Snowball or Slushball Earth Glaciation 2.4Ga?
Resolving microanalytical evidence in subglacially hydrothermally-altered (down to -27.3‰ δ18O) rocks and coeval supergene materials

Ilya Bindeman, University of Oregon

Collaborators: A.K. Schmitt (UCLA), D.A.D. Evans (Yale), N.S. Serebryakov (Moscow), A. Bekker (Manitoba)

Thanks to: P. Hoffman (U Victoria), Guan B, J Eiler (Caltech) J Vazquez (USGS)
NSF grant EAR 108786
The world “record”: 2.45Ga, -27.3‰ δ^{18}O metagabbro/gneisses from Karelia, Russia δD= -235‰

Global Distribution of water isotopes www.waterisotopes.org
Comparison with Modern climates

-25%e and below

Greenland-like,
-20°C to -35°C

Low-δ¹⁸O rocks and magmas track cold climates
Belomorian Belt

In 2.4 Ga gabbro
2.6 Ga gneiss

The lowest isotope values:

Locality, min.
1. Piasetsk, +26%
2. Lyagkoino, -4%
3. Voev. -30, -14%
4. M. Udarn, -1%
5. Khotkovo, -29%
6. Patino, -20%
7. Vandelk, -19%
8. Polna, -7%
9. Kuzmich, 6%
10. Mirnova Guba, -2%
11. Kl. +6%
“Old” isotope sampling map 2011

and 2012:

Red – low $\delta^{18}$O
Yellow - normal
Isotope Profiles in other localities:

- Bindeman and Serebryakov, EPSL, 2011

Equilibrium within crystal clusters, $\delta^{18}O$ heterogeneity on cm, m, 10 m scales

**Explanation:**
**Rifting under ice**

---

**Diagram:**

- **a:** Long transport
- **b:** Short transport

**Legend:**
- **ΔPO = 15%**
- **ΔPO = 30%**
- **Vapor**
- **Ocean**
- **Temperate**
- **Cold**
- **ΔPO = ±1%**
- **RIFT**
Summary of field/geological observations

- 2.6 Ga Gneiss, 2.4 Ga mafic intrusions, 1.9 Ga metamorphism
- Depletions of $\delta^{18}$O and $\delta$D are in or near contacts with 2.4-2.45 Ga mafic intrusions
- These intrusions are related to rifting
- Depletions of $\delta^{18}$O and $\delta$D form “bull’s eye” concentric pattern, characteristic of modern hydrothermal systems
- Depleted localities occur over 220 km

Bindeman et al. 2013 in press
Karelian samples firmly belong to the “Equilibrium” terrestrial $^{18}\text{O}/^{16}\text{O} - ^{17}\text{O}/^{16}\text{O}$ fractionation line
Cometary Impact? No: $\Delta^{17}O = 0^{\circ\circ}$

Analysis of individual minerals in crystal clusters

Bindeman et al. 2010
Isotope Mapping of a single corundum crystal

Hydrogen Isotopes Insights - record low δD of -235‰.
2.4Ga Subglacial Rifting

Karelia in the Paleoproterozoic:
Paleoproterozoic (Paleoprot.) glacial deposits after assembly in the Nuna supercontinent.
Using zircon to resolve the timing of $\delta^{18}$O depletion

- Perfect mineral to retain U-Pb age and $\delta^{18}$O values
- Requires high T (ca>650°C) to recrystallize or exchange O
- So it only records magmatic or metamorphic episodes
- Untouched by hydrothermal alteration

Dating synglacial intrusions = Dating glaciations (and rise of atmospheric oxygen)
Zircon Story:

2.6Ga rock

2.4 Ga hydrothermal alteration

1.9Ga metamorphism

Low-$\delta^{18}$O matrix $\pm 27\%$

Intact 2.6 Ga, +7‰ zircon

Low-$\delta^{18}$O matrix, zircon cores, 1.9Ga, -27‰ rims

When did the $\delta^{18}$O depletion happen?

Supercontinents: Nuna

Glacials

Superia

When did the $\delta^{18}$O depletion happen?
13.07.13

**Generalized Gneiss:**
- 2537 Ma, 7.9%
- AB-3513-3_3.1
- 385 ppm U

**Generalized Gabbro:**
- 2.4 or 2.1 Crises

**Tectonic Story**
- 2.6 Ga
- ~2.5 Ga initiation of rifting, volcanism
- ~2.4 Ga rifting, glaciation, local hydrothermal alteration by glacial meltwaters
- ~1.85 Ga Svecofennian metamorphism

**Zircon Story**
- Normal δ⁰⁶O matrix, zircon
- Near-surface residence
- Normal δ⁰⁶O matrix, detrital (?) zircon
- 2.4 Ga hydrothermal alteration
- Low δ⁰⁶O matrix, 2.7% intact 2.6 Ga, +7% zircon
- 1.85 Ga metamorphism
- Low δ⁰⁶O matrix, 1.96 Ga, +7% zircon rims
How did it happen?

Do Karelian rocks record Snowball or “Slushball Earth”?
Tiny amounts, mixed with snowflakes

Jormangund Climate State (2011):
Dorian Abbot (U Chicago)
Figure 8. Schematic diagram of the Jormungand global climate state.
Slush-Ball vs Hard Snow Ball Earth climate models and implications
$^{18}\text{O}/^{16}\text{O}$ in Global Circulation Model of Slushball Earth

Coupled AGCM and an ice-sheet dynamics model in which a polar supercontinent is glaciated to the equator, but tropical ocean waters remain above 0°C. Model does not include sea-ice dynamics and the prescribed paleogeography would make for a relatively warm global climate if the $p\text{CO}_2$ was self-adjusted by silicate weathering feedback.
Conclusions and what’s next?

- Karelian Gneiss record depletion during ~2.4 “Slushball Earth” or Jurmangand episode (the first of the 3) to allow for effective vapor $\delta^{18}$O, $\delta$D distillation

- What is next? We are trying to find sedimentary rock that would correspond in age to the Slushball Earth episode

- Testing stability of the Slushball Earth model is required
Supracrustal Materials that *may* record $\delta^{18}O_{\text{water}}$:  
- Secondary Quartz – Amygdaloids
- Glacial Rock flower
- Pillow basalts
- Shales

Comparison with Antarctica
Why most depleted oxygen isotopes are found in mid- to ultrahigh-pressure metamorphic rocks?

- Dabie Shan - Sulu (China) coesite-bearing eclogites, \(-10\) to \(+2\)‰ (Rumble and Yui, 1998; Zheng et al. 2004-2010) 800-200 Ma

500 papers published on \(\delta^{18}O\) in Dabie Shan!

- Kokchetav (Kazakhstan), coesite-bearing, down to \(-3.9\)‰ (Masago, Rumble et al 2003) 580-530 Ma

Now Karelia -27‰! Mid grade kyanite-bearing gneisses 2.6-1.8 Ga

### Table 2. Oxygen isotope analysis of ultra-high-pressure crustal rocks with diamonds and coesites

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mineral</th>
<th>Locality</th>
<th>Rock Lithology</th>
<th>(\delta^{18}O), ‰ SMOW</th>
<th>UHP minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-AA96</td>
<td>Grt</td>
<td>Alpe Arami, Italy</td>
<td>Grt peridotite</td>
<td>5.39</td>
<td>diamonds, 300 kbar pressure</td>
</tr>
<tr>
<td>7-AAA6-1</td>
<td>Grt</td>
<td>Alpe Arami, Italy</td>
<td>Eclogite</td>
<td>3.83</td>
<td>diamonds, 300 kbar pressure</td>
</tr>
<tr>
<td>ED05</td>
<td>Grt</td>
<td>Ergertarpe, Saxonia, Germany</td>
<td>Grt-Bi gneiss</td>
<td>10.58</td>
<td>diamond</td>
</tr>
<tr>
<td>201-93</td>
<td>Grt</td>
<td>Fionftef, Norway</td>
<td>Grt-Bi-Ky gneiss</td>
<td>12.18</td>
<td>diamond</td>
</tr>
<tr>
<td>MP-1</td>
<td>Qz</td>
<td>Rodopi, Greece</td>
<td>Grt-Bi-gneiss</td>
<td>11.32</td>
<td>diamond</td>
</tr>
<tr>
<td>126</td>
<td>Qz</td>
<td>Seferson, Greece</td>
<td>Grt-Bi-gneiss</td>
<td>13.41</td>
<td>diamond</td>
</tr>
<tr>
<td>K.210</td>
<td>Zr</td>
<td>Kimlikul, Kokchetav, Kazakhstan</td>
<td>gneiss</td>
<td>6.54</td>
<td>diamond</td>
</tr>
<tr>
<td>MakBit</td>
<td>Grt</td>
<td>Makbit, Tajikistan</td>
<td>Grt-eclogite</td>
<td>6.87</td>
<td>coesite</td>
</tr>
</tbody>
</table>

See Dorozhinoetskaya et al. 2007 for sample description

Bindeman et al., 2013 in press
Oxygen isotopic values of diamond-bearing, exhumed UHP metamorphic rocks:
Mostly high-$\delta^{18}$O

Sample collection of Larissa Dobrzhinetskaya, UC Riverside

How long does it take?

10^6 (?) yrs

hot aftermath

SNOWBALL EARTH EPISODE

Climate model
(Pierrehumbert, 2002)

global mean surface temperature (°C)

Paleogeography from Powell et al. (2001)

750 Ma

223 243 263 283 303 323

global mean surface temperature (K)
Fig. A Retrogression of oxygen isotopic values in a typical corundum bearing assemblage as a function of cooling and differential closure using Fast Grain Boundary diffusion model of Eiler, Baumgartner, and Valley, (1993). Notice that even at slow cooling rate of 1 degree per million years corundum, garnet, hornblende, staurolite, and kyanite do not retrogress and preserve their original, peak metamorphic temperature of formation. Plagioclase, rutile, and biotite display retrogression of less than 0.7 permil. Sizes of minerals and their proportions are given in the table. At faster cooling rate even less retrogression is expected. Therefore, isotope heterogeneity observed within hand specimen (see Table A1 and Bindeman et al. 2010, Fig. 2) cannot be explained by differential retrogression and must reflect source variability and interaction with external fluids.
Extra Generic Snowball Earth
slides from SnowballEarth.org
Paleoproterozoic Glaciations

Hydrologic Cycle on Snowball Earth? None

LOW-LATITUDE MARGIN:

ICE SHEET

'SIKUSSAK'
permanent landfast ice

SEA GLACIER

TRADE WINDS

Macdonaldryggen Member
Vaalbara supercraton

Paleomag. (De Kock et al., 2009)

Meteorite Bore Member, Kungarra Fm (Pilbara)

Makganyene Fm (Kaapvaal)

Paleoproterozoic glacial deposits

original distribution in the Superia supercraton

reassembled in Nuna

Figure after Ernst & Bleeker 2008
Stratigraphic column of the Huronian Supergroup in Ontario, Canada (modified from Bekker et al., 2006: One OR Three Glaciations?}

**Paleoproterozoic units**
- Meteorite Bore: 05°
- Makganyene: 11°
- Gowganda: 03° (?)
- Sariolian: 07-27°

**Glacial paleolatitudes**

darker shade indicates more reliable paleomagnetic data
Field relations between different rock types: a) original Chupa gneiss; b) St-Pl pseudomorphs over large crystal of Ky at Khitostrov; c) rock with large Crn; d) St-Pl pseudomorphs over large crystal of Ky at Khitostrov; d) Corundum-bearing rock (pen is pointing to Crn), impregnated by plagioclazite at Khitostrov; e) large crystals of garnet in chloritic rock inside amphibolite at Mt. Dyadina.