dependent geomagnetic field corrected scaling methods. Uncertainty in age at 1σ reflects the AMS error and 10% error in production rate.

2.1.4. Pre-LGM Moraines

2.1.4.1. Elk Meadow Morainal Group

The Elk Meadow morainal group consists mostly of multiple, inset, arcuate, lateral moraines on the east side of the large Redfish Lake morainal complex.
A group of younger moraines, the Salmon River morainal group, crosscut the youngest Elk Meadow moraines (Figs. 3, 4). About half a dozen nested, Elk Meadow moraines are the oldest moraines mapped by Williams (1961) in the Redfish Lake area. He mapped them as Bull Lake 1, based on their weathering characteristics and topographic position relative to the next younger moraines.

Four samples were collected from large granitic boulders at three locations on the moraines near the terminus. The $^{10}$Be ages of the samples were $200 \pm 25$ ka, $161 \pm 20$ ka, $107 \pm 14$ ka, and $105 \pm 15$ ka.

2.1.4.2. Salmon River Morainal Group

The Salmon River morainal group consists of at least seven nested lateral and end moraines southeast of Redfish Lake (Figs. 3, 4). The Salmon River moraines cut across the upper Elk Meadow moraines (Figs. 3, 4) and are bounded by a pair of long lateral moraines enclosing at least five lateral and end moraines (Fig. 4). A high Pinedale lateral moraine (~300 m above Redfish Lake) cuts across the Salmon River moraines (Fig. 4). Williams (1961) mapped these moraines as Bull Lake 2, based on their weathering characteristics and topographic position relative to the Pinedale Redfish Lake moraines (Fig. 4). The morphology of the moraines is less subdued than the Elk Meadow moraines and the boulder frequency seems unusually high for Bull Lake moraines.

Two samples from moraines of the Salmon River Group were dated at $312 \pm 42$ ka and $229 \pm 30$ ka. The overlap in ages between the Elk Meadow
and Salmon River group may be due to a combination of inherited $^{10}$Be and differences in boulder weathering rates. The six boulders dated on the two moraine sequences have a similar distribution to boulders exposure dated at the Bull Lake type locality in Wyoming, and, considering soils and moraine morphology observations are unlikely to have been deposited during the LGM.

2.1.5. LGM Moraines

2.1.5.1. Redfish Lake Morainal Group

High, massive lateral moraines that bound Redfish Lake (Figs. 3, 5) are here named the Redfish Lake morainal group. They were mapped by Williams (1961) as Pinedale moraines on the basis of their morphology, stratigraphic position, and degree of weathering, but he had no numerical chronology for them. The morainal group includes at least two dozen lateral moraines and several end moraines extending over a distance of several kilometers (Fig. 5). The dominant, enclosing lateral moraines are massive, reaching 300 m above lake level and cut across the Salmon River and Elk Meadow morainal groups (Fig. 4). The surface of the moraines is littered with many
very large (several meters high) granitic boulders, mostly pink granite derived from the Eocene phase of the Idaho batholith, well suited to cosmogenic exposure dating.

The Pinedale LGM at Redfish Lake was dated at 18.8 ± 2.3 ka from a boulder on the terminal moraine and dates of 20.3 ± 2.5 ka and 18.1 ± 2.2 ka from the highest lateral moraines. An age of 13.6 ± 1.7 ka was obtained from the highest lateral moraine at Stanley Lake.

Terminal moraines at Alturas Lake (Fig. 2) were first mapped as Pinedale by Williams (1961). Thackray et al. (2004) distinguished two groups of moraines there, based on moraine morphology and relative weathering. They inferred that the older set of moraines is at least 10 ka older than the younger moraines and that the age is probably considerably older, prior to 27,000 years B.P. We attempted to locate boulders suitable for TCN dating on the outer Alturas and Pettit Lake moraines, but boulders are rare because the granitic source rock is the Cretaceous portion of the Idaho batholith, which does not generate boulders as large as does the Eocene granite at Redfish Lake. Only two boulders met our sampling criteria, both on the outer Alturas Lake moraine. Sample ID-RL-04-033 is from a boulder on the second oldest Alturas Lake moraine (Fig. 1). The $^{10}$Be ages of the boulders are 17.5 ± 2.1 ka and 18.4 ± 2.3 ka. These dates indicate that the ages of the Busterback Ranch moraines inferred by Thackery et al. (2004) are incorrect and that all of the moraines at Alturas Lake are late Pinedale.

FIGURE 5  The Redfish Lake morainal group. Curved lines indicate moraine crests.
About two dozen nested lateral moraines mark the systematic retreat of Pinedale ice from the Redfish Lake LGM (Fig. 5). Six $^{10}$Be dates from these moraines range from 16.1 ka near the terminus to 14.6 ka at Redfish Lake (Table 1, Fig. 5). Other LGM recessional positions at Redfish Lake but higher in elevation have dates of 15.1 ka, 16.2 ka, and 16.7 ka. The innermost recessional moraine at Lake Stanley was dated at 13.6 ± 1.7 ka.

2.1.6. Younger Dryas Moraines

2.1.6.1. Bench Lakes Morainal Group

Bench Lakes comprise five paternoster lakes that occur at successively higher elevations in the mountains on the north side of Redfish Lake (Figs. 2, 6). Four of the lakes are rimmed by moraines representing sequentially rising ELAs.

The $^{10}$Be ages of three boulders from a moraine at the distal end of Fourth Bench Lake (Fig. 6) ranged from 11.8 ± 1.4 ka to 12.2 ± 1.5 ka. A boulder on a moraine at Third Bench Lake about 100 m lower (Fig. 6) was dated at 11.9 ± 1.4 ka. Although all four ages fall within the Younger Dryas, at least two phases of moraine building took place during the YD, the younger of which occurred when ELAs were ~100 m higher. No boulders meeting our systematic sampling strategy were present on the other (higher) moraines.

2.1.7. Summary of Sawtooth Mts. Late Pleistocene Ice Dynamics

The moraine maps and TCN chronology support the following conclusions:

1. The oldest moraines in the region appear equivalent to the Bull Lake moraine deposits at their type locality, and may represent an advance in OIS-6 if we assume some of the older TCN apparent ages were due to inheritance, or a combination of OIS-6 and older glaciations as proposed by Phillips et al. (1998).
2. No evidence for an OIS-4 glaciation exists on the basis of the exposure ages, so the LGM advance was more extensive than OIS-4 in the Sawtooth Range.
3. The timing of initial retreat from the last Pinedale maximum was between about 16.2 ka and 15.8 ± 1 ka.
4. Late Pleistocene retreat rate in the piedmont was 2 m/year. No other significant ice-marginal positions occur between the piedmont and Bench Lakes and on this basis we interpret the Bench Lakes moraines to represent a significant climate signal, not merely a series of recessional moraines, although of course we cannot preclude the latter.

2.1.8. Correlations

While it is tempting to correlate the Sawtooth Moraines to other moraine records of ice sheet and ice caps, we recognize that large ice masses may not be in
<table>
<thead>
<tr>
<th>Age (ka ± 1s)</th>
<th>Sample number</th>
<th>Description</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>Elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Younger Dryas Dates from Cirque Moraines at Bench Lakes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.8 ± 1.4</td>
<td>ID-RL-04-017</td>
<td>Post-LGM Pinedale moraine, Bench Lk</td>
<td>N44 06.653</td>
<td>W114 58.073</td>
<td>2,532</td>
</tr>
<tr>
<td>12.0 ± 1.5</td>
<td>ID-RL-04-018</td>
<td>Post-LGM Pinedale moraine, Bench Lk</td>
<td>N44 06.685</td>
<td>W114 58.042</td>
<td>2,518</td>
</tr>
<tr>
<td>12.2 ± 1.5</td>
<td>ID-RL-04-016</td>
<td>Post-LGM Pinedale moraine, Bench Lk</td>
<td>N44 06.694</td>
<td>W114 57.970</td>
<td>2,508</td>
</tr>
<tr>
<td>11.9 ± 1.4</td>
<td>ID-RL-04-020</td>
<td>Post-LGM Pinedale moraine, Bench Lk</td>
<td>N44 06.862</td>
<td>W114 57.740</td>
<td>2,424</td>
</tr>
<tr>
<td><strong>Recessional Moraines from LGM at Redfish Lake</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.6 ± 1.8</td>
<td>ID-RL-04-023</td>
<td>Inner moraine</td>
<td>N44 08.888</td>
<td>W114 54.667</td>
<td>2,014</td>
</tr>
<tr>
<td>15.1 ± 1.8</td>
<td>ID-RL-04-015</td>
<td>Lateral moraine outside Bench Lks</td>
<td>N44 06.704</td>
<td>W114 57.347</td>
<td>2,450</td>
</tr>
<tr>
<td>15.8 ± 1.9</td>
<td>ID-RL-04-024</td>
<td>Recessional moraine</td>
<td>N44 09.181</td>
<td>W114 54.407</td>
<td>2,022</td>
</tr>
<tr>
<td>15.8 ± 1.9</td>
<td>ID-RL-04-026</td>
<td>Recessional moraine</td>
<td>N44 09.585</td>
<td>W114 54.267</td>
<td>2,013</td>
</tr>
<tr>
<td>15.8 ± 1.9</td>
<td>ID-RL-04-025</td>
<td>Recessional moraine</td>
<td>N44 09.223</td>
<td>W114 54.408</td>
<td>2,003</td>
</tr>
<tr>
<td>16.1 ± 2.0</td>
<td>ID-RL-04-012</td>
<td>Moraine near terminus</td>
<td>N44 09.931</td>
<td>W114 53.888</td>
<td>2,011</td>
</tr>
<tr>
<td>16.7 ± 2.0</td>
<td>ID-RL-04-039</td>
<td>Right lateral moraine</td>
<td>N44 06.012</td>
<td>W114 55.164</td>
<td>2,271</td>
</tr>
<tr>
<td>16.2 ± 2.0</td>
<td>ID-RL-04-014</td>
<td>Lateral moraine outside Bench Lks</td>
<td>N44 06.932</td>
<td>W114 57.113</td>
<td>2,386</td>
</tr>
<tr>
<td>Moraine Type</td>
<td>Location</td>
<td>Age (yr)</td>
<td>Coordinates</td>
<td>Elevation (m)</td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>----------</td>
<td>----------</td>
<td>-------------</td>
<td>--------------</td>
<td></td>
</tr>
<tr>
<td><strong>Recessional Moraine from LGM at Stanley Lake</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.6 ± 1.7 ID-SL-04-035</td>
<td>Recessional moraine at Stanley Lake</td>
<td>NN44 15.071</td>
<td>W115 03.492</td>
<td>2,002</td>
<td></td>
</tr>
<tr>
<td><strong>Redfish Lake LGM</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18.1 ± 2.2 ID-RL-04-040</td>
<td>Highest right lateral moraine</td>
<td>N44 05.962</td>
<td>W114 55.180</td>
<td>2,279</td>
<td></td>
</tr>
<tr>
<td>18.8 ± 2.3 ID-RL-04-013</td>
<td>Terminal moraine</td>
<td>N44 09.969</td>
<td>W114 54.819</td>
<td>2,003</td>
<td></td>
</tr>
<tr>
<td>20.3 ± 2.5 ID-RL-04-038</td>
<td>Highest right lateral moraine</td>
<td>N44 06.316</td>
<td>W114 55.042</td>
<td>2,311</td>
<td></td>
</tr>
<tr>
<td><strong>Alturas Lake LGM</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.5 ± 2.1 ID-AL-04-034</td>
<td>Alturas Lake terminal moraine</td>
<td>N43 57.206</td>
<td>W114 50.630</td>
<td>2,153</td>
<td></td>
</tr>
<tr>
<td>18.4 ± 2.3 ID-AL-04-033</td>
<td>Alturas Lake terminal moraine</td>
<td>N43 57.299</td>
<td>W114 50.707</td>
<td>2,151</td>
<td></td>
</tr>
<tr>
<td><strong>Stanley Lake LGM</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.3 ± 2.5 ID-SL-04-049</td>
<td>Highest left lateral moraine</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>South Redfish Bull Lake 2 Moraines</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>229 ± 30 ID-RL-04-045</td>
<td>Salmon River moraine</td>
<td>N44 05.395</td>
<td>W114 54.370</td>
<td>2,183</td>
<td></td>
</tr>
<tr>
<td>312 ± 42 ID-RL-04-043</td>
<td>Salmon River moraine</td>
<td>N44 05.460</td>
<td>W114 55.262</td>
<td>2,226</td>
<td></td>
</tr>
<tr>
<td><strong>South Redfish Bull Lake 1 Moraines</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>105 ± 13 ID-RL-04-028</td>
<td>Elk Meadow moraine</td>
<td>N44 08.009</td>
<td>W114 53.200</td>
<td>2,069</td>
<td></td>
</tr>
<tr>
<td>107 ± 14 ID-RL-04-027</td>
<td>Elk Meadow moraine</td>
<td>N44 08.433</td>
<td>W114 53.498</td>
<td>2,077</td>
<td></td>
</tr>
<tr>
<td>161 ± 20 ID-RL-04-031</td>
<td>Elk Meadow moraine</td>
<td>N44 05.787</td>
<td>W114 52.308</td>
<td>2,048</td>
<td></td>
</tr>
<tr>
<td>200 ± 25 ID-RL-04-029</td>
<td>Elk Meadow moraine</td>
<td>N44 06.530</td>
<td>W114 52.558</td>
<td>2,100</td>
<td></td>
</tr>
</tbody>
</table>
equilibrium with climate everywhere along their margins. However, smaller alpine glaciations are demonstrably sensitive to regional precipitation and temperature changes and such correlations can be instructive. We first compare the new Sawtooth chronology with LGM records in the region and globally. Then we compare the YD moraine chronologies. We recognize that there have been several important changes in the ages since the time that these previous results were published. For instance, radiocarbon calibrations have matured, and the production rates, scaling methods, and half-life of cosmogenic isotopes have changed. However, as demonstrated by Heyman et al. (2011), the changes in the TCN ages have not been greater than 10% in most locations. Furthermore, we are uncertain of the actual snow and tree shielding corrections that are necessary at many locations, or if they were calculated in a fashion consistent with our ages. Furthermore, for $^{10}$Be ages, we are unable to re-standardize the original $^{10}$Be/$^9$Be measurements for the new half-life in cases where the authors have not provided the AMS standard used. Therefore, for the following discussion we use the originally published ages. Even with a 20% uncertainty to account for these differences, certain correlations are still apparent.

2.2. Global LGM Moraines

2.2.1. Cordilleran Ice Sheet

The Cordilleran Ice Sheet advanced across the Canadian border into the U.S. 18–21,000 $^{14}$C years B.P., retreated, then advanced to its LGM terminal position 14–15,000 $^{14}$C years B.P. (Fig. 7) (Easterbrook, 1969, 1992, 1994).
2.2.2. Scandinavian Ice Sheet

The Scandinavian Ice Sheet reached its LGM in northern Europe about 20–22,000 years ago. Deglaciation began about 17,500 years B.P. and ended at the close of the Younger Dryas (Tschudi et al., 2000).

2.2.3. Wallowa Lake, Cascade Range, Oregon

Wallowa Lake is held in by multiple late Pinedale moraines (Figs. 8, 9). Two glacial phases are represented—older moraines giving $^{10}\text{Be}$ ages of 20–22,000 ka and younger inset moraines dated at 15–17,000 ka.
FIGURE 8  Late Pleistocene moraines at Wallowa Lake, Oregon (Licciardi et al., 2004).

FIGURE 9  $^{10}$Be ages from Wallowa Lake moraines (Licciardi et al., 2004).
2.2.4. **Bloody Canyon, Sierra Nevada, California**

The LGM at Bloody Canyon consists of two moraines, Tioga 2 (early LGM) and Tioga 3 (late LGM). The less extensive, latest Pleistocene glacial readvances (Tioga 4) have been dated at 13–15 ka.

$^{10}$Be ages range from the Tioga 3 moraine, range from 16.2 ka to 19.7 ka, with a mean value of 17.8 ± 1.5 ka. These ages are consistent with earlier $^{36}$Cl data from the Bloody Canyon Tioga 3 moraines with a mean 16.4 ± 1.4 ka, and with $^{36}$Cl ages from the Tioga 3 moraine at nearby Bishop Creek (mean 17.7 ± 0.7 ka) (Phillips et al., 1996).

$^{36}$Cl ages (ka)

<table>
<thead>
<tr>
<th>Moraine, Location</th>
<th>Age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tioga 3, Bloody Canyon</td>
<td></td>
</tr>
<tr>
<td>BCCR90-5</td>
<td>14.5</td>
</tr>
<tr>
<td>BCCR86-1</td>
<td>17.4</td>
</tr>
<tr>
<td>BCCR86-3</td>
<td>16.1</td>
</tr>
<tr>
<td>BCCR86-5</td>
<td>17.5</td>
</tr>
<tr>
<td>Tioga 3, Bishop Creek</td>
<td></td>
</tr>
<tr>
<td>BPCR91-4</td>
<td>17.3</td>
</tr>
<tr>
<td>BPCR90-73</td>
<td>16.8</td>
</tr>
<tr>
<td>BPCR90-74</td>
<td>17.3</td>
</tr>
<tr>
<td>BPCR90-75</td>
<td>18.9</td>
</tr>
<tr>
<td>BPCR91-1</td>
<td>17.2</td>
</tr>
<tr>
<td>BPCR91-3</td>
<td>18.1</td>
</tr>
<tr>
<td>BPCR90-22</td>
<td>18.3</td>
</tr>
<tr>
<td>BPCR90-24</td>
<td>16.8</td>
</tr>
<tr>
<td>BPCR90-25</td>
<td>18.2</td>
</tr>
<tr>
<td>BPCR90-26</td>
<td>18.1</td>
</tr>
</tbody>
</table>

2.2.5. **Fremont Lake, Wind River Range, Wyoming**

The classic late Pinedale moraines at Fremont Lake in the Wind River Range, Wyoming were $^{10}$Be-dated by Gosse et al. (1995a,b). Dates from the outer moraines range 18.5–22 ka and dates from inner moraines range from 14.3 ka to 17.7 ka with an average of 17.6 ± 0.8 ka (Phillips et al., 1997). These dates correlate well with $^{36}$Cl-dated, late Pinedale moraines in southern and northern Colorado (Benson et al., 2005) (Fig. 10).

2.2.6. **Yellowstone National Park, Wyoming**

$^{10}$Be ages from late Pinedale moraines of the Yellowstone ice cap range from 18.6 ka to 14.4 ka with a mean age of 16.5 ± 0.4 ka (Licciardi et al., 2001) (Fig. 11).

2.2.7. **Northern Switzerland**

During the LGM, the Rhone piedmont glacier expanded into the northern foreland of the Swiss Alps. The oldest $^{10}$Be age of four boulders on the
FIGURE 10 $^{10}$Be ages from boulders on late Pinedale moraines at Fremont Lake, Wyoming (Gosse et al., 1995a,b).

FIGURE 11 Late Pinedale moraines of the Yellowstone ice cap (from Licciardi et al., 2001).
outermost terminal moraine is $20.8 \pm 0.9$ ka and the mean is $19.3 \pm 1.8$ ka. A limiting date of $17,700^{14}\text{C}$ cal years B.P. has been obtained from the inner moraines.

2.2.8. New Zealand
LGM moraines bounding Lake Pukaki in the Southern Alps of New Zealand range in age from 19.3 to 14.1 (Schaefer et al., 2006; Easterbrook et al., 2004) (Fig. 12).

2.2.9. Australia
Moraines in Snowy Mountains of the Tasmanian highlands of SE Australia consist of a distinct outermost LGM moraine and recessional moraines

![Figure 12](image_url)  
*Figure 12* $^{10}\text{Be}$ dates from moraines at Lake Pukaki, New Zealand (Schaefer et al., 2006).
(Barrows et al., 2001, 2002). Nineteen $^{10}$Be ages range from 15.0 ka to 19.1 ka, with a mean of 16.8 ± 1.3 kyr.

2.2.10. Lago Buenos Aires, Andes Mts., Argentina
Two sets of LGM moraines (Fenix II and Fenix I) surround Lago Buenos Aires in Patagonia (Kaplan et al., 2004). The oldest boulder age on Fenix II (outer) moraines is 20.4 ± 0.7 ka. $^{10}$Be ages of 16.0 ± 0.4 ka and 18.8 ± 1.5 ka were obtained for two boulders on the Fenix I moraine.

2.3. Global Younger Dryas Moraines

2.3.1. Multiple Younger Dryas Moraines
Despite early evidence for a late-glacial readvance of the CIS in western North America (Armstrong, 1960; Easterbrook, 1963; Armstrong et al., 1965), the apparent absence of pollen evidence for the YD in North America led to a generally-held belief that the YD climatic event did not affect North America. However, in recent years, effects of the YD climatic changes have been recognized at a number of localities in the Pacific Northwest (Easterbrook, 1994a,b, 2002, 2003a,b; Easterbrook and Kovanen, 1998; Kovanen and Easterbrook, 2001, 2002; Kovanen, 2002; Kovanen and Slaymaker, 2005; Licciardi et al., 2004), in the Rocky Mts. (Gosse et al., 1995a,b; Easterbrook et al., 2004), and in California (Owen et al., 2003). Planktonic faunal records from the Pacific Northwest and Alaska confirm that the YD event did indeed affect western North America. Alkenone SST estimates from marine cores west off Vancouver Island indicate a temperature drop of ~3 °C during the YD (Kienast and McKay, 2001). Cool-water foraminifera, suggesting YD cooling, have been found on the British Columbia shelf and in the Santa Barbara Basin. Cooling during the YD is also shown from pollen records in SW British Columbia, NW Washington, Oregon, and SE Alaska.

2.3.2. Cordilleran Ice Sheet
Morphologic, stratigraphic, and chronologic evidence of multiple moraines associated with oscillations of the remnants of the Cordilleran Ice Sheet (CIS) in the Fraser Lowland of British Columbia and Washington has revealed multiple, post-LGM fluctuations of the CIS (Kovanen and Easterbrook, 2002). The chronology of the ice margin fluctuations and timing of ice retreat during the Sumas Stade (Fig. 13) has been bracketed by 70 radiocarbon dates and tied to morphologic and stratigraphic evidence. Two of these, fall within the YD. The CIS chronology, which closely matches that of the GISP2 and GRIP ice cores from Greenland, and sea surface temperatures in the north Pacific (Kienast and McKay, 2001) also compares well with the chronology of post-LGM alpine moraines in the western U.S.
2.3.3. Laurentide Ice Sheet

The Laurentide Ice Sheet readvanced during the YD and built moraines in SW Canada (Grant and King, 1984; Stea and Mott, 1986, 1989). These moraines have been $^{14}$C dated as YD in age.

2.3.4. Scandinavian Ice Sheet

Multiple YD moraines of the Scandinavian Ice Sheet (Fig. 14) have long been documented and a vast literature exists. The Scandinavian Ice Sheet readvanced during the YD and built two extensive Salpausselka end moraines across southern Finland, the central Swedish moraines, and the Ra moraines of southwestern Norway. $^{14}$C dates suggest an age of ~10,700 $^{14}$C years B.P. for the outer Salpausselka moraine and ~10,200 $^{14}$C years B.P. for the inner moraine, very similar to the Cordilleran and Laurentide Ice Sheets.

Thus, all three major Pleistocene ice sheets experienced double moraine-building episodes. Apparently, at least two significant climatic changes that occurred in the Northern Hemisphere during the YD were synchronous.

2.3.5. Younger Dryas in the Western U.S.

The extent to which the climate change of the YD was recorded in North America has long been contentious. Failure to find well-defined YD changes in the pollen
record led to early beliefs that the YD did not affect North America. In recent years, with the advent of cosmogenic dating, more and more evidence for YD moraines indicates that the YD did indeed affect North American glaciers.

Dated YD moraines occur in the Wind River Range at Titcomb Basin and Temple Lake, and many similar, but more poorly dated, moraines occur throughout the Rocky Mts. What is apparent from these examples of YD moraines is that not only was the YD climatic event recorded by alpine glaciers in western North America, but in many places double moraines record a dual YD climatic change.

2.3.5.1. Wind River Range, Wyoming

Cirque glaciers expanded twice during the YD at Titcomb Lakes in the Wind River Range, WY. Erratics on moraines and glaciated bedrock (Fig. 15) ~33 km upvalley from LGM moraines at Freemont Lake, Wyoming, Pinedale have been $^{10}\text{Be}$ dated between 12.3 and 10.6 $^{10}\text{Be}$ years B.P. (Gosse et al., 1995a,b). Nine of ten boulder cosmogenic exposure ages of the inner of the two moraines plot between these dates. The Titcomb Lakes moraines (Fig. 15) have been correlated with the Temple Lake moraines in the Wind River Range to the southwest where multiple late Pleistocene moraines occur (Miller and Birkeland, 1974; Zielinski and Davis, 1987; Davis, 1988; Davis and Osborn, 1987) (Fig. 15).
2.3.5.2. Sawtooth Range, Idaho

Cirque moraines at multiple elevations in the Sawtooth Range of Idaho also record two YD climatic events. Bench Lakes, north of Redfish Lake, consist of five tarns at successively higher elevations, representing sequentially rising YD ELAs. Moraines rim four of the lakes. The $^{10}\text{Be}$ ages of three boulders from a moraine at the distal end of Fourth Bench Lake range from 11.7 ± 0.6 ka to 11.4 ± 0.5 ka. A boulder on a moraine at Third Bench Lake about 100 m lower was dated at 11.7 ± 0.6 ka. Thus, at least two phases of moraine building took place during the YD, the younger of which occurred when ELAs were ~100 m higher than the preceding phase.

2.3.5.3. North Cascades, Washington

Distinctive moraines and ice-contact deposits derived from local sources in the North Cascades and carried to their depositional sites by post-LGM alpine valley glaciers 23–45 km long have been recognized (Kovanen and Easterbrook, 2001; Easterbrook et al., 2004). Soon after 12 ka $^{14}$C years B.P., the Nooksack Middle Fork alpine glacier retreated upvalley and then built a moraine containing logs dated at 10,680 ± 70 to 10,500 ± 70 $^{14}$C years B.P. (Fig. 16) (Kovanen and Easterbrook, 2001; Kovanen and Slaymaker, 2005), establishing their YD age. In the Nooksack North Fork, outwash contains charcoal layers dated at 10,603 ± 69 and 10,788 ± 77.

2.3.5.4. Mt. Rainier, Washington

In the Cascade Range near Mt. Rainier, Crandell and Miller (1974) mapped cirque moraines designated as McNeely I (outer moraine) and McNeely II
The McNeeley I moraines were overlain by Mt. Rainier ash dated at 8750 ± 280 14C years B.P., suggesting that the moraines were probably late Pleistocene. Heine (1998) cored bogs and lakes associated with the moraines and concluded that McNeeley I moraines were older than the YD, and that McNeeley II moraines were post-YD. However, lakes just upvalley from McNeeley I moraines became ice-free shortly before 11,000 14C years B.P. and are floored with clastic sediment deposited between 11,090 and 10,150 14C years ago, the source of which must have been upvalley (i.e., at the site of the McNeeley II moraines), strongly suggesting that the McNeeley II moraines were built during the YD when the basin behind the moraines was filled with ice and meltwater was flowing from there into the lakes behind the McNeeley I moraines. Cores from lakes behind the McNeeley II moraine have no sediment deposited between 10 and 11,000 14C years B.P., confirming that the basin was filled with ice until sometime after 10,000 14C years B.P. Thus, the McNeeley II moraines were deposited during the YD. Whether or not a second YD moraine exists in these basins remains unclear as field reconnaissance has shown the presence of additional moraines not mapped by Heine.

2.3.5.5. Icicle Creek, Cascade Range, Washington

Double, post-LGM moraines occur at the junctions of Eight-mile and Rat Creeks with Icicle Creek about 12 km upvalley from LGM moraines at Leavenworth, WA (Page, 1939; Porter, 1976; Long, 1989). Boulders at Eight-mile Creek were 10Be dated at 12.6 ± 0.6 ka and 12.3 ± 1.1 ka and boulders on the Rat Creek moraines were dated at 11.3 ± 0.7 ka and 11.9 ± 0.6 ka. All of the dates from the inner and outer moraines fall within the YD (Fig. 17).
36Cl dates of the Icicle Creek moraines by Porter and Swanson (2008) yielded ages ranging from 11 ka to 17 ka with averages of 13,575 and 13,145 years for the inner and outer moraines respectively. These ages are about 1,500 to 2,000 years older than the 10Be ages, probably as a result of a ~2,000 year error in the 36Cl production rate used (Swanson and Caffee, 2001; Easterbrook, 2003a).

Multiple, as-yet-undated, post-LGM moraines occur at Snoqualmie Pass in the North Cascades. Half a dozen closely spaced moraines at Snoqualmie Pass well upvalley from the LGM record several periods of glacial retreat and stillstand. No direct numerical ages have been published for these moraines, although a 14C date of 11,050 ± 50 14C years B.P. was obtained from wood at the contact of basal peat on gravel downvalley from the youngest moraines (Porter, 1976).

2.3.5.6. San Bernadino Mts., California

Three sets of moraines occur in the San Bernadino Mts. of southern California. 10Be of the outermost LGM moraines ranges from 18 ka to 20 ka and ages from the inner moraines range from 15 ka to 16 ka (Owen et al., 2003) (Fig. 18).
10Be dates from moraines less than 1 km from the cirques were dated 12–13 ka and were considered by Owen et al. (2003) to be broadly correlative with the Younger Dryas.

2.3.6. Swiss Alps

At Julier Pass near St. Moritz, Switzerland, a complex moraine system contains two main morainal ridges. The outer moraine has been dated by 10Be, 26Al, and 36Cl at 11.75 ka and the inner moraine at 10.47 ka (Fig. 19) (Ivy-Ochs et al., 1996, 1999; Kerschner et al., 1999). At Maloja Pass, less than 10 km from Julier Pass, a bog just inside the outermost of three Egesen moraines yielded a 14C age of 10,700 14C years B.P. (Heitz et al., 1982).
2.3.7. Scotland

Among the first multiple YD moraines to be recognized were the Loch Lomond moraines of the Scottish Highlands (Sissons, 1974, 1979, 1980; Ballantyne, 1989, 2002; Ballantyne et al., 1998; Benn and Ballantyne, 2000, 2005; Benn et al., 1992; Bennett and Boulton, 1993; Rose et al., 1998). Alpine glaciers and icefields in Britain readvanced or re-formed during the YD and built extensive moraines at the glacier margins. The largest YD icefield at this time was the Scottish Highland glacier complex, but smaller alpine glaciers occurred in the Hebrides and Cairngorms of Scotland (Sissons, 1980), in the English Lake District, and in Ireland.

The Loch Lomond moraines consist of single or several moraines, sometimes multiple, nested, recessional moraines. Radiocarbon dates constrain the age of the Loch Lomond moraines between 12.9 and 11.5 cal years. B.P. Although the Loch Lomond YD doesn’t show a consistent pattern of double moraines, the multiple moraines are consistent with multiple phases of YD global climate.

2.3.8. Southern Alps, New Zealand

The YD double-moraine pattern is also found in the Southern Alps of New Zealand at Arthur’s Pass and at Birch Hills along Lake Pukaki ~40 km upvalley
from the LGM moraine. Five $^{10}$Be dates from the outermost Birch Hills moraine (Figs. 20, 21) average 12.8 ka (Fig. 20) and four $^{10}$Be dates from the inner moraine average 11.2 ka (recalculated ages by Ivy-Ochs, personal communication). Another pair of YD moraines occurs at Arthur’s Pass where the mean $^{10}$Be age of the distal moraine is 11.8 ka and of the proximal moraine
is 11.4 ka (Ivy-Ochs et al., 1999). A morainal complex at Prospect Hills in the Arrowsmith Range (Burrows, 1975) yielded $^{10}$Be dates of 12.7 and 12.8 years B.P. (Easterbrook, 2002) (Fig. 22).

On the west coast of South Island, wood in the Waiho Loop moraine, deposited by the Franz Josef Glacier about 20 km behind the LGM moraine, has been dated at 11,200 $^{14}$C years B.P. (Fig. 14) (Mercer, 1982, 1988; Denton and Hendy, 1994).
FIGURE 23  Double Younger Dryas event recorded in the GISP2 ice core (Grootes and Stuiver, 1997; Stuiver and Grootes, 2000).

FIGURE 24  Localities having double Younger Dryas moraines.
3. CONCLUSIONS

The multiple nature of LGM and YD moraines in widely separated areas in both hemispheres suggests a common, global, climatic cause. From the evidence presented above, the following conclusions are reached:

1. The LGM in both the Northern and Southern Hemispheres is characterized by two phases, ~20–24 ka and ~14–17 ka with multiple recessional moraines.
2. The YD is characterized by two distinct moraines in widely separated parts of both the Northern and Southern Hemispheres and in the Pacific and Atlantic regions, indicating that the YD consisted of more than a single climatic event.
3. The twin YD response occurred virtually simultaneously globally.
4. Both ice sheets and alpine glaciers were sensitive to the dual YD phases.
5. The GISP2 ice core shows two peaks within the YD that appear to match the morainal record (Fig. 23).
6. The global synchronicity of the late Pleistocene deglaciation and twin YD phases indicates a global atmospheric cause.
7. The absence of a time lag between the N and S Hemispheres glacial fluctuations precludes an ocean cause.
8. The sensitivity and synchronicity of worldwide glacial events with no apparent time lag between hemispheres mean that abrupt climatic changes such as the YD were caused by virtually instantaneous global changes.
9. The lack of a lag time in glacial events between hemispheres infers that changes in the North Atlantic deep water circulation were not cause the Younger Dryas cooling.

These synchronous glacial fluctuations in the western U.S., Europe, and New Zealand, i.e., in both hemispheres and on both sides of North America (Fig. 24), suggest that several abrupt, global, simultaneous, climatic changes occurred during the late Pleistocene. Such changes cannot be explained by changes in the North Atlantic Deep Current alone because of the contemporaneity of glacial responses in both hemispheres with no time lag between hemispheres. The global sensitivity of the double YD suggests a common global cause, rather than an oceanic event that was propagated across the equator. Both $^{14}$C and $^{10}$Be production rates in the upper atmosphere changed during the YD, raising the possibility of changes in incoming radiation.

ACKNOWLEDGMENTS

We wish to thank Louden Stanford for creating the DEMs used in this paper. JCG was supported by an NSERC-Discovery Grant.
REFERENCES


Easterbrook, D.J., 1994a, Evidence for abrupt late Wisconsin climatic changes during deglaciation of the Cordilleran Ice Sheet in Washington: Geological Society of America Abstracts with Program.


Chapter 2 Evidence for Synchronous Global Climatic Events


