Snowball or Slushball Earth Glaciation 2.4Ga? Resolving microanalytical evidence in subglacially hydrothermally-altered (down to -27.3‰ $\delta^{18}O$) rocks and coeval supergene materials

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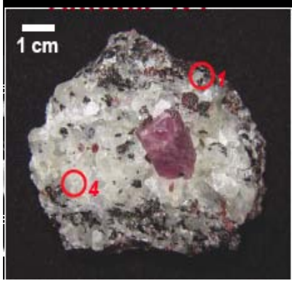
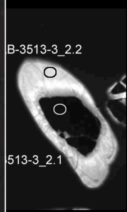
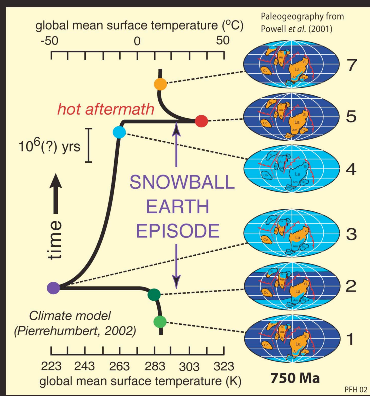
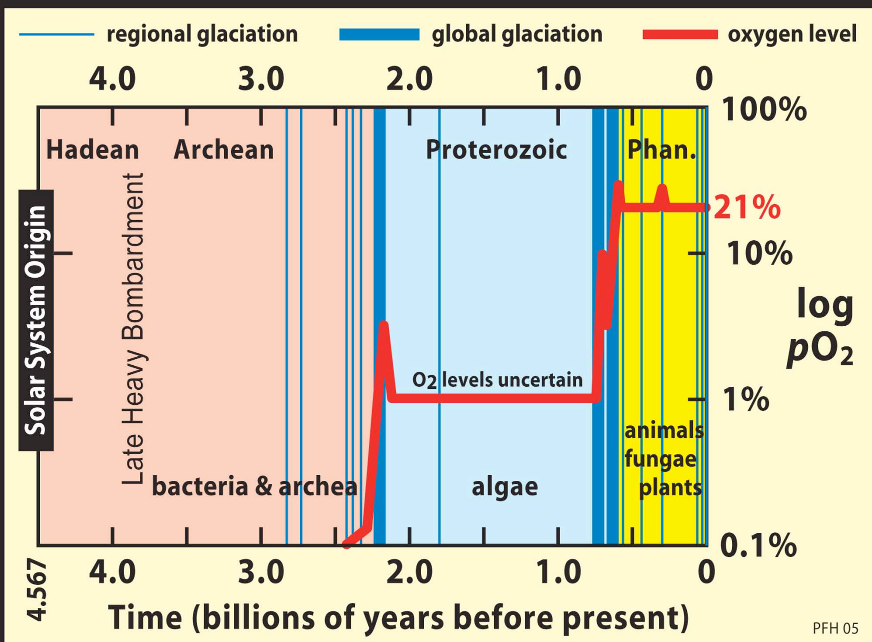
Thanks to: P. Hoffman (U Victoria),
Guan B, J Eiler (Caltech)
J Vazquez (USGS)
NSF grant EAR 108786

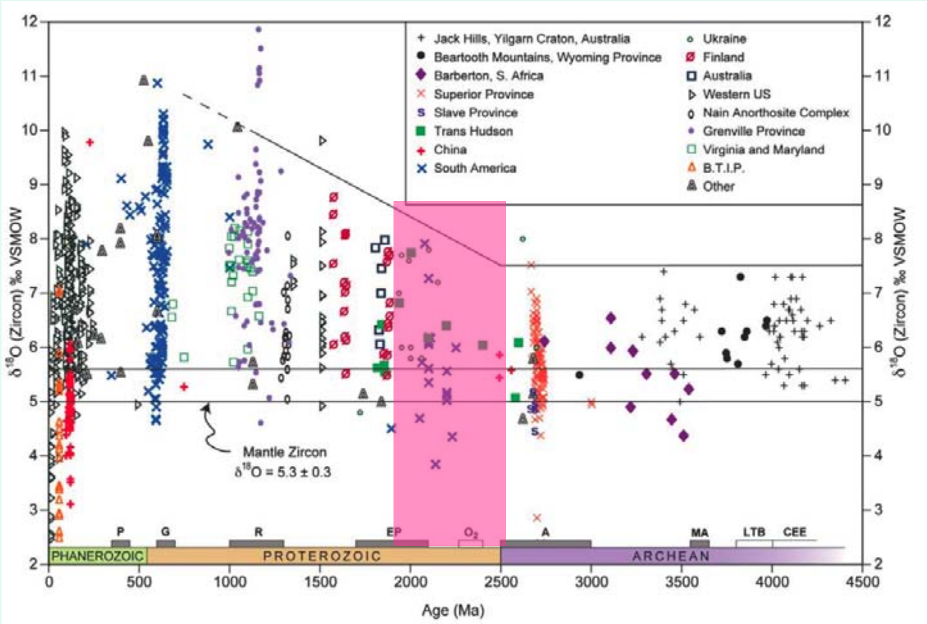






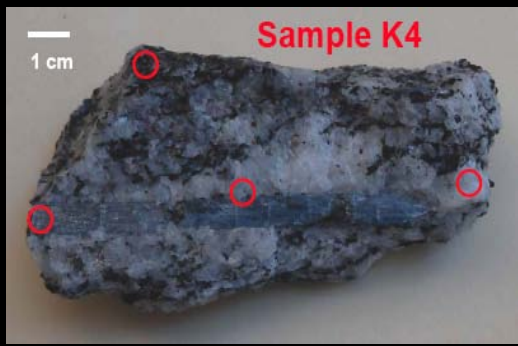


Snowballearth.org

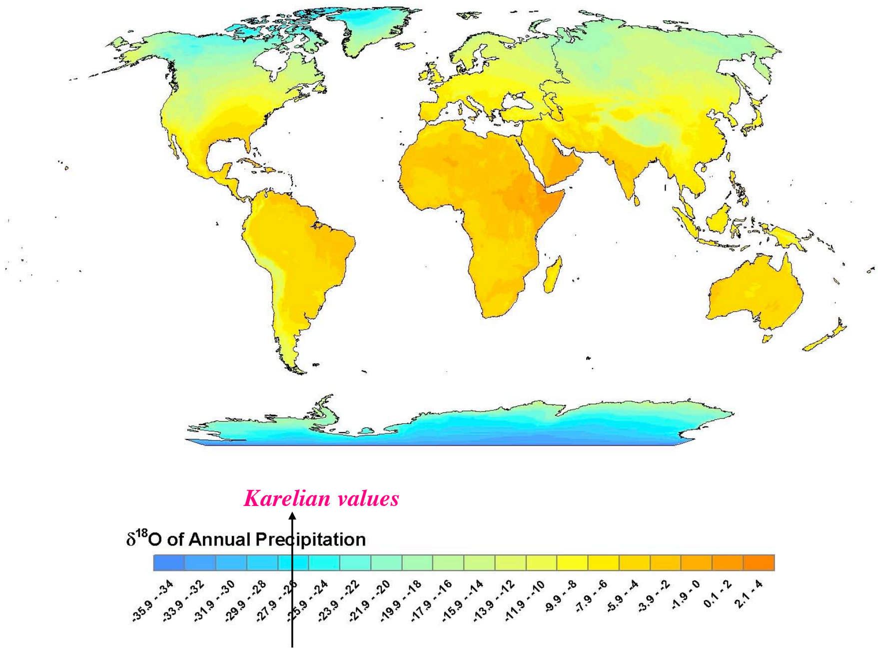


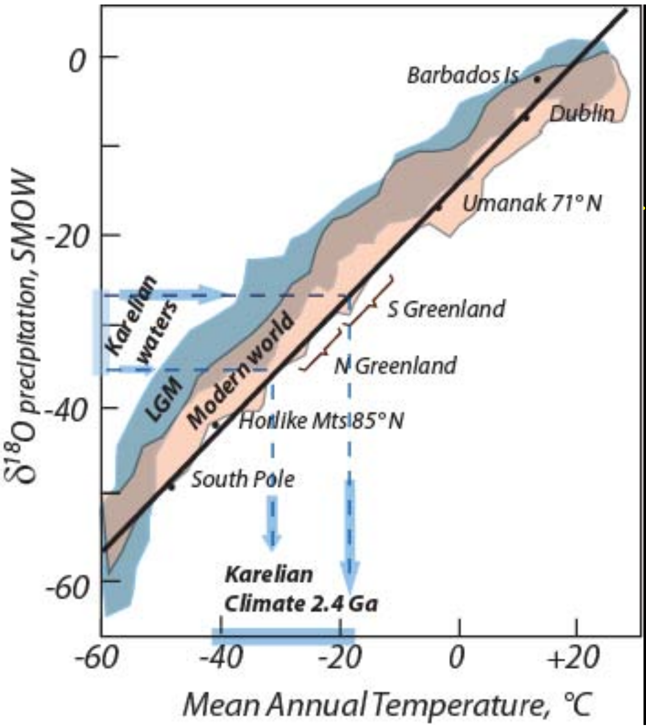
Valley et al., 2005

The world "record": 2.45Ga, -27.3‰ $\delta^{18}O$ metagabbro/gneisses from Karelia, Russia
δD= -235‰



Global Distribution of water isotopes www.waterisotopes.org

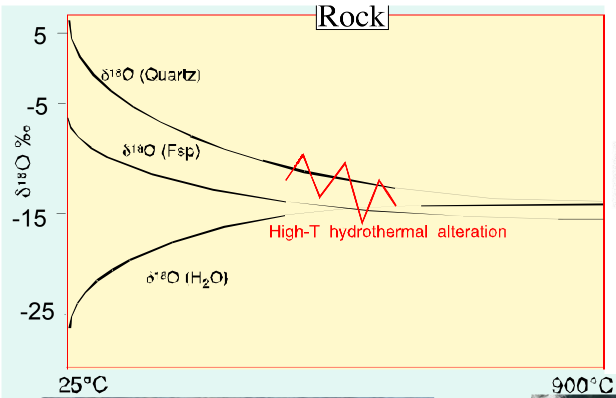


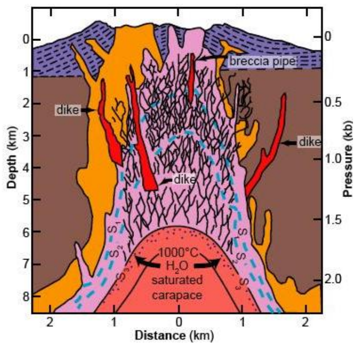


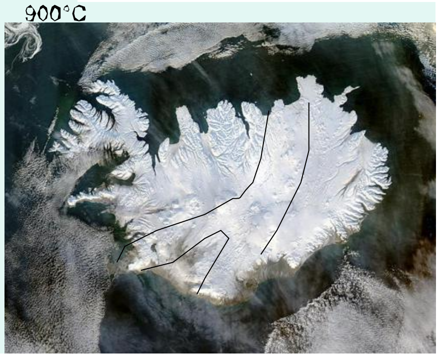
Comparison with Modern climates

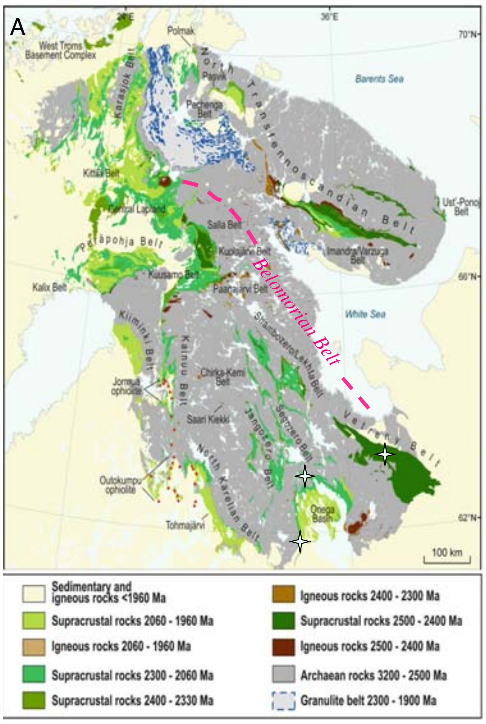
-25‰ and below

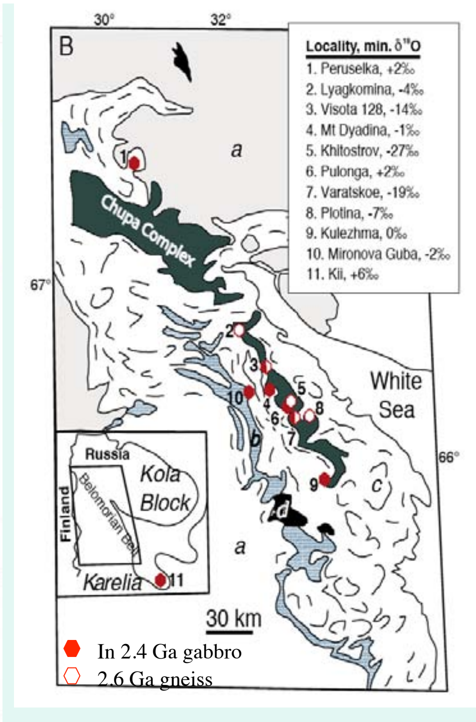
Greenland-like, -20°C to -35°C



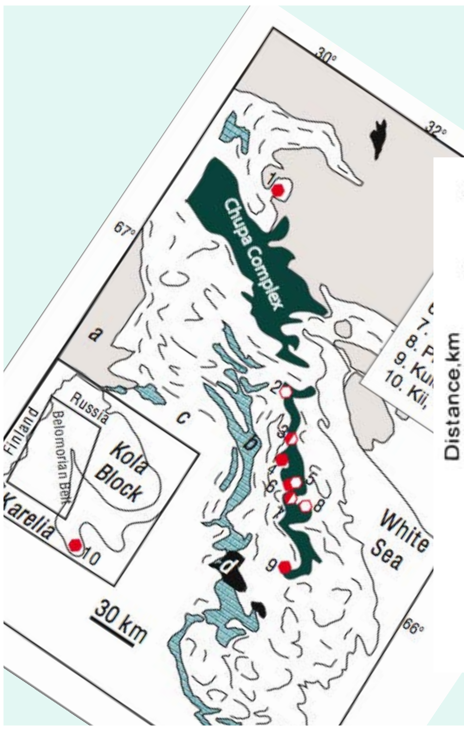


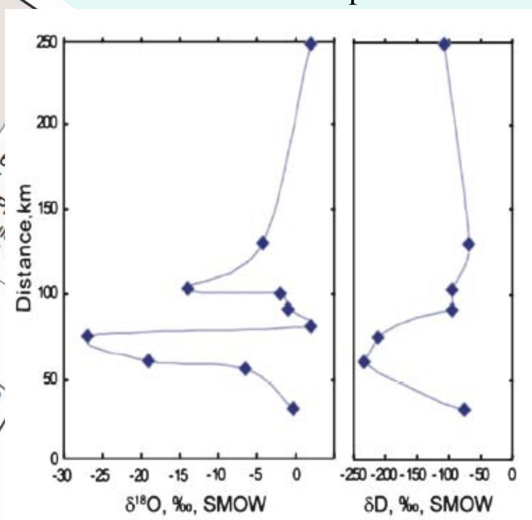






The lowest isotope values:

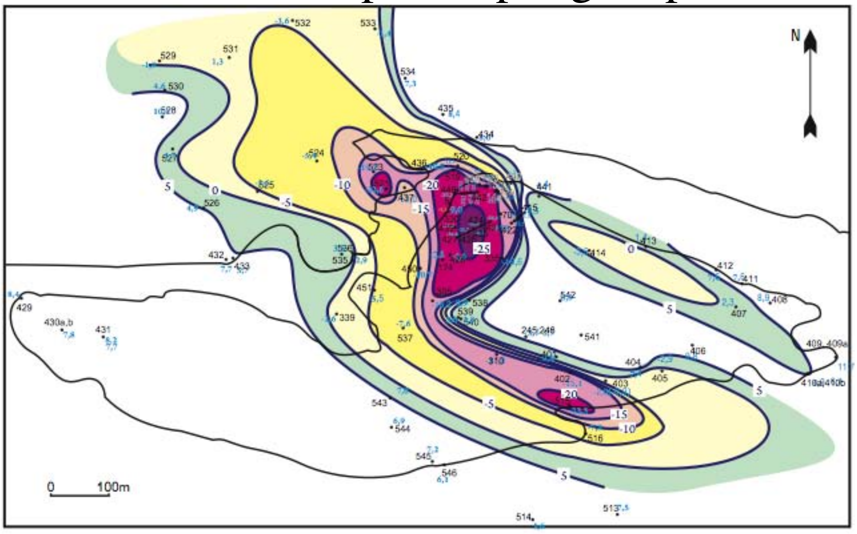




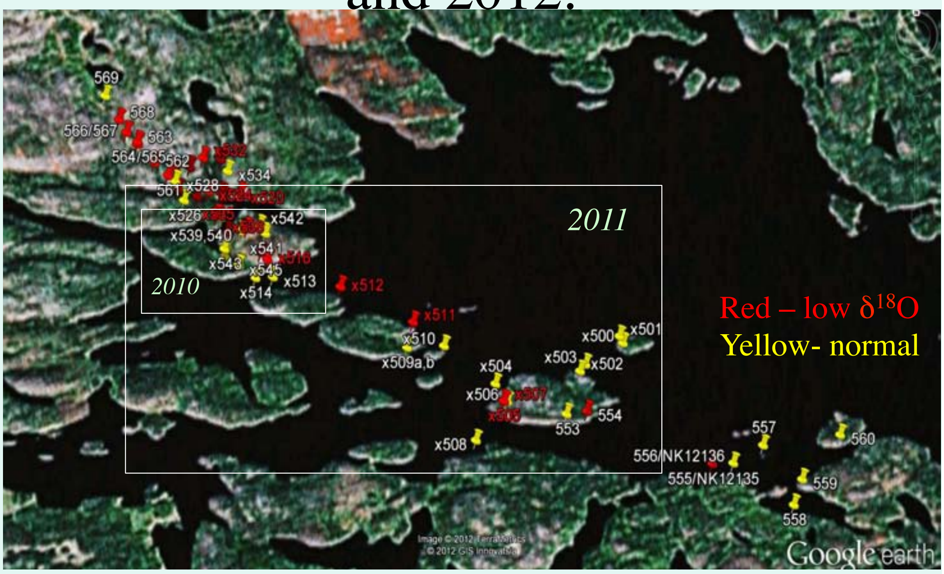

a
b
c
Grt-Bi
Ky-Grt-Bi
Ruby-Grt-Bi
N
Grt-gabbro
200 m


-26‰
-27.3‰

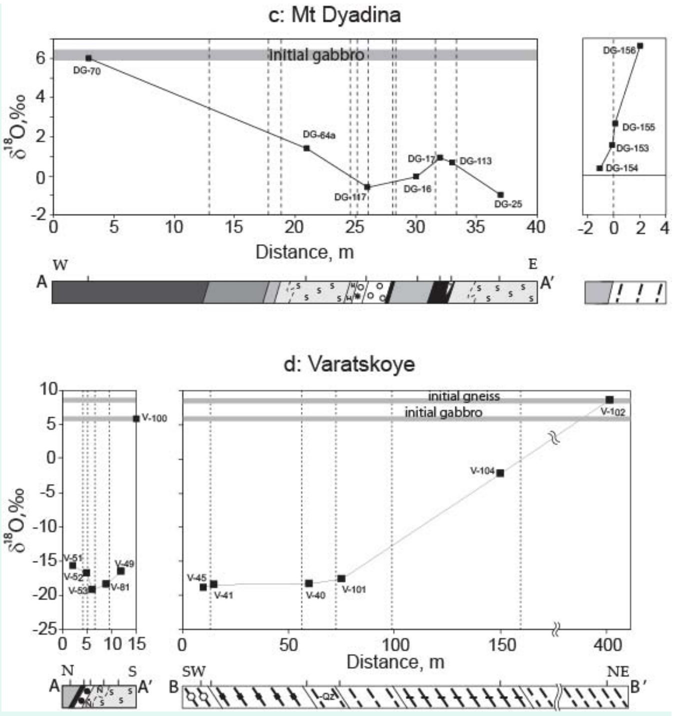
“Old” isotope sampling map 2011



and 2012:

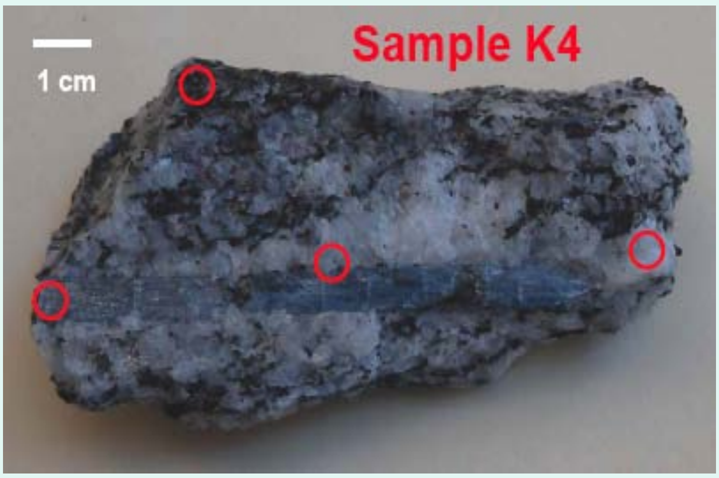


Isotope Profiles in other localities:

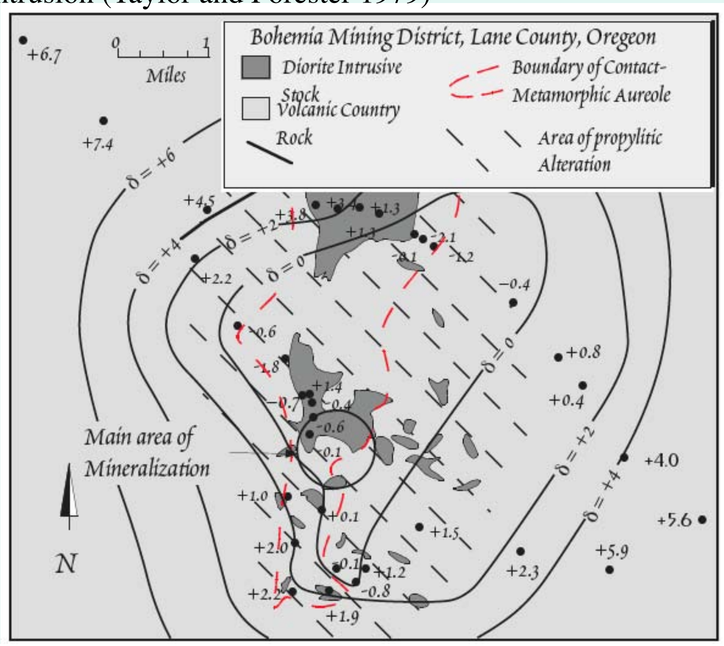


Bindeman and Serebryakov, EPSL, 2011

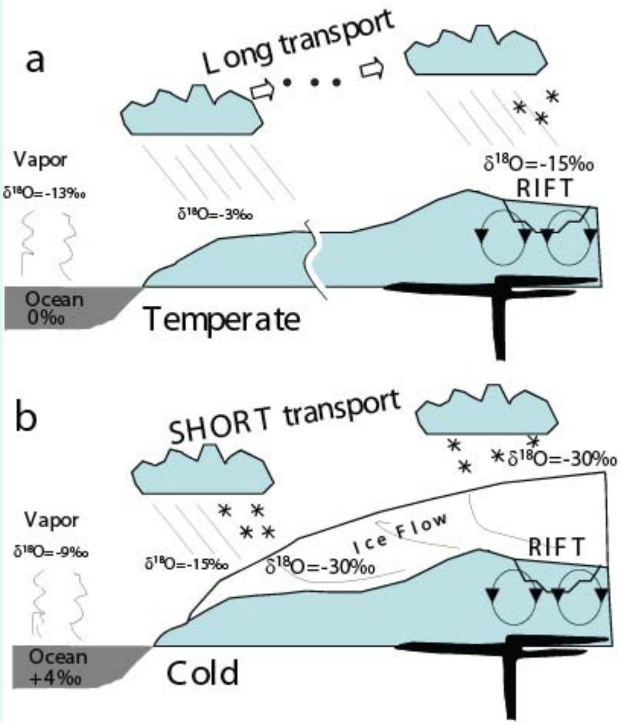
Equilibrium within crystal clusters, $\delta^{18}O$ heterogeneity on cm, m, 10 m scales



Bull's Eye patterns are very common in ore deposits (Taylor, 1973, 1974), in Skaergaard Intrusion (Taylor and Forester 1979)



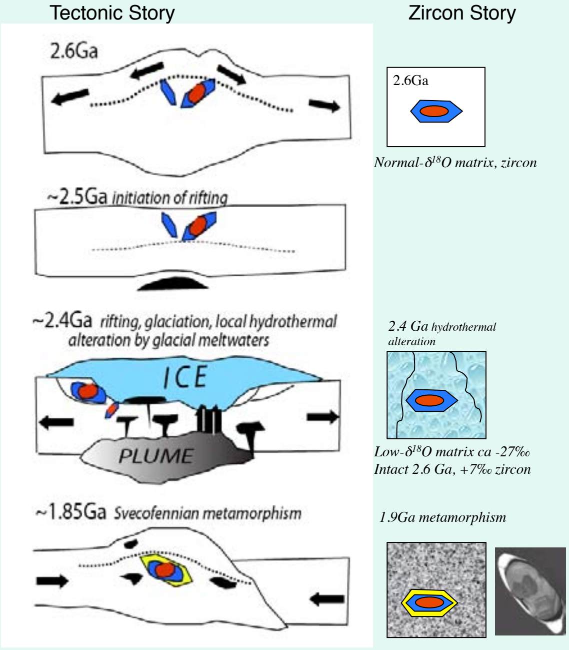
Explanation: Rifting under ice



Summary of field/geological observations

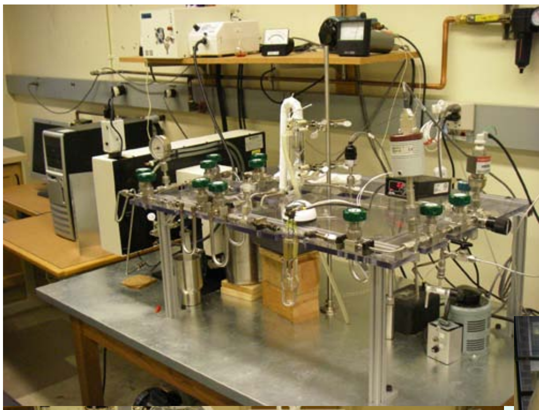
- 2.6 Ga Gneiss, 2.4 Ga mafic intrusions, 1.9 Ga metamorphism
- Depletions of $\delta^{18}O$ and δD are in or near contacts with 2.4-2.45 Ga mafic intrusions
- These intrusions are related to rifting
- Depletions of $\delta^{18}O$ and δD form "bull's eye" concentric pattern, characteristic of modern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

Tectonic Story | Zircon Story

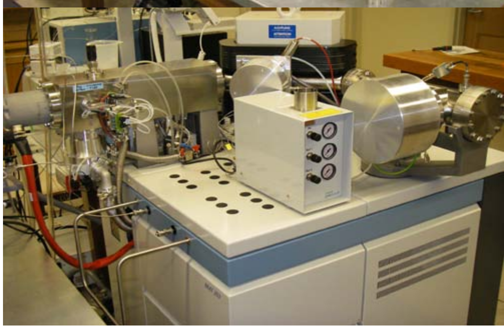


Low-$\delta^{18}O$ matrix, 1.9Ga, -27‰ rims

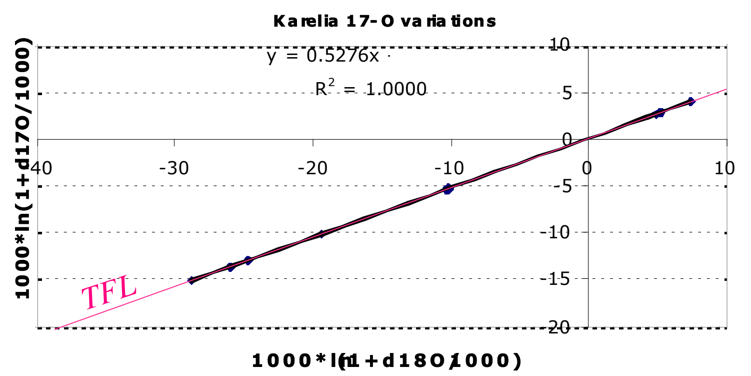
Bindeman et al. 2013 in press



Methods

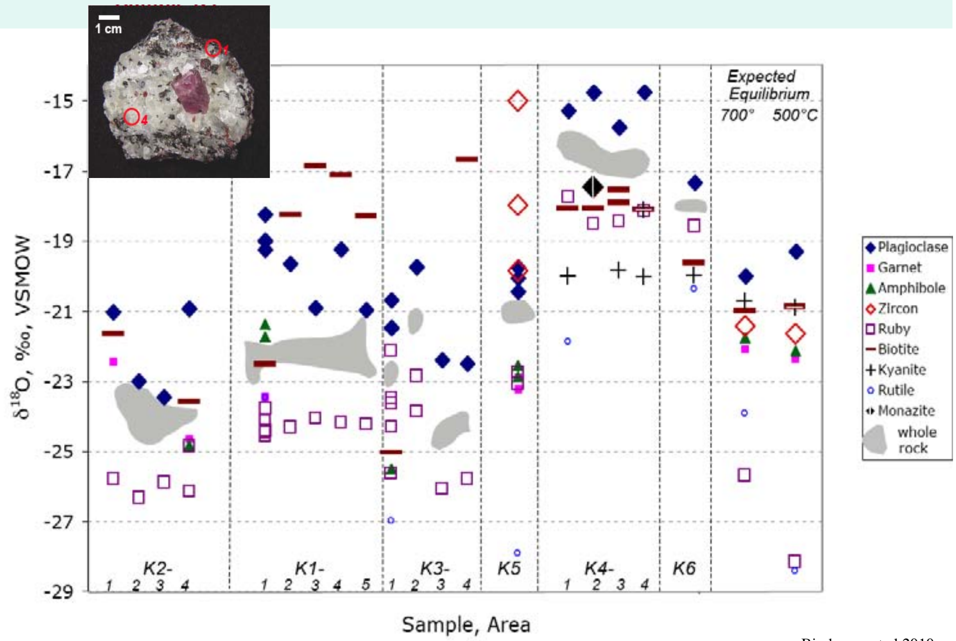


Karelian samples firmly belong to the
"Equilubrium" terrestrial $^{18}O/^{16}O$ -$^{17}O/^{16}O$ fractionation line



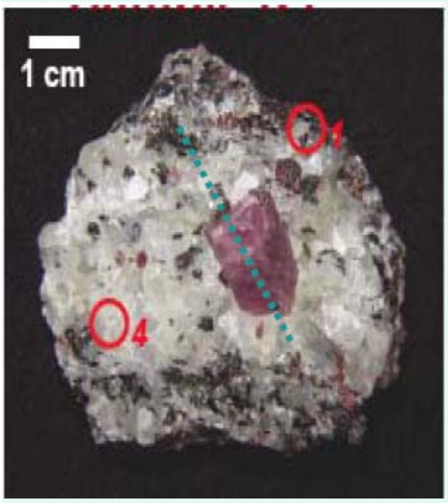
Cometary Impact? No: $\Delta^{17}O = 0‰$

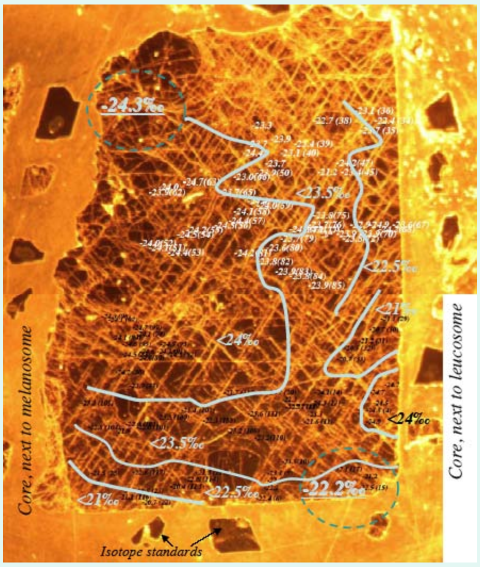
Analysis of individual minerals in crystal clusters



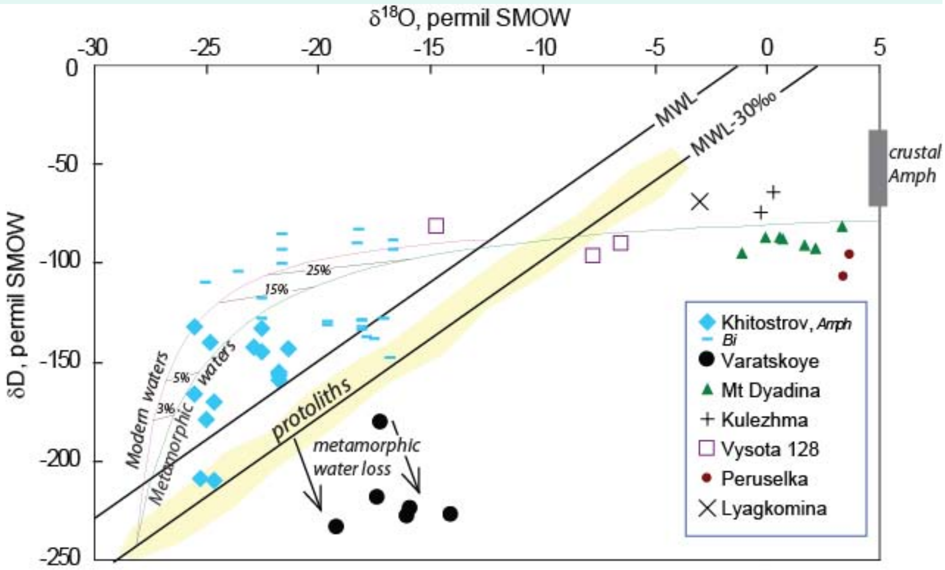
Bindeman et al 2010

Isotope Mapping of a single corundum crystal

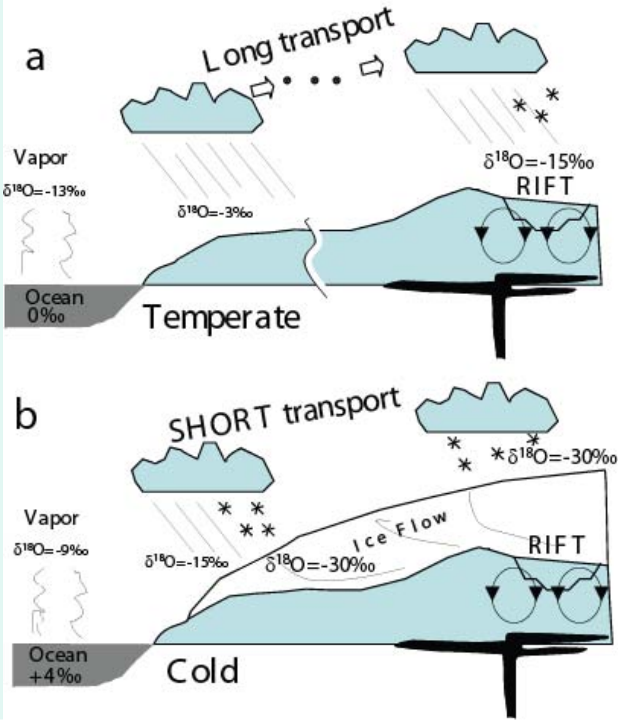




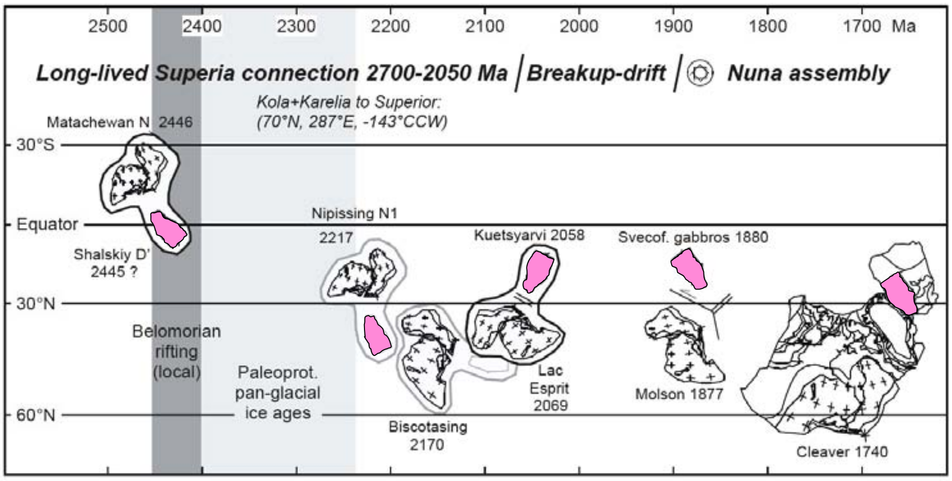
Hydrogen Isotopes Insights - record low δD of -235‰



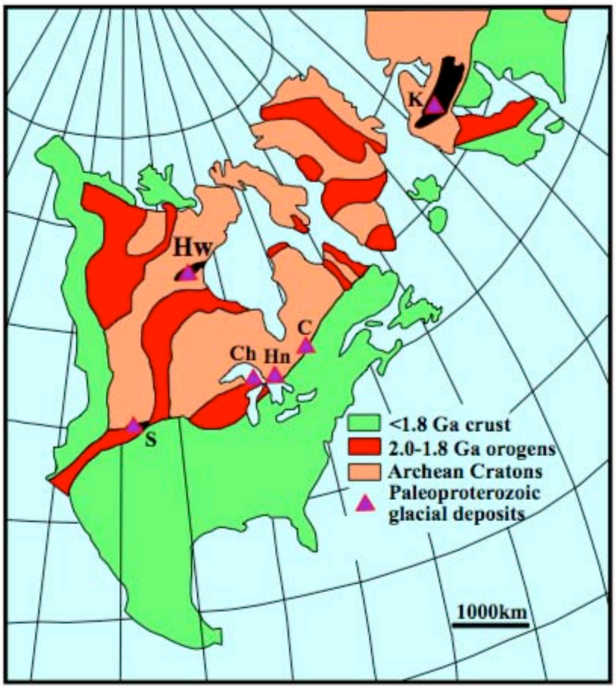
2.4Ga Subglacial Rifting



Karelia in the Paleoproterozoic:



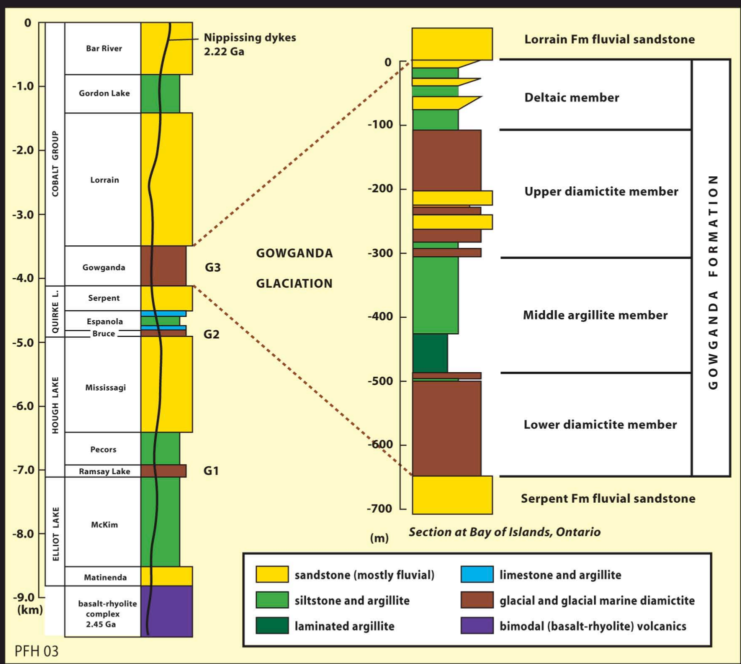
Bindeman Schmit Evans 2010



Paleoprot. glacial deposits

after assembly in the Nuna supercontinent

Figure from Young, 2004



Gowganda Formation:

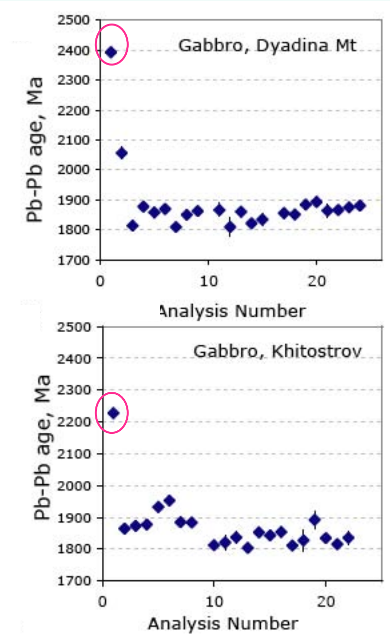
Youngest of three units of glacial or periglacial origin in the Huronian succession, north shore Lake Huron, Canada

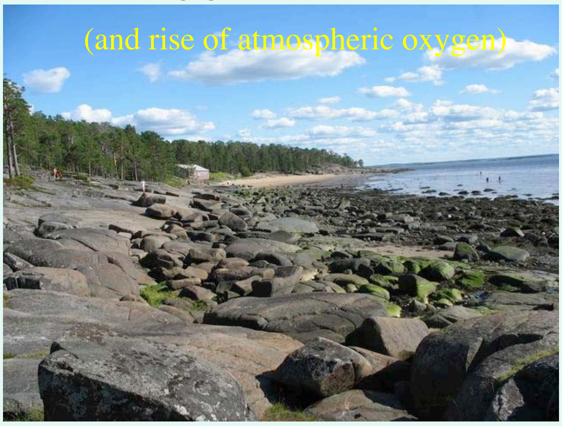
Atmospheric oxygen first rose between Matinenda & Lorrain time, according to paleosol data and mass-independent sulfur isotope data.

Using **zircon** to resolve the timing of $\delta^{18}O$ depletion

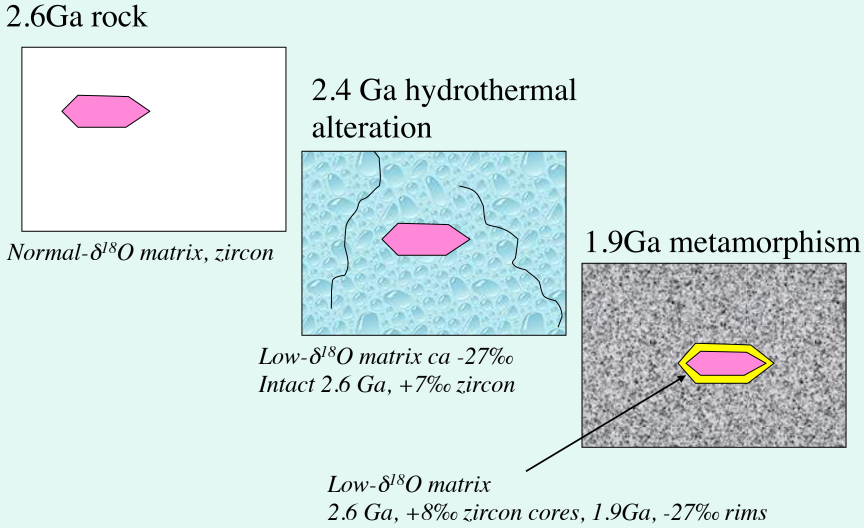
- Perfect mineral to retain U-Pb age and $\delta^{18}O$ values
- Requires high T (ca>650°C) to recrystallize or exchange O
- So it only records magmatic or metamorphic episodes
- Untouched by hydrothermal alteration

Dating synglacial intrusions = Dating glaciations

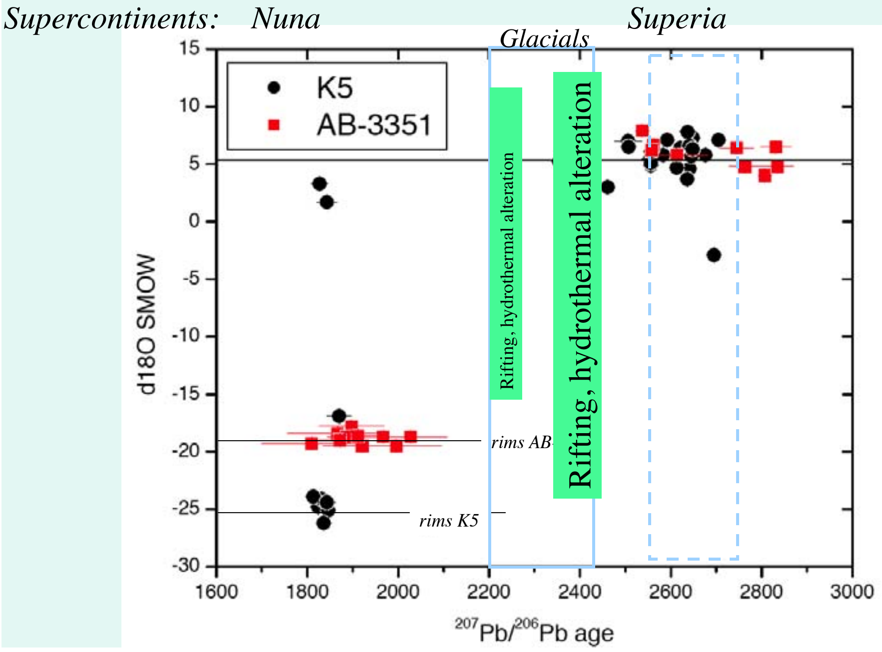


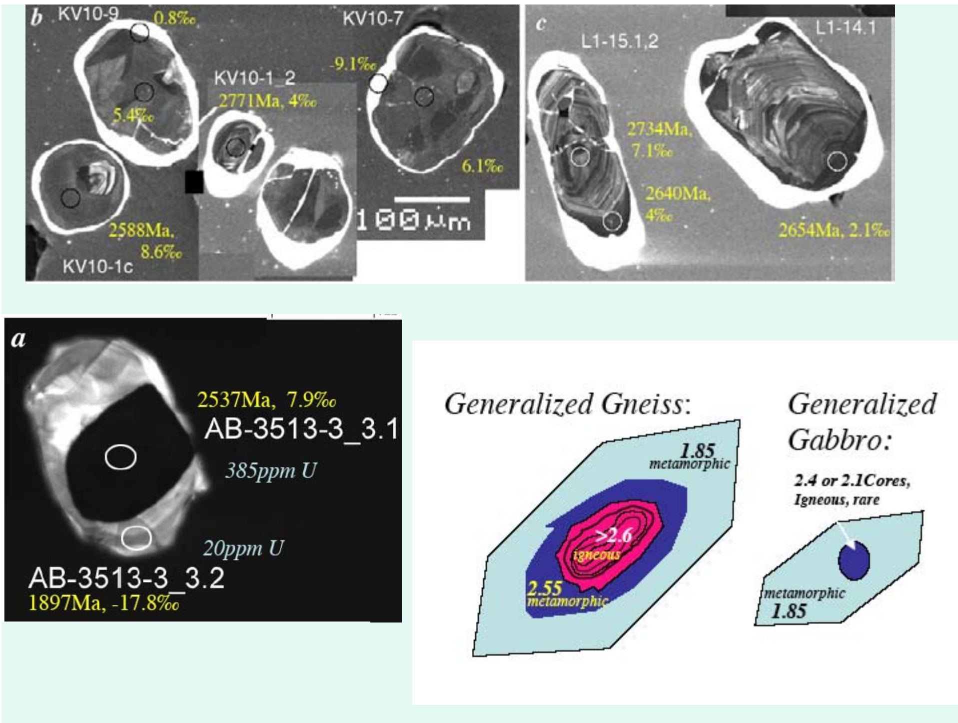


Zircon Story:

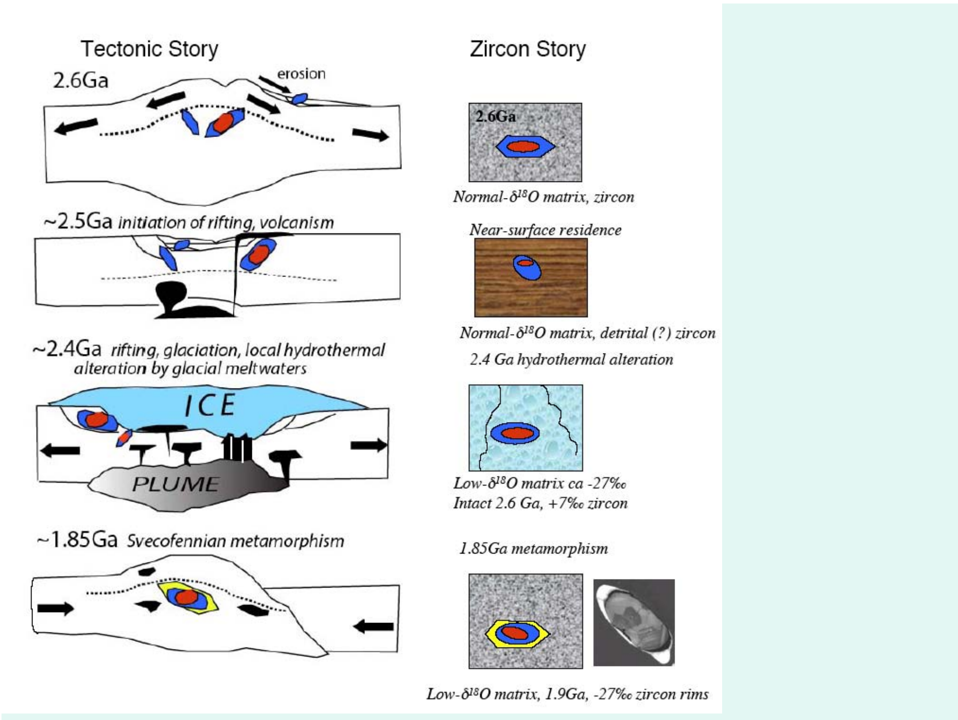


When did the $\delta^{18}O$ depletion happen?



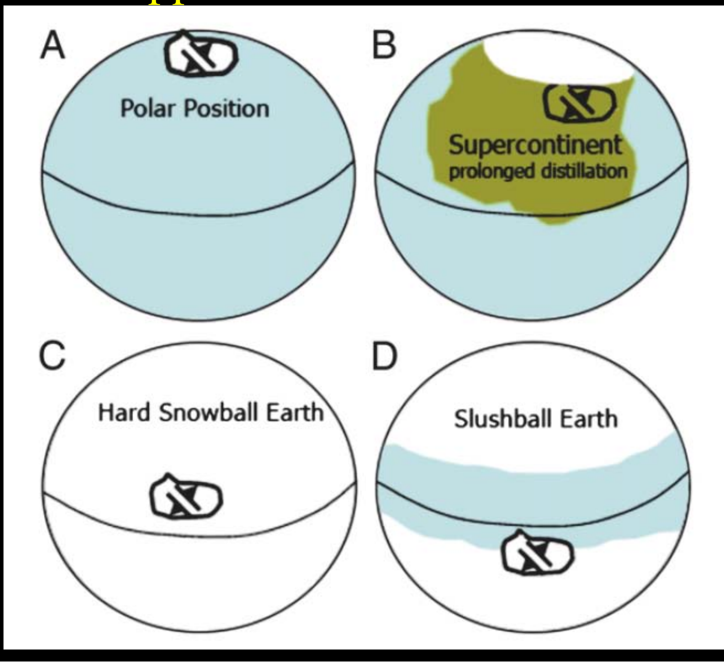


b KV10-9 0.8‰
5.4‰
KV10-1_2
2771Ma, 4‰
KV10-7
-9.1‰
6.1‰
2588Ma, 8.6‰
KV10-1c
100 µm
c L1-15.1,2
2734Ma, 7.1‰
2640Ma, 4‰
L1-14.1
2654Ma, 2.1‰
a
2537Ma, 7.9‰
AB-3513-3_3.1
385ppm U
20ppm U
AB-3513-3_3.2
1897Ma, -17.8‰
Generalized Gneiss:
1.85 metamorphic
>2.6 igneous
2.55 metamorphic
Generalized Gabbro:
2.4 or 2.1Cores, Igneous, rare
metamorphic 1.85

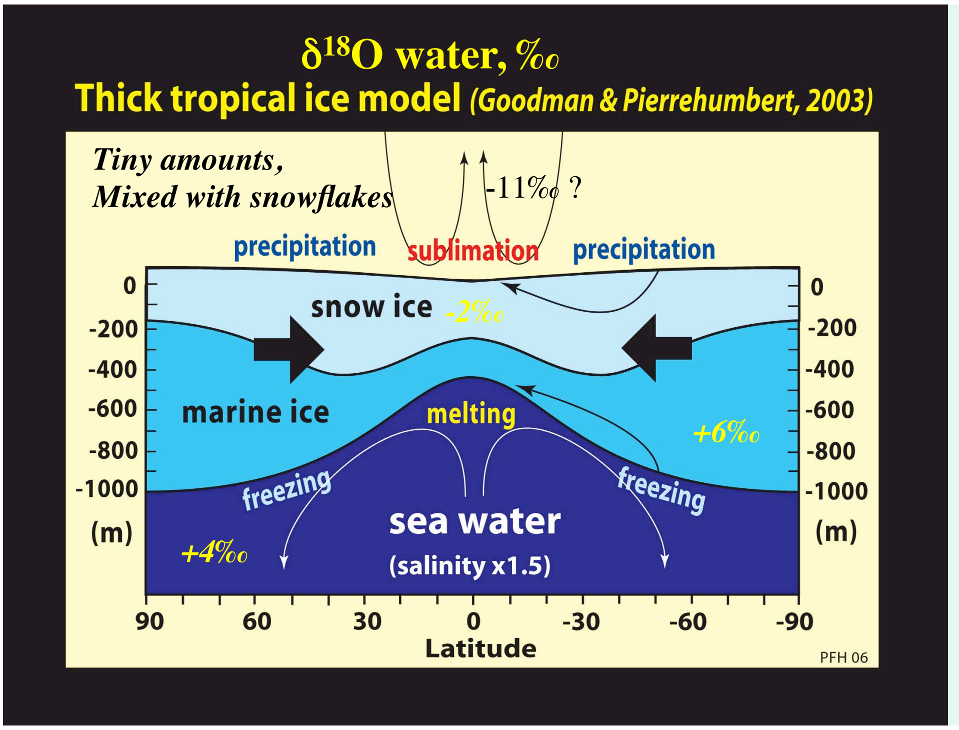


Tectonic Story
2.6Ga
erosion
~2.5Ga initiation of rifting, volcanism
~2.4Ga rifting, glaciation, local hydrothermal alteration by glacial meltwaters
ICE
PLUME
~1.85Ga Svecofennian metamorphism
Zircon Story
2.6Ga
Normal-δ18O matrix, zircon
Near-surface residence
Normal-δ18O matrix, detrital (?) zircon
2.4 Ga hydrothermal alteration
Low-δ18O matrix ca -27‰
Intact 2.6 Ga, +7‰ zircon
1.85Ga metamorphism
Low-δ18O matrix, 1.9Ga, -27‰ zircon rims

How did it happen?

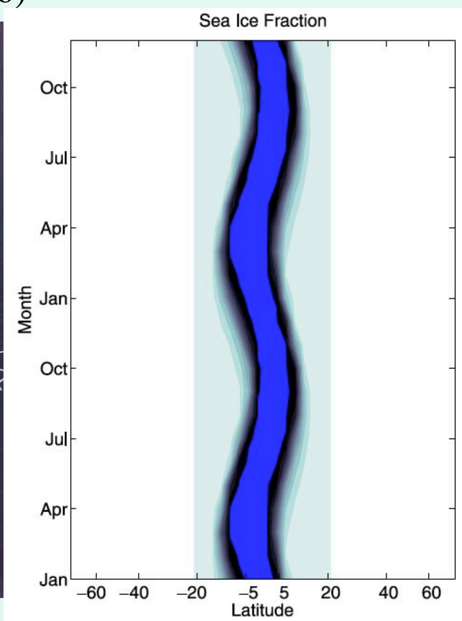


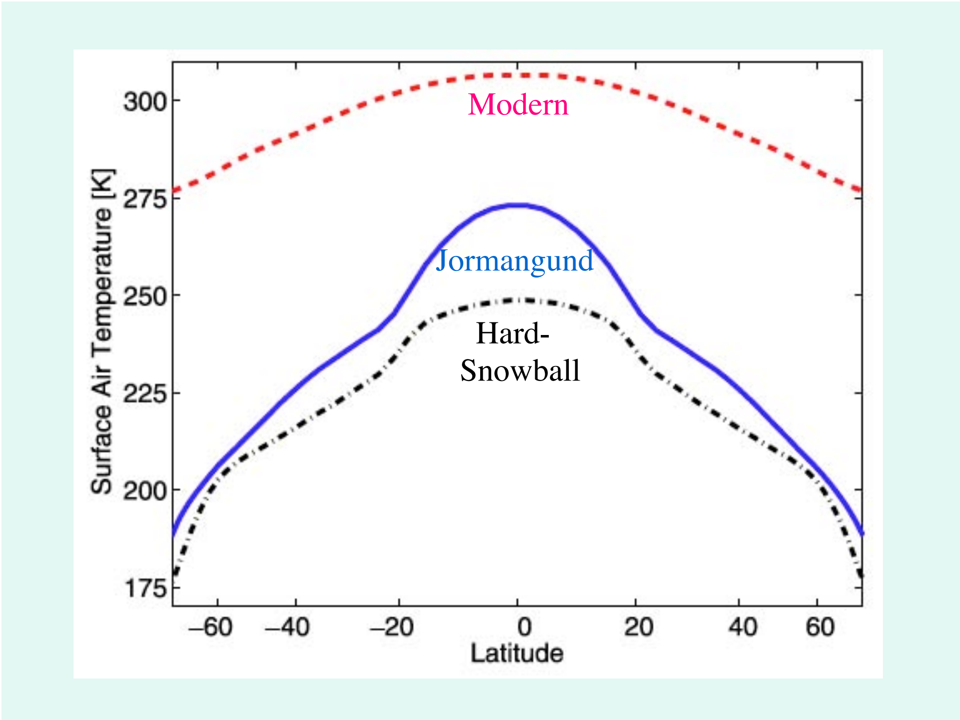
Do Karelian rocks record Snowball or "Slushball Earth"?



Jormangund Climate State (2011):

Dorian Abbot (U Chicago)





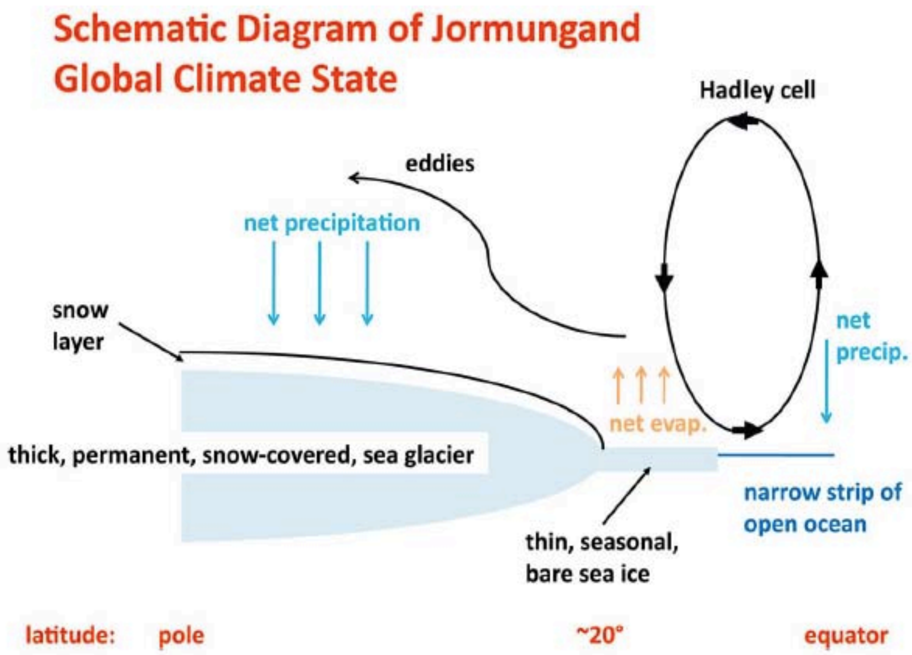
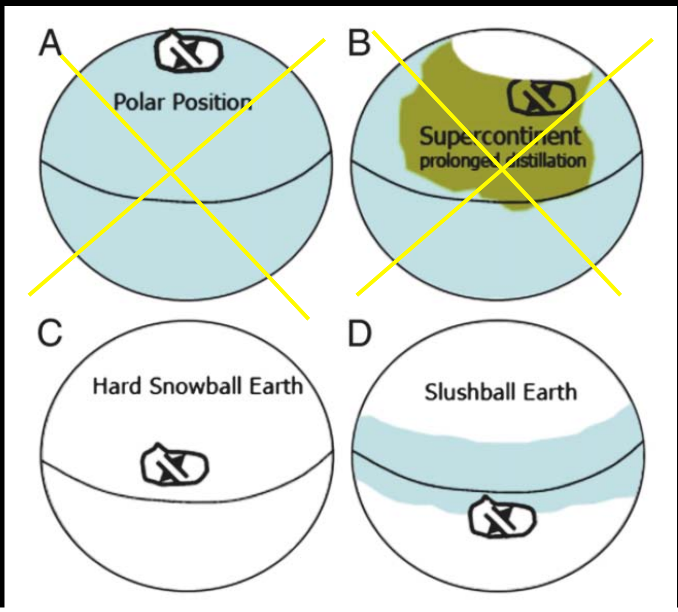
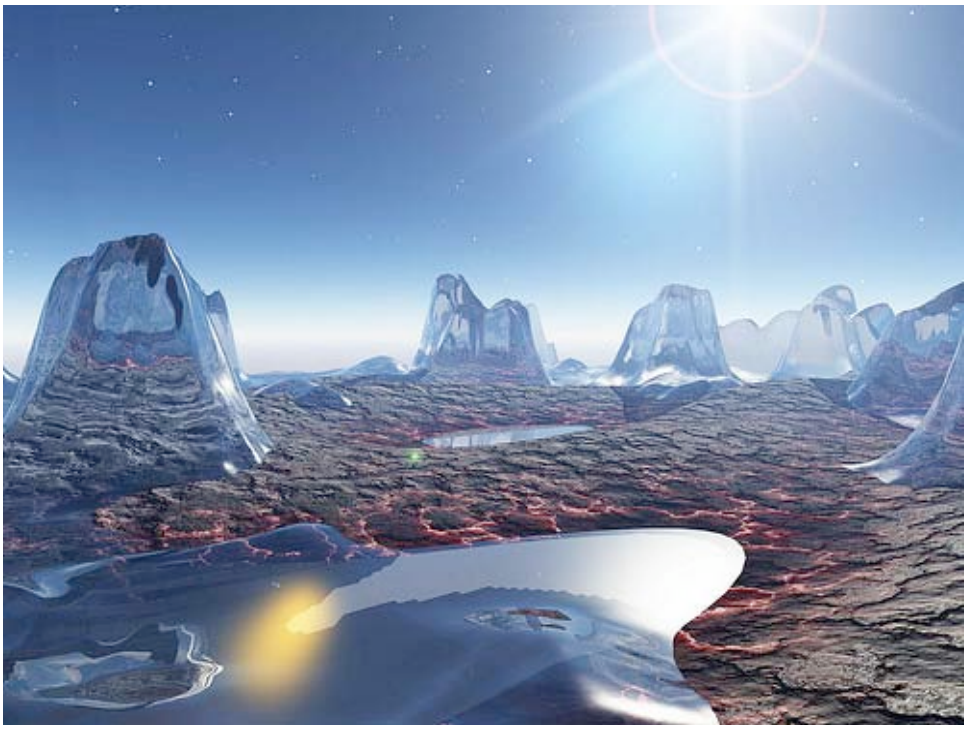


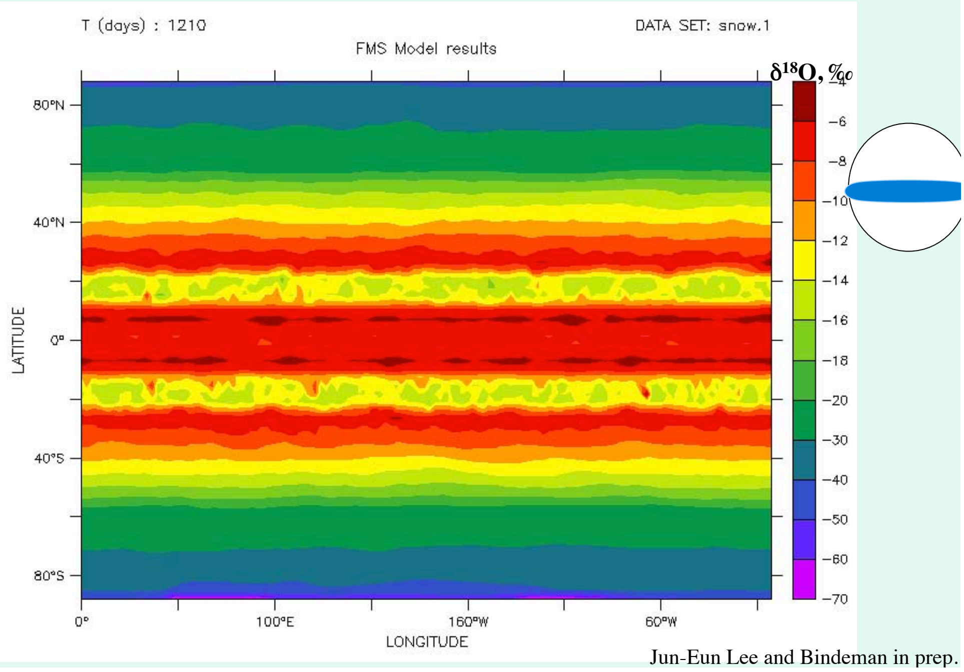
Figure 8. Schematic diagram of the Jormungand global climate state.

Slush-Ball vs Hard Snow Ball Earth climate models and implications



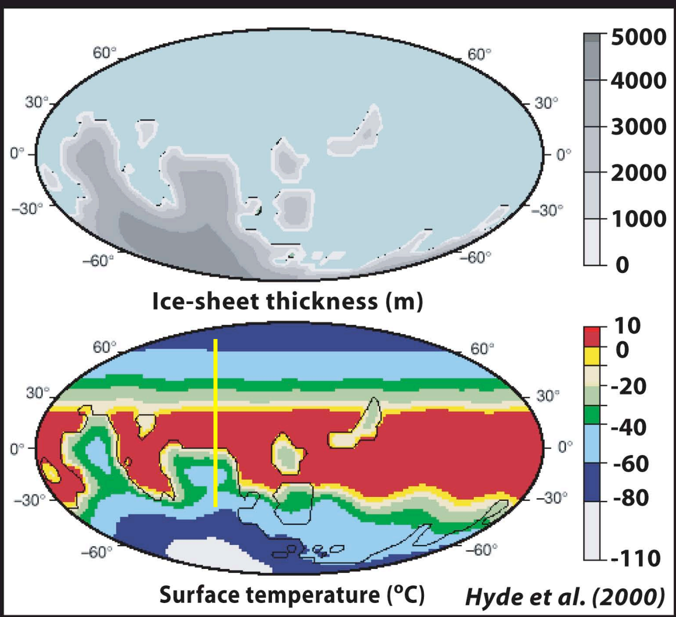


$^{18}O/^{16}O$ in Global Circulation Model of Slushball Earth

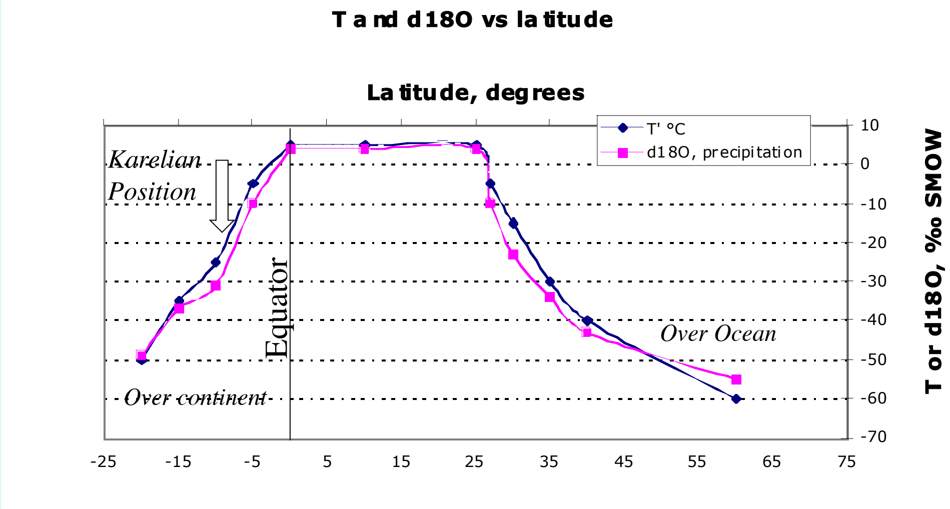


Jun-Eun Lee and Bindeman in prep.

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 pCO_2 was self-adjusted by silicate weathering feedback.



Hyde et al. (2000)

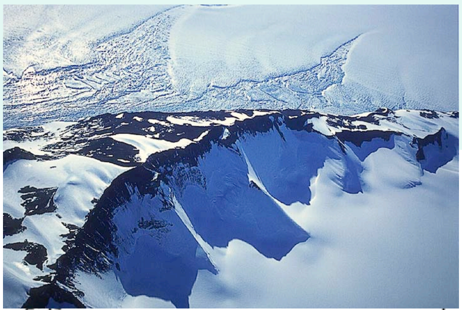


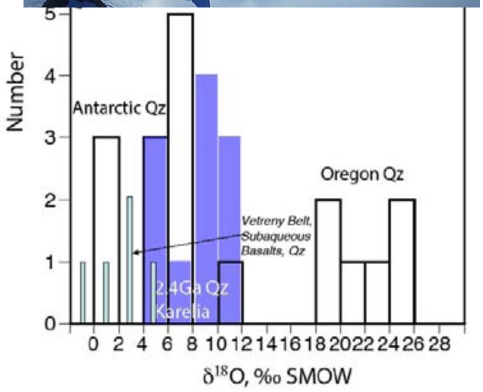
Conclusions and what's next?

- Kareilan Gneiss record depletion during ~2.4 "Slushball Earth" or Jurmangand episode (the first of the 3) to allow for effective vapor $\delta^{18}O$, δD 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 $\delta^{18}O_{water}$:

- 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*

Pergamon
Geochimica et Cosmochimica Acta, Vol. 62, No. 19/20, pp. 3307–3321, 1998
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PII S0016-7037(98)00239-7

The Qinglongshan oxygen and hydrogen isotope anomaly near Donghai in Jiangsu Province, China

Douglas Rumble,*[1] and T.-F. Yui[2]
[1]Geophysical Laboratory, 5251 Broad Branch Road, Washington, D.C. 20015, USA
[2]Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan

J. metamorphic Geol., 2003, 21, 579–587

Low $\delta^{18}O$ eclogites from the Kokchetav massif, norther.. Kazakhstan

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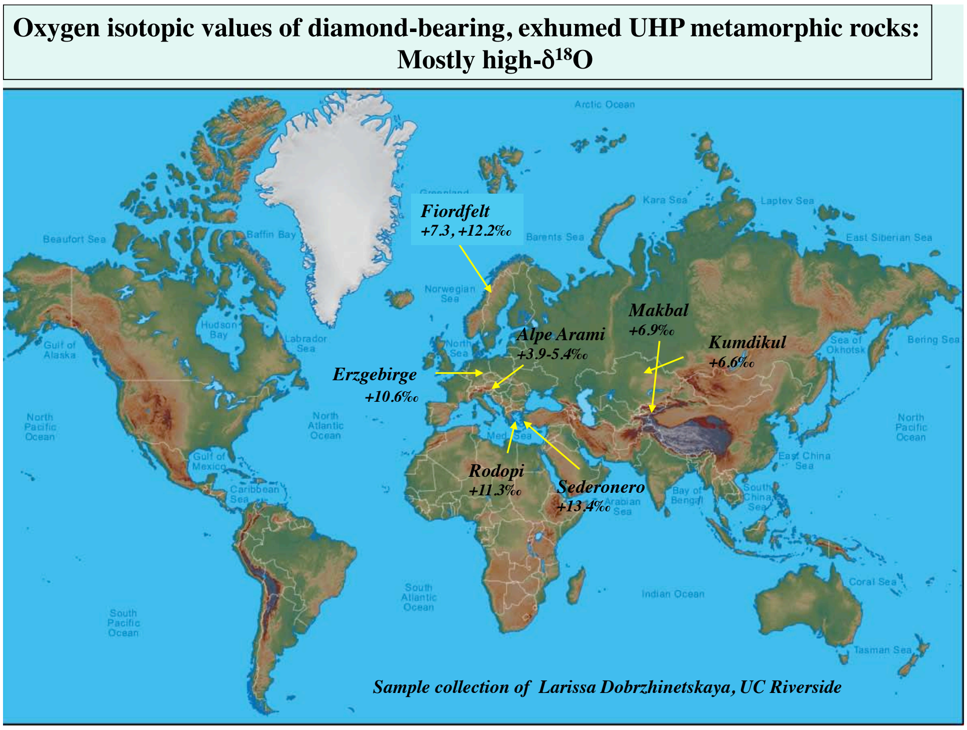
[2]Geophysical Laboratory, Carnegie Institution of Washington, 5251 Broad Branch Rd., NW, Washington, DC, 20015–1305, USA
[3]Department of Geological and Environmental Sciences, Stanford University, Stanford, CA, 94305–2115, USA
[4]Department of Geological Sciences, University of South Carolina, Columbia, SC, 29208, USA

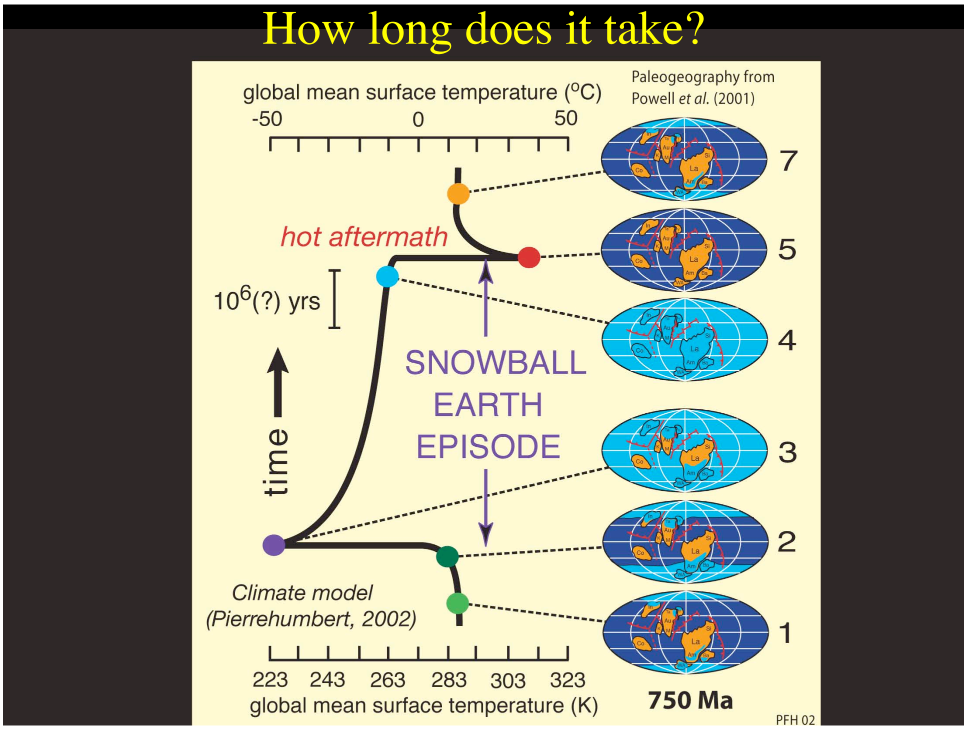
Table 2. Oxygen isotope analysis of ultra-high-pressure crustal rocks with diamonds and coesites

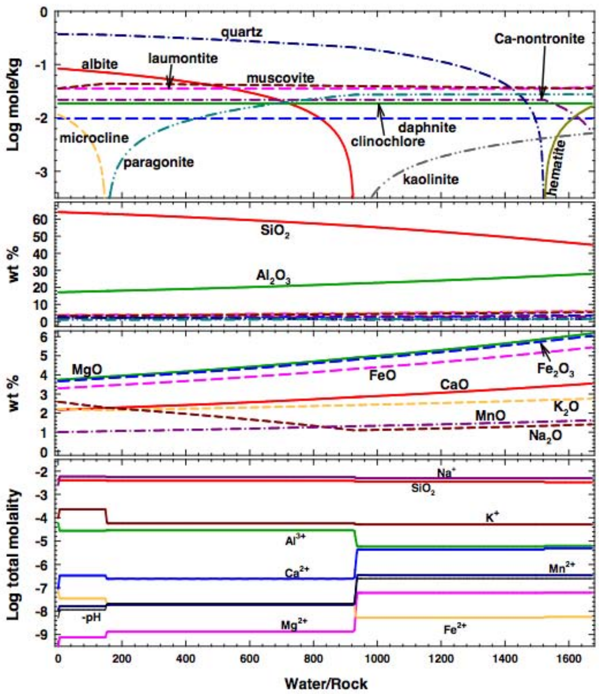
Sample	Mineral	Locality	Rock lithology	δ18O, ‰ SMOW	UHP minerals
6-AA-96	Grt	Alpe Arami, Italy	Grt peridotite	5.39	diamonds, 300km pressure
7-AA96-1	Grt	Alpe Arami, Italy	Eclogite	3.93	diamonds, 300km pressure
ED05	Grt	Erzgerbirge, Saxonia, Germany	Grt-Bi gneiss	10.58	diamond
20/1-93	Grt	Fiordfeft, Norway	Grt-Bi-Ky gneiss	12.18	diamond
20-1/93	Grt	Fiordfeft, Norway	Grt-Bi-Ky gneiss	7.29	diamonds
MP-1	Qz	Rodopi, Greece	Grt-Bi-gneiss	11.32	diamond
126	Qz	Sederonero, Greece	Grt-Bi-gneiss	13.41	diamond
K-210	Zircon	Kimdikul, Kokchetav, Kazakhstan	gneiss	6.54	diamond
MakBal	Grt	Makbal, Tajikistan	Grt-eclogite	6.87	coesite

See Dorbzhinetskaya et al. 2007 for sample description

Bindeman et al., 2013 in press


Oxygen isotopic values of diamond-bearing, exhumed UHP metamorphic rocks: Mostly high-δ18O
Fiordfelt
+7.3, +12.2‰
Alpe Arami
+3.9-5.4‰
Makbal
+6.9‰
Kumdikul
+6.6‰
Erzgebirge
+10.6‰
Rodopi
+11.3‰
Sederonero
+13.4‰
Sample collection of Larissa Dobrzhinetskaya, UC Riverside

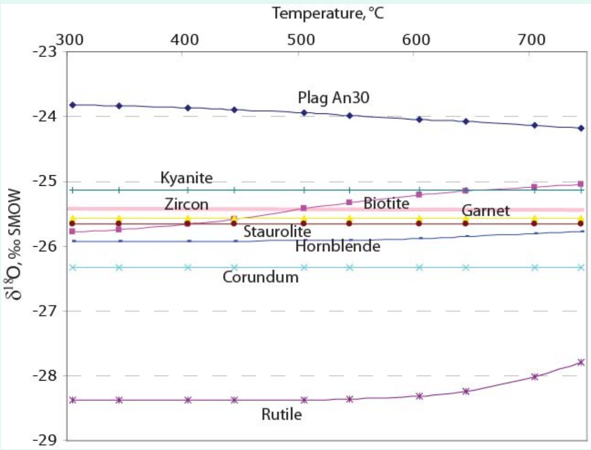

How long does it take?
global mean surface temperature (°C)
-50
0
50
Paleogeography from
Powell et al. (2001)
hot aftermath
10^6(?) yrs
time
SNOWBALL
EARTH
EPISODE
Climate model
(Pierrehumbert, 2002)
7
5
4
3
2
1
223
243
263
283
303
323
global mean surface temperature (K)
750 Ma
PFH 02



Modeling Chemical change to make high-Al lithology

Dissolution in 200°C fresh water

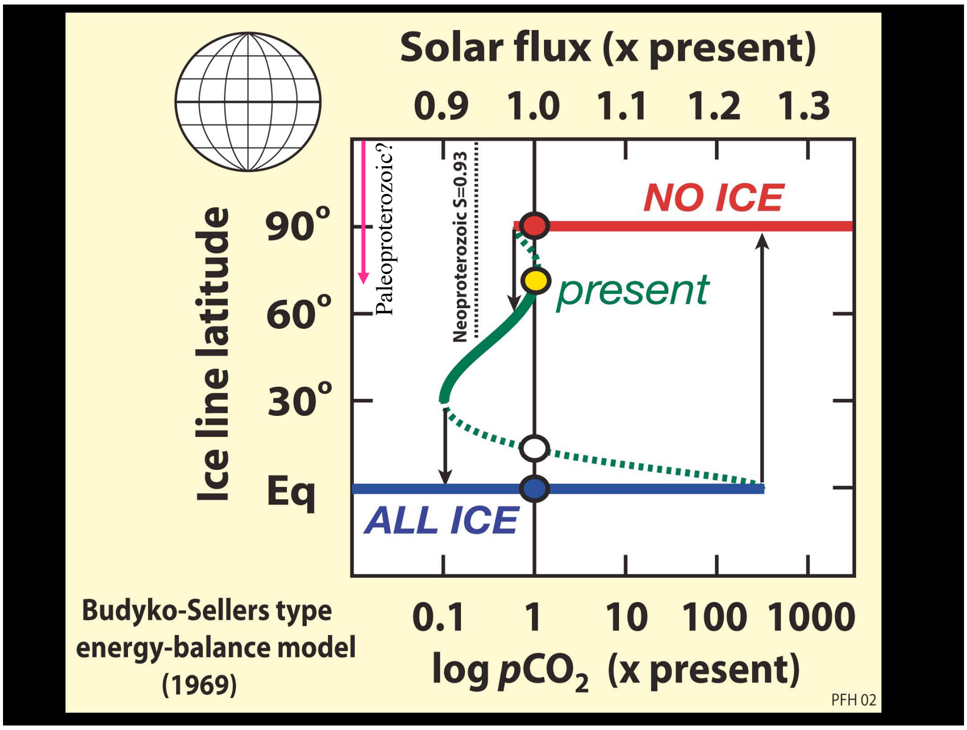
Reed et al. Chiller Program



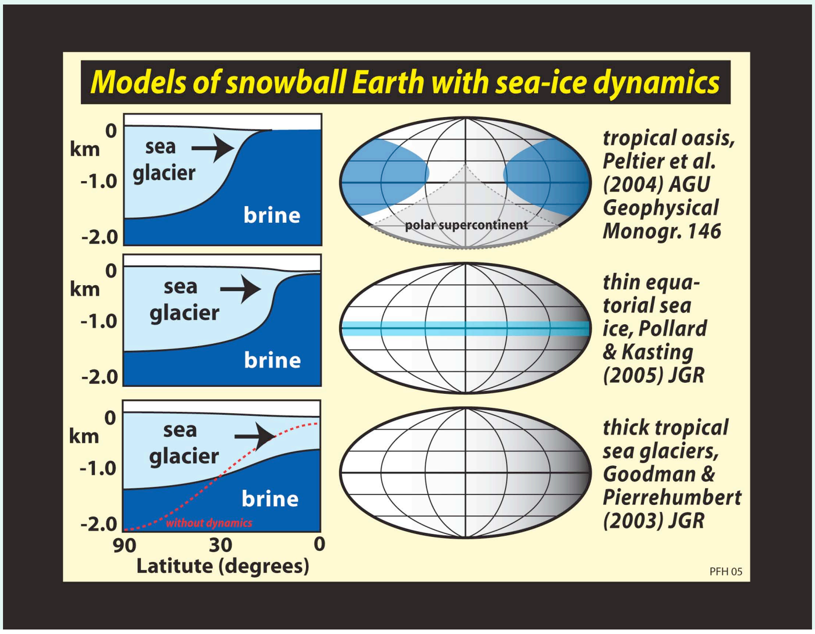
COOLING:	1 degree C per million years	
Minerals	Size, mm	Proportion
Plag An30	2	0.44
Hornblende	2.5	0.3
Biotite	2.5	0.15
Garnet	2	0.05
Corundum	2.5	0.02
Rutile	0.1	0.01
Staurolite	2	0.02
Kyanite	1.5	0.01

Fig. A Retrogression of oxygen isotopic values in a typical corundum bearing assemblage as a function of cooling and d ifferential 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.

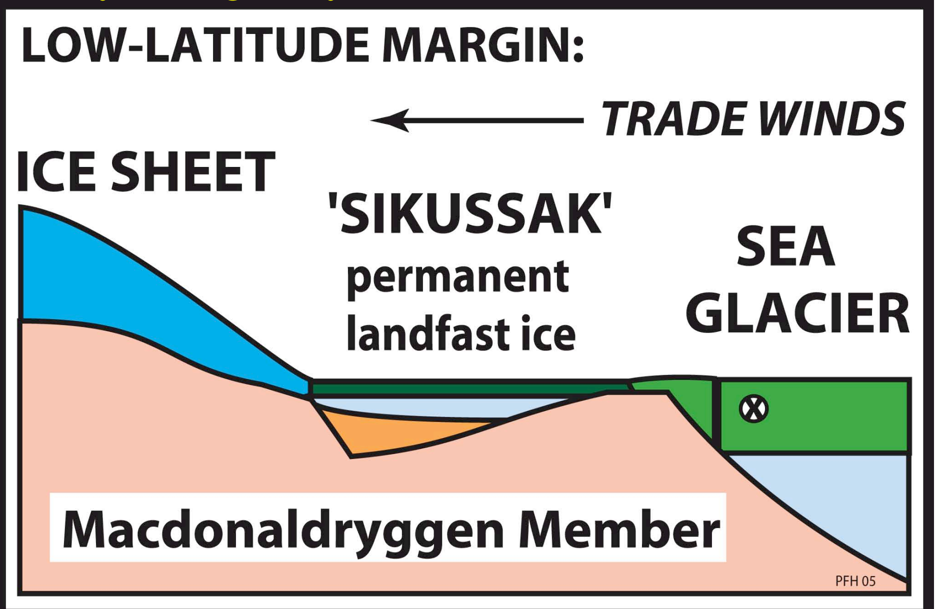
Extra Generic Snowballearth slides from Snowballearth.org



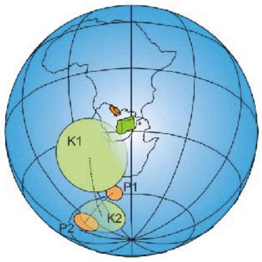
Paleoproterozoic Glaciations

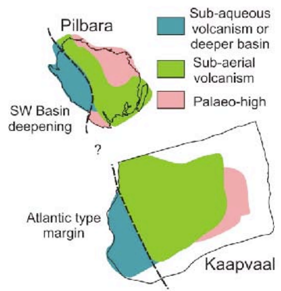


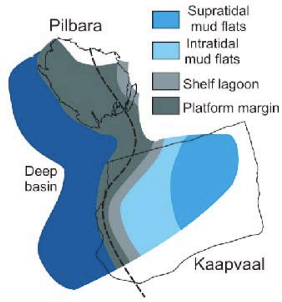
Hydrologic Cycle on Snowball Earth? None



Vaalbara supercraton



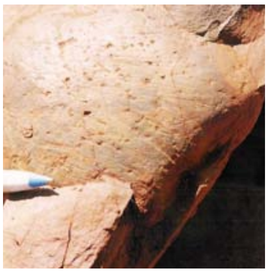




Paleomag. (De Kock et al., 2009)

~ 2.70 Ga

~ 2.50 Ga



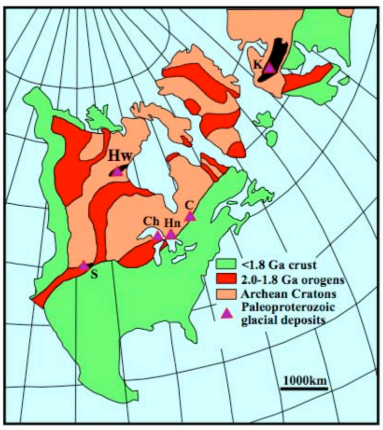
Meteorite Bore Member, Kungarra Fm (Pilbara)

Makganyene Fm (Kaapvaal)

Paleoproterozoic glacial deposits

original distribution in the Superia supercraton

reassembled in Nuna



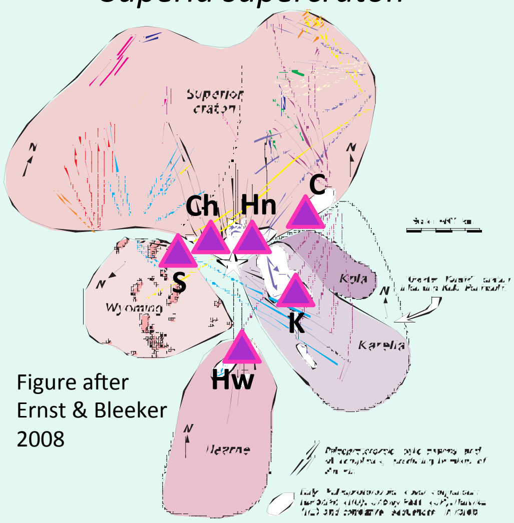
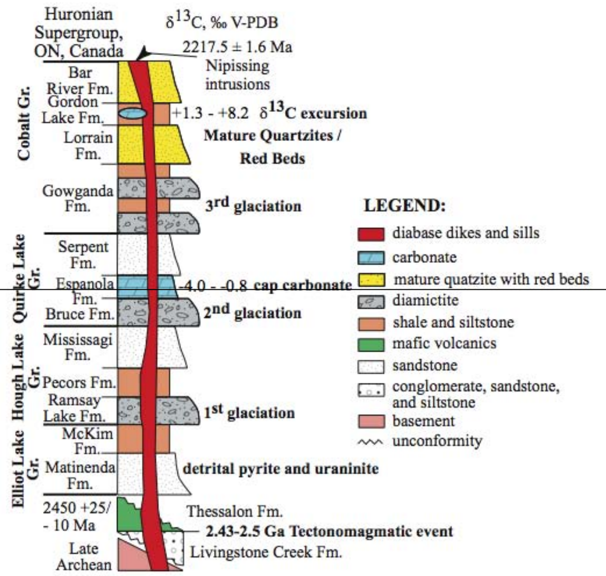


Figure after Ernst & Bleeker 2008

Stratigraphic column of the Huronian Supergroup in Ontario, Canada (modified from Bekker et al., 2006: **One OR Three Glaciations?**



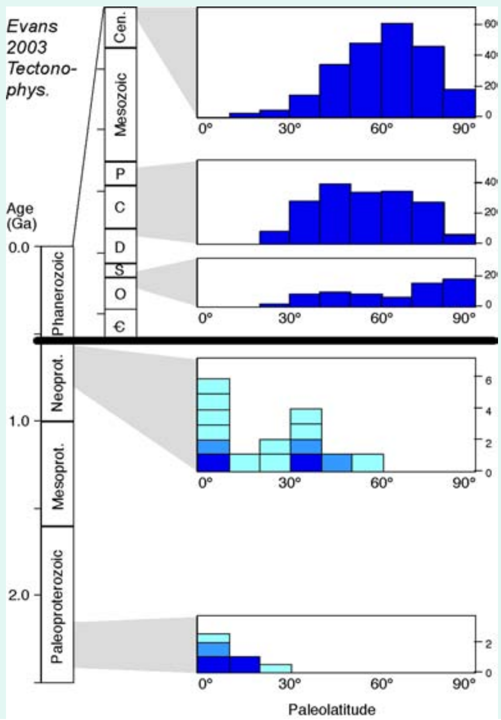
2.32Ga

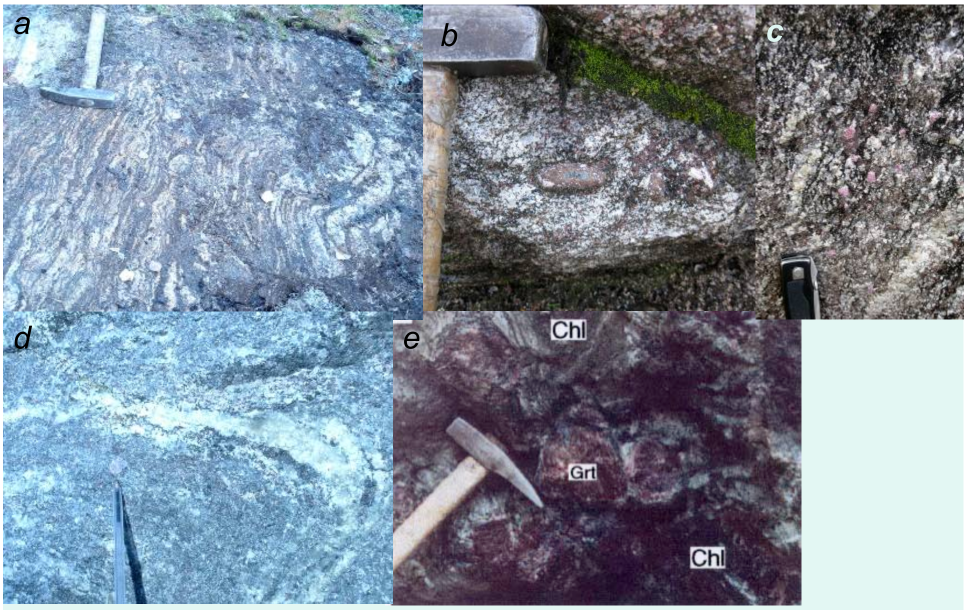
2.4 Ga Karelia Glaciation

Glacial paleolatitudes

darker shade indicates more reliable paleomagnetic data

<u>Paleoproterozoic units</u>
Meteorite Bore: 05°
Makganyene: 11°
Gowganda: 03° (?)
Sariolian: 07-27°





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.