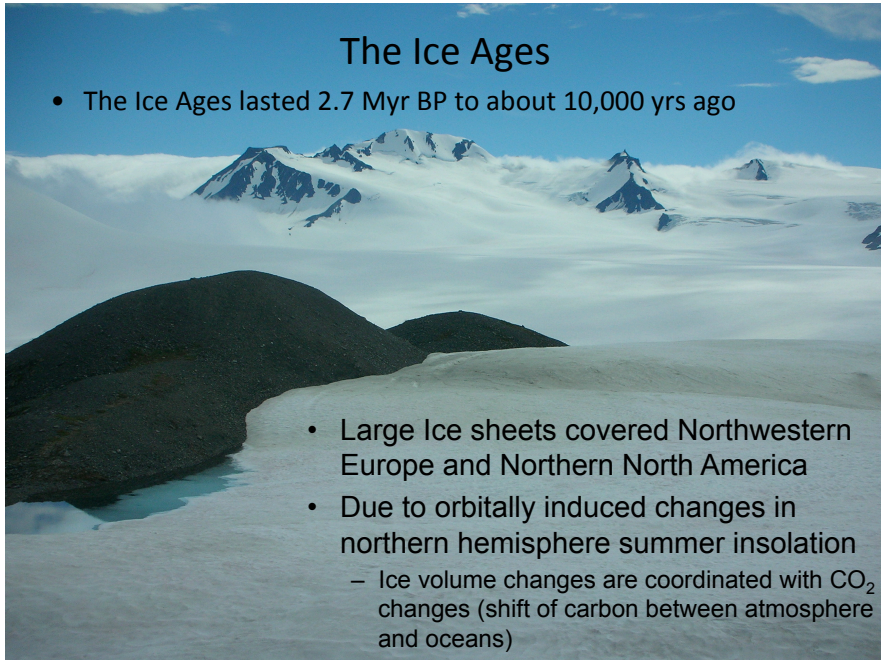


## The Ice Ages

- The Ice Ages lasted 2.7 Myr BP to about 10,000 yrs ago



- Large Ice sheets covered Northwestern Europe and Northern North America
- Due to orbitally induced changes in northern hemisphere summer insolation
  - Ice volume changes are coordinated with CO<sub>2</sub> changes (shift of carbon between atmosphere and oceans)

## Geologic Evidence For the Ice Ages

- Moraines, erratics, pollen records, etc
- Ocean sediments
  - Oxygen Isotopes in the shells of organism in the deep sea provide evidence of global ice volume
- Ice core records
  - Oxygen isotopes record local temperature
  - Air bubbles provide record of CO<sub>2</sub> and other gases
  - Remarkable correlation between local temperature and CO<sub>2</sub>
- Cause of glacial cycles
  - Trigger involves changes in summer insolation in northern hemisphere due to orbital changes
  - Ice-albedo and water vapor feedbacks are important
  - CO<sub>2</sub> is coordinated with the changes in ice volume, but it is a minor feedback to the Ice Ages (mainly responsible for SH cooling)

## Evidence of Glaciations: Moraines



Tasman Glacier, NZ

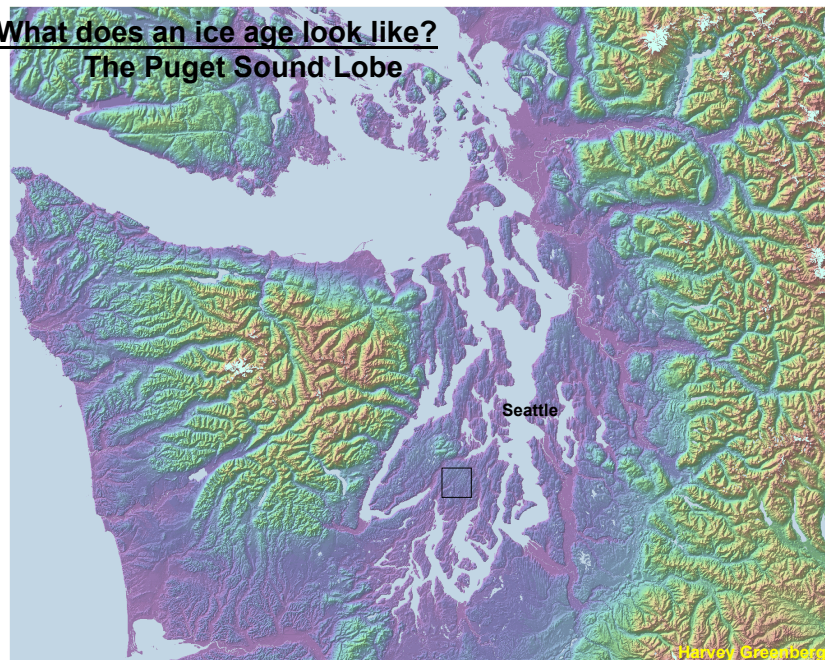
Moraines and erratics can be dated



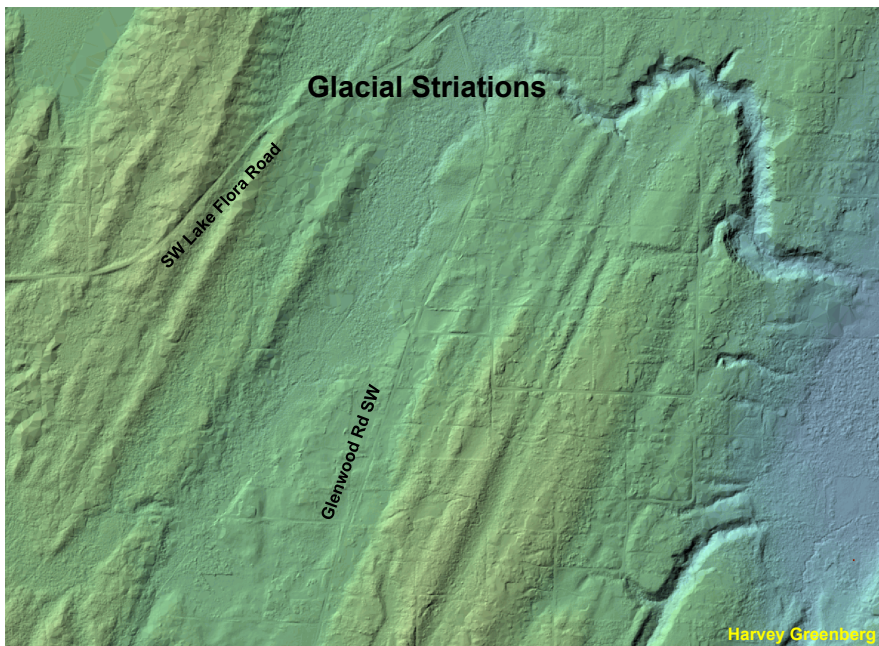
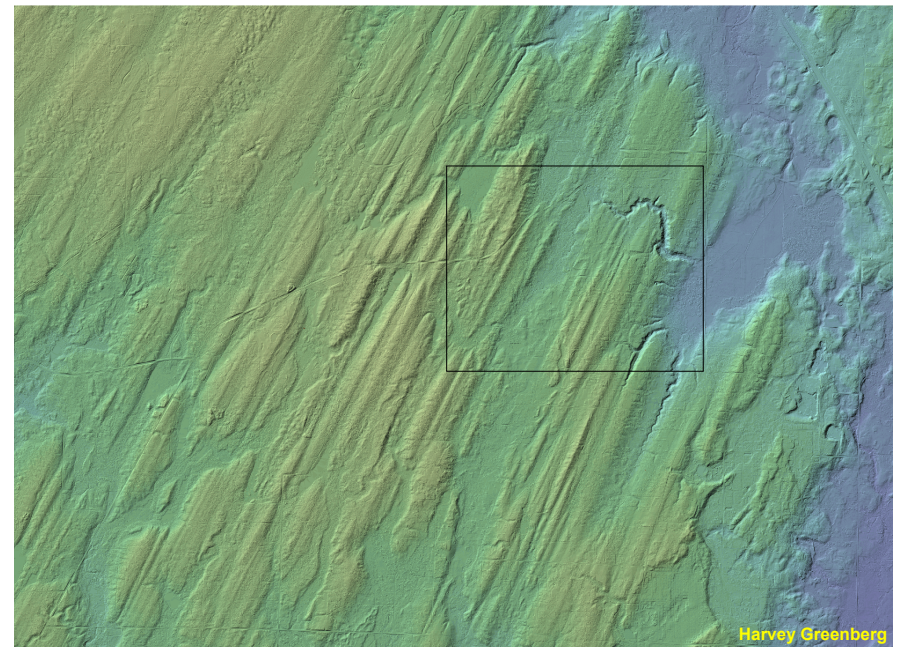
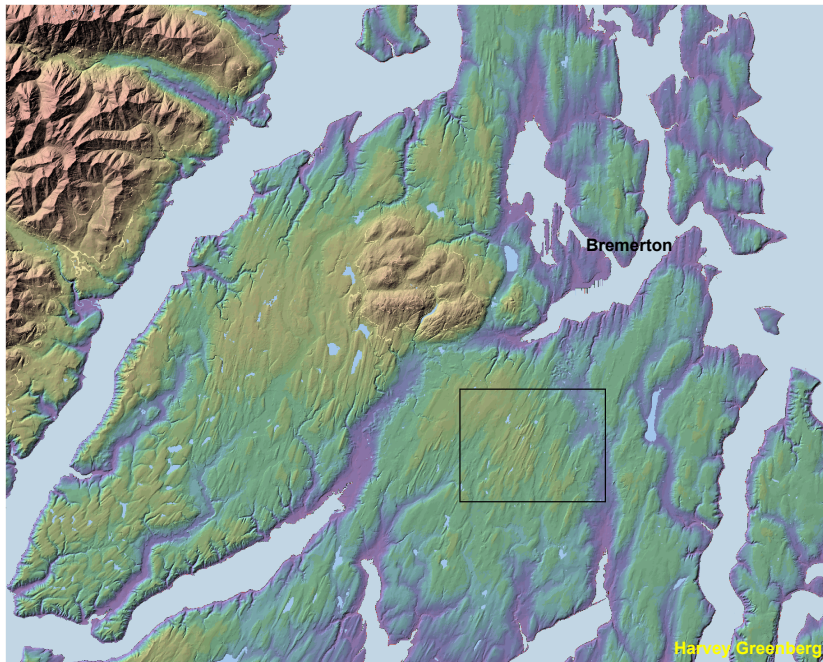
Mueller Glacier, NZ

## What does an ice age look like?

### The Puget Sound Lobe



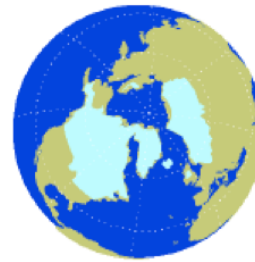
Harvey Prossberg



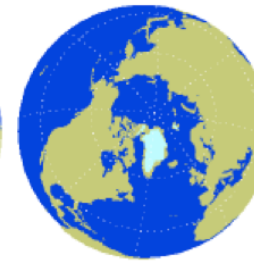
**What does an ice age look like?**

**Last Glacial Maximum Conditions**

- The Ice sheets
  - Extent determine by landscape morphology (e.g, moraines)
  - Volume determined by isotopes in ocean sediment cores
  - Shape determined by ice sheet models and present-day



**Last Glacial Maximum**



**Present**

Global sea level was 125 meters lower than today!

Large Ice sheets covered Northwestern Europe and Northern North America; the ice sheet was up to 5 km thick over Canada; 1-2km over Washington

Greenland 25°C colder, tropics 4°C colder

# Geologic Evidence For the Ice Ages

- Moraines, erratics, pollen records, etc
- Ocean sediments
  - Oxygen Isotopes in shells of organism in deep sea provide evidence of glacial ice amount



- Ice core records
  - Oxygen isotopes record local temperature
  - Air bubbles provide record of CO<sub>2</sub> and other gases

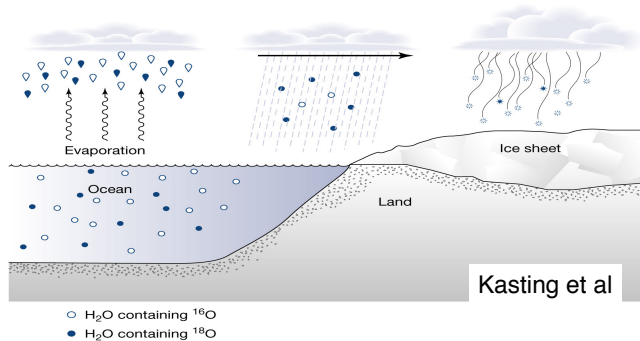


National Ice Core Freezer in NH

## Isotopic Evidence

H<sub>2</sub><sup>16</sup>O vs H<sub>2</sub><sup>18</sup>O  
 "light" (normal) vs "heavy"

- evaporation selects for "light water"
- condensation (precipitation) selects for "heavy water"



<sup>18</sup>O in ocean sediments records glacial ice volume: "lighter water" in ice-sheets means remaining ocean water is "heavier".

<sup>18</sup>O in ice-cores indicates local temperature: Colder conditions means more precipitation en route so "lighter" snow.

# Vocabulary: Isotopes

**an atom (or element) is defined by number of protons**  
 H(1), C(6), O(8), Pb(82)

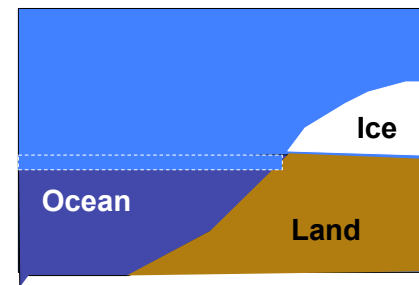
**atomic mass: number of protons plus neutrons**  
 H normally 1+0 = 1  
 C normally 6+6 = 12  
 O normally 8+8 = 16

**isotope: same element, different atomic mass**  
**>> that is, different number of neutrons**  
<sup>1</sup>H (normal), <sup>2</sup>H (deuterium), <sup>3</sup>H (tritium; radioactive)  
<sup>12</sup>C (normal), <sup>13</sup>C, <sup>14</sup>C (radioactive)  
<sup>16</sup>O (normal), <sup>18</sup>O

## Basic Idea

No land ice (interglacial)

Ocean Composition  
 40 H<sub>2</sub><sup>18</sup>O  
 4000 H<sub>2</sub><sup>16</sup>O  
 $\frac{H_2^{18}O}{H_2^{16}O} = 0.0100$



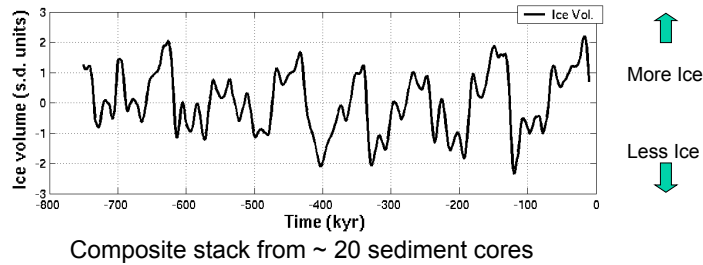
Lots of land ice (glacial)

Ice Sheet Composition  
 1 H<sub>2</sub><sup>18</sup>O  
 150 H<sub>2</sub><sup>16</sup>O  
 $\frac{H_2^{18}O}{H_2^{16}O} = 0.0067$

Ocean Composition  
 40 - 1 = 39 H<sub>2</sub><sup>18</sup>O  
 4000 - 150 = 3850 H<sub>2</sub><sup>16</sup>O  
 $\frac{H_2^{18}O}{H_2^{16}O} = 0.01013$

**Light water accumulates in ice sheets and ocean gets relatively heavy**

# The ice volume time series



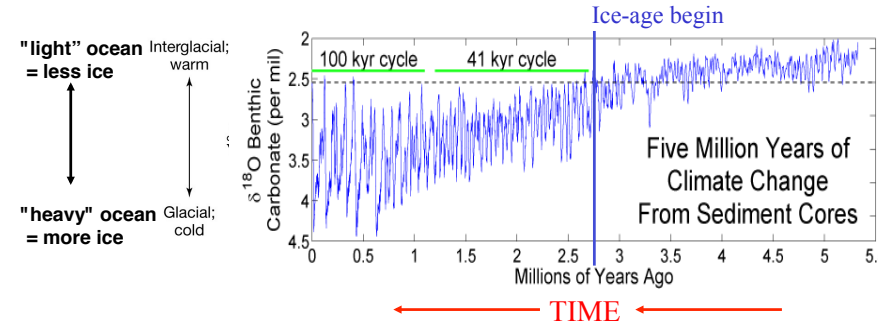
- the fraction of  $^{18}\text{O}$  to  $^{16}\text{O}$  in the shells of organisms preserved in deep sea sediment cores is proportional to ice volume:

"lighter water" stored in ice-sheets means remaining ocean water is "heavier". Critters in ocean grow shells that contain material with the isotopic composition of the ocean water.

Imbrie et al., 1984

# 3 Million Year Record of Global Ice Volume

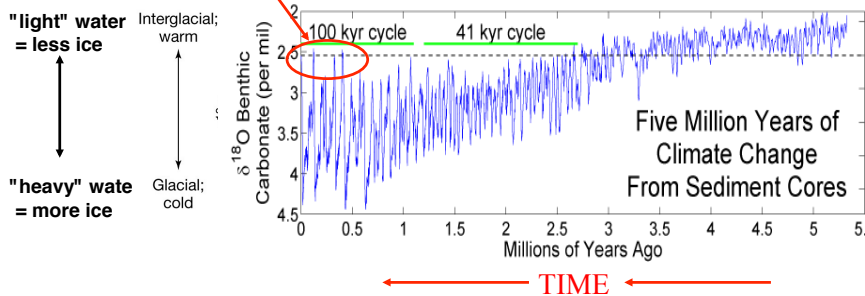
## Oxygen Isotope Concentration in Shells of Organisms Growing in the Deep Ocean



- Early on, 40,000 year cycles dominated
  - Obliquity having a direct effect
- More recently, 100,000 year cycles have been most prevalent

# 3 Million Year Record of Global Ice Volume

## Short (10,000 yr long) Warm Episodes



Kasting et al

# CO<sub>2</sub>\*, CH<sub>4</sub>\* and Temperature in Vostock Antarctica

\*CO<sub>2</sub> and CH<sub>4</sub> are well mixed in the atmosphere, so this is also a global record of CO<sub>2</sub> & CH<sub>4</sub>

