Stable Isotope Systematics

S. Chakraborty

Indian Institute of Tropical Meteorology
Isotopes

- Mass Number = A
- Atomic Number = Z

$C^{12}_6$
$C^{14}_6$
Isotope effects are useful in studying molecular structure
Isotope effects are useful in studying

- molecular structure
- quantum effects
Isotope effects are useful in studying

- molecular structure
- quantum effects
- chemical kinetics
Isotope effects are useful in studying

- molecular structure
- quantum effects
- chemical kinetics
- growth & morphology of plants & animals
Isotope effects are useful in studying

- molecular structure
- quantum effects
- chemical kinetics
- growth & morphology of plants & animals
- origin and evolution of the planetary atmosphere/solar system
Isotope effects are useful in studying

- molecular structure
- quantum effects
- chemical kinetics
- growth & morphology of plants & animals
- origin and evolution of the planetary atmosphere/solar system
- paleotemperature
Isotope effects are useful in studying

- molecular structure
- quantum effects
- chemical kinetics
- growth & morphology of plants & animals
- origin and evolution of the planetary atmosphere/solar system
- paleotemperature
- biogeochemistry
Isotope effects are useful in studying:

- molecular structure
- quantum effects
- chemical kinetics
- growth & morphology of plants & animals
- origin and evolution of the planetary atmosphere/solar system
- paleotemperature
- biogeochemistry
- anthropogenic effects
Climate Change – Geologic time

Isotope Systematics: Chakraborty – IITM

Ruddiman: Earth’s Climate: Past and Future
Under commonly assumed greenhouse forcing scenarios, atmospheric carbon dioxide concentrations of 500–600 ppmv — roughly twice the preindustrial level — would be required to produce the climate of the Pliocene.
climate archives contain many indicators of past climate

Proxy analysis involves: understanding the mechanism by which climate signals are recorded by proxy indicators in order to decipher climate changes.

Two kind of proxies used are:

1. **Biotic proxies**
   (changes in the composition of plant and animal group)

2. **Geological-geochemical proxies**
   (quantifies mass movement of Earth’s materials through the climate system, either as discrete (physical) particles or in dissolved (chemical) form.)
Climate proxies (continued)

**Biotic proxy**
(plant fossil, spores/pollen, plankton, cocoliths, diatom)

- Morphology
- Pollen count
- Stomatal index/density
- Ring width
- Physical property
- Elemental ratio
- **Isotopic ratio** (stable/radio isotope)

**Geological/Geochemical proxy**
(major/minor/complex ions/magnetic property/isotopic ratio/elemental ratio/)

Isotope Systematics: Chakraborty – IITM

Sub: Earth System Science and Climate
Climate proxies (continued)

**Biotic proxy**
(plant fossil, spores/pollen, plankton, cocoliths, diatom)

**Geological/Geochemical proxy**
(major/minor/complex ions/magnetic property/isotopic ratio/elemental ratio/)

- Morphology
- Pollen count
- Stomatal index/density
- Ring width
- Physical property
- Elemental ratio

**Isotopic ratio** (stable/radio isotope)

16O, 18O, 13C, 12C, 2H, H
Isotope fractionation

Carbon atom

12
Carbon atom
Isotope fractionation (contd.)

Carbon atom

12
13
14
Because of difference in size and atomic weight, different isotopes can react at slightly different rates.

Carbon atom

Isotope Fractionation

Isotope Systematics: Chakraborty – IITM
Sub: Earth System Science and Climate
Isotopic fractionation involves the partial separation of isotopes during physical, chemical or biological processes.
Isotope fractionation (mechanism)

No. of electrons control the chemical reaction of the atom undergoes

Atomic mass determines the vibrational energy of the nucleus

So differences in mass $\rightarrow$ Reaction Rate and Bond Strength

Why mass difference leads to difference in physical behavior?

K.E. is constant for a given element in a given environmental condition (const. $T$)

$$KE = \frac{1}{2} mv^2$$

So higher mass (isotope) possesses lower velocity
If \( L \) stands for \( \text{H}_2^{16}\text{O} \) and \( H \) for \( \text{H}_2^{18}\text{O} \)

Then

\[
\frac{v_L}{v_H} = \left(\frac{m_H}{m_L}\right)^{1/2}
\]

So

\[
\frac{v_{16}\text{O}}{v_{18}\text{O}} = (20/18)^{1/2}
\]

So at any temp the velocity of \( \text{H}_2^{16}\text{O} \) is 1.05 times faster than \( \text{H}_2^{18}\text{O} \)
Fractionation is the process by which one isotope is favoured over the other during a phase change (e.g. liquid evaporating to vapour, or precipitation of CaCO$_3$ from dissolved bicarbonate in drip waters)

1. Isotope exchange reaction (equilibrium isotope distribution)
2. Kinetic processes (depends primarily on differences in reaction rates of isotopic molecules)

Isotope exchange is used for all situations in which there is no net reaction, but in which the isotope distribution changes between different chemical phases

\[
\text{H}_2\text{H}^{18}\text{O} + \text{C}^{16}\text{O}_2 \leftrightarrow \text{H}_2\text{O} + \text{C}^{18}\text{O}^{16}\text{O}
\]

$^{18}\text{O}$ forms a stronger covalent bond with carbon than does $^{16}\text{O}$
Isotope fractionation processes

**Kinetic isotopic fractionation** results when rates of reactions or physical processes differ.

It also results from irreversible i.e., one way physical or chemical processes

Example:

- Evaporation of water with immediate withdrawal of the vapor
- Absorption and diffusion of gases
- Bacterial decay of plants
- Rapid calcite precipitation
Kinetic isotope effects: Kinetic isotope effects generally relate to difference in the dissociation energies of molecules composed of different isotopes.

For example, the rate determining step in a set of chemical reactions might involve the breakage of a bond. It is substantially easier to break the bonds of molecules that contain the lightest isotopes, which is plausible because the vibrational frequency of such bonds will tend to be higher, then the lighter isotopes will be preferentially incorporated in the products of incomplete reactions, while the heavy isotopes will become enriched in the unreacted residue.

Evaporation: It is an unidirectional, non-equilibrium processes that can cause isotope fractionation. In this case higher translational velocities of molecules containing the lightest isotopes may allow them to preferentially break through the liquid surface and escape into the atmosphere.
Isotope fractionation factor

\[ \alpha_{A-B} = \frac{R_A}{R_B} \]

\( R_A = \) ratio of the heavy isotope to light isotope in phase A

\( R_B = \) the same in phase B

Calcium carbonate precipitation and paleo-thermometer

\[ \alpha_{\text{calcite-water}} = \frac{(^{18}\text{O}/^{16}\text{O})_{\text{CaCO}_3}}{(^{18}\text{O}/^{16}\text{O})_{\text{H}_2\text{O}}} = 1.0286 \text{ at } 25^\circ\text{C} \]

\[ \text{H}_2^{18}\text{O} + \frac{1}{3}\text{CaC}^{16}\text{O}_3 \leftrightarrow \text{H}_2^{16}\text{O} + \frac{1}{3}\text{CaC}^{18}\text{O}_3 \]

\[ t^\circ\text{C} = 16.9 - 4.2 (\delta_c - \delta_w) + 0.13 (\delta_c - \delta_w)^2 \]
\[ \delta = \left[ \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right] \times 1000 \% \]

where

\[ R = \frac{^{13}\text{C}}{^{12}\text{C}} \text{ or } \frac{D}{H} \text{ or } \frac{^{18}\text{O}}{^{16}\text{O}} \]

Natural abundance

\[ ^{13}\text{C} : ^{12}\text{C} = 1.11 : 98.89 \]
\[ ^{18}\text{O} : ^{16}\text{O} = 0.2 : 99.76 \]
\[ D : H = 0.015 : 99.98 \]

Rel. mass Diff.

~8%
~12%
100%
\[ \delta_x^y = \left( \frac{R_x - R_y}{R_y} \right) \times 1000 = \left( \frac{R_x}{R_y} - 1 \right) \times 1000 \]

\[ R_{13c} = \frac{[\text{mass13}]}{[\text{mass12}]} \]
Molecular abundance ratio

Oxygen isotopes

\[ ^{16}\text{O} \quad ^{18}\text{O} \]

Abundance: A \quad Abundance: B

\[ A + B = 1; \quad A \gg B \]

Molecular abundance = \((A+B)^2\)
Isotopologues of water

\[
\begin{align*}
^{16}\text{O} &= 99.7621 \\
^{17}\text{O} &= 0.03790 \\
^{18}\text{O} &= 0.20004 \\
\text{H} &= 99.9844 \\
\text{D} &= 0.01557
\end{align*}
\]

\[
\begin{align*}
\text{H}_2^{16}\text{O}; \text{H}_2^{17}\text{O}; \text{H}_2^{18}\text{O}; \text{HD}^{16}\text{O}; \text{HD}^{17}\text{O}; \ldots
\end{align*}
\]

Abundance of \text{H}_2^{16}\text{O} = (0.999844)^2 (0.997621) = 0.997310 -> 99.73%

\[
\text{HD}^{16}\text{O} = 2 (0.99928) (0.000156) (0.99759) = 0.0003146 \quad \rightarrow 0.03\%
\]
Isotopologues of water

\[
\begin{align*}
\textsuperscript{16}O &= 99.7621 \\
\textsuperscript{17}O &= 0.03790 \\
\textsuperscript{18}O &= 0.20004 \\
\text{H} &= 99.9844 \\
\text{D} &= 0.01557
\end{align*}
\]

\[
\begin{align*}
\text{H}_2\textsuperscript{16}O; \text{H}_2\textsuperscript{17}O; \text{H}_2\textsuperscript{18}O; \text{HD}\textsuperscript{16}O; \text{HD}\textsuperscript{17}O; \ldots
\end{align*}
\]

Abundance of \( \text{H}_2\textsuperscript{16}O \) = \((0.999844)^2 (0.997621) = 0.997310 \) \( -> 99.73\% \)

HD\textsuperscript{16}O = 2 \((0.99928) (0.000156) (0.99759) = 0.0003146 \) \( -> 0.03\% \)
Mass spectrometer is an instrument designed to separate charged atoms and molecules based on their mass to charge ratio in an electric and/or magnetic field.
Basic components of a mass spectrometer

- inlet
- Ion source
- analyzer
- detector

Vacuum system
Electron Trap

\[ M + e^- \rightarrow M^+ + 2e^- \quad (M^+ = \text{Molecular cat ion}) \]

Efficiency \( \approx \) sensitivity of the Mass Spectrometer

e\(^-\) energy = 50 – 150 eV

Isotope Systematics: Chakraborty – IITM

Sub: Earth System Science and Climate
Mass Spectrometer (contd.)

\[ ^{12}\text{C}^{16}\text{O}^{16}\text{O} = 44 \quad ^{13}\text{C}^{16}\text{O}^{16}\text{O} = 45 \quad ^{12}\text{C}^{16}\text{O}^{18}\text{O} = 46 \]

\[ BeV = \frac{mv^2}{r} \quad \frac{m}{e} = \frac{B^2r^2}{2V} \]

Magnetic analyzer
Mass Spectrometer (contd.)

\[
BeV = \frac{mv^2}{r} \quad \frac{m}{e} = \frac{B^2r^2}{2V}
\]

Isotope Systematics: Chakraborty – IITM

Sub: Earth System Science and Climate
$^{45}\text{CO}_2/^{44}\text{CO}_2 \sim ^{13}\text{C}/^{12}\text{C}$  
$^{46}\text{CO}_2/^{44}\text{CO}_2 \sim ^{18}\text{O}/^{16}\text{O}$
Elemental Analyzer

Gas Bench
Foraminifera: a repository of past ocean variability
Paleotemperature over the past 70 million years: the $\delta^{18}$O record of benthic foraminifera

14°C cooling of the ocean, or deep ocean temp. was about 16°C

Possible mechanisms

• Decreased input of CO$_2$ from the earth’s interior

• Increased removal of CO$_2$ from the atmosphere due to enhanced weathering

• Progressive decrease in pole-ward heat transport arising due to the change in land-ocean distribution
Orbital Scale Climate Variability

Milankovitch Hypothesis
### Ice ages through geological time

<table>
<thead>
<tr>
<th>ERA</th>
<th>PERIOD</th>
<th>AGE (Myr)</th>
<th>ICE AGES</th>
<th>EPOCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>PALEOZOIC</td>
<td>Quaternary</td>
<td>0.01</td>
<td></td>
<td>Holocene</td>
</tr>
<tr>
<td></td>
<td>Tertiary</td>
<td>2</td>
<td></td>
<td>Pleistocene</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td></td>
<td>Pliocene</td>
</tr>
<tr>
<td></td>
<td></td>
<td>26</td>
<td></td>
<td>Miocene</td>
</tr>
<tr>
<td></td>
<td></td>
<td>37</td>
<td></td>
<td>Oligocene</td>
</tr>
<tr>
<td></td>
<td></td>
<td>53</td>
<td></td>
<td>Eocene</td>
</tr>
<tr>
<td></td>
<td></td>
<td>65</td>
<td></td>
<td>Paleocene</td>
</tr>
<tr>
<td>MESOZOIC</td>
<td>Cretaceous</td>
<td>136</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jurassic</td>
<td>190</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Triassic</td>
<td>225</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Permian</td>
<td>280</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CENOZOIC</td>
<td>Carboniferous</td>
<td>345</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Devonian</td>
<td>395</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Silurian</td>
<td>430</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ordovician</td>
<td>500</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cambrian</td>
<td>570</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Pleistocene Glaciations

North America at about 20,000 years ago
Pleistocene Glaciations

AMERICA DURING LAST ICE AGE

- Ocean
- Ice Sheet
- Land
- Land exposed by Lowered Sea Level
- Human Migration Route
What has caused Earth to oscillate in and out of glacial states over the past 2 million years?

What geologic evidence substantiates theories about the causes of glaciations?

How are the glacial to interglacial cycles related to changes in Earth’s orbit?

Have components of the Earth system amplified the glacial climate response?
Moraines formed by the bulldozing action of advancing glaciers

Loess: fine grained sediment produced by glacial abrasion and transported to the site of deposition by wind

Tillites: mix of sediments of various types & sizes resulting from the indiscriminate transportation of glaciers
Why and how does the climate system drop back into global glaciations?
First deep sea core recovered: 1950s
Continental records: showed four glaciations
Marine records → dozens of climate swings (over the Pleistocene)

Northern hemispheric glaciation – every 100 kyr in 700 kyr
Global avg T ~ 9-10 °C; pCO₂ ~200 ppm

Interglacials: Greenland, Antartica avg T ~ 15°C, pCO₂ ~280 ppm
Glacial interglacial cycle

Oxygen isotopic record of sediment core (benthic foraminifera) from the subpolar north Atlantic

Isotope Systematics: Chakraborty – IITM

δ¹⁸O anomaly

Sub: Earth System Science and Climate
At low obliquity, Earth has less contrast in insolation between the seasons.

At high obliquity, the seasonal contrast is greater.
Causes of seasonality

- June: Earth's position with respect to the Sun, showing the tilt of the Earth's spin axis.
- December: Similar depiction, showcasing the seasonal effects.

Tilt of the Earth's spin axis with respect to its orbit.
Causes of seasonality

Earth in October

Earth in January (closest to sun)

Foci of the elliptical orbit

Earth in April

Earth in July (farthest from sun)
Astronomical theory of long term climate change
Eccentricity

Periodicity: 100,000 yr and 410,000 yr
Astronomical theory of long term climate change

Periodicity: 41,000 yr
Precession of Solstices and Equinoxes
Periodicity: 19,000 and 23,000 yr
Earth rotates 365 times a year.

Earth precesses once in 24,000 years.

Spin axis position 12,000 years ago

~ 20,000 years ago  ~ 10,000 years ago  ~ 5,000 years ago  Today

Spin axis position today

Earth on June 21
Made calculations (1920-1930) elucidating the time sequence of seasonal changes of insolation reaching at 65°N latitude.
Changes in insolation calculated using the Milankovitch theory
Past changes in ice volume
To test the Milankovitch theory one has to determine the **Temporal variation of temperature**

Harold Urey first proposed how to measure paleotemperature

$^{18}\text{O}/^{16}\text{O}$ in $\text{CaCO}_3$

Willard Libby invented the method of radio carbon dating in 1950s
Emiliani estimated rather a large change in glacial-interglacial temp change by \(~7^\circ C\) (he assumed temp effect was dominant) by analysing planktic foraminifera.

Nic Shackleton disagreed the estimate.

\[ \delta^{18}O \text{ range } \sim 1.75 \text{‰} \]
\[ \text{Ice volume } \sim 1.05 \text{‰} \]
\[ \text{Temp } \sim 0.70 \text{‰} \]

Glacial age tropical cooling \(~2.5^\circ C\)
N. Hemisphere June insolation (Q: climate forcing) and marine oxygen isotope ratio (climate response) and their dominant periodic component
Testing the hypothesis

- Glaciation
- $\delta^{18}O$
- Interglacial

$\delta^{18}O$ record of ice volume and deep water temperature change

- 41,000 years
- $\sim$100,000 years
- 23,000 years

Martinson et al. 1987
Ice age record from ocean sediments

Testing the hypothesis
The ice “library”
Vostok ice core record (Antarctic) [Petit et al. 1999]
Ice core record

Map of Greenland showing locations of NGRIP, GISP2, and GRIP. A graph on the right shows NGRIP δ¹⁸O (%) over time, with intervals studied and other geological periods labeled.
Air bubbles trapped in ice
Co-variation of high CO$_2$ and warm climate

420,000 yr. Vostok record: Temperature (top), CO2 (bottom).
Ice core data from Vostok
Radiocarbon: a unique tracer in studying the Earth System Processes
Dating Methods

**RADIOISOTOPES**

- Direct measurements of radioisotopes or decay products ($^{14}$C, K/Ar)
- Equilibrium measurements (U-series)
- Integrated effects (TL, FT)

**BIOLOGICAL**

- Growth rates
- Growth layers

**CHEMICAL**

- Organic
- Inorganic
- Weathering rates
- Finger printing

**PALAEO MAGNETIC**

- Incidence of reversal
- Secular variations

Radiocarbon dating: Chakraborty – IITM

Sub: Earth System Science and Climate
Nuclear (n,p) reaction of cosmic ray generated neutron and stable isotope of nitrogen in upper atmosphere:

\[ _7^{}N^{14} + _0^1n \rightarrow _6^{14}C + _1^1H \]

- Reaction with upper atmospheric O\(_2\) to form CO and CO\(_2\):

\[ ^{14}C + O_2 \rightarrow ^{14}CO_2 \]

- Gradually mixes with lower atmosphere

Atmospheric CO\(_2\) is the only natural source of \(^{14}C\) for all other carbon reservoirs in nature.
$^{14}\text{C}$ production in Atmosphere

$^{14}\text{N} + p \rightarrow ^{14}\text{C}$

$^{14}\text{C} ightarrow ^{14}\text{CO}$

$^{14}\text{CO} \rightarrow ^{14}\text{CO}_2$

$^{14}\text{C} \rightarrow ^{14}\text{N}$

$\text{t}_{1/2} = 5730 \text{ yr}$

Radiocarbon dating: Chakraborty – IITM

Sub: Earth System Science and Climate
Equilibrium of $^{14}$C in nature:

The rate of $^{6}$C$^{14}$ production = the rate of $^{6}$C$^{14}$ decay (Globally)

- In plant and animal body the concentration of $^{14}$C in their life time remains the same by the similar principle.

- When the organism dies, intake of $^{14}$C stops, but decay continues and activity decreases with time.

Radiocarbon dating: Chakraborty – IITM

Sub: Earth System Science and Climate
Assumptions

- $A_0$ of all plant and animal tissue are same and constant and independent of time for last 70,000 years.

- $A_0$ is independent of geographic location and species of the dead plant and animal whose dead tissues are being dated.

- Sample should not be contaminated with modern carbon and radioactive impurities.
\[ A = A_0 \ e^{-\lambda t} \]

\( A \) = measured activity in disintegration per minute per gm of carbon

\( A_0 \) = activity of the same specimen when the organism died

\( \lambda \) = decay constant

\[ t = - \left( \frac{1}{\lambda} \right) \ln(A/A_0) \]

For tree rings, corals, oceanographic samples

\[ \Delta^{14}C \ (\text{‰}) = \left[ \left( \frac{A_{SN} e^{\lambda(y-x)}}{A_{abs}} \right) - 1 \right] \times 1000 \]

\( A_{SN} \) = normalized sample activity, \( A_{abs} \) = standard activity

\( y \) = yr. of measurement, \( x \) = year of growth
Causes of uncertainties

- Atmospheric production rate of $^{14}$C depends on proton flux which varies over time due to changes in the Earth’s magnetic field.

- Climatic forcing that alters the carbon concentration in different carbon reservoirs

- Anthropogenic effect

  All of these could alter the initial activity $A_0$

- Age determination is also affected by isotopic fractionation
Applications of radiocarbon dating

To establish the chronology of natural deposition and climate reconstruction

Understanding ocean circulation, mixing rate, age of water mass

Study of solar activity, sunspot number and geomagnetic variabilities

Atmospheric transport processes

Estimating Rate of carbon transfer among carbon reservoirs

Archaeology
Different $^{14}\text{C}$ reservoirs in nature and their relation

- Atmosphere
  - Respiration
  - Photosynthesis
  - Exchange through ocean-water interface

- Biosphere (Plants and animals)
  - Transport through rivers
  - Weathering
  - Burial of organisms

- Hydrosphere
  - Sedimentation
  - Solution

- Lithosphere

Radiocarbon dating: Chakraborty – IITM
Sub: Earth System Science and Climate
Carbon inventories
Number in **red**: $C \times 10^6$ moles
Number in *italic*: $^{14}C/^{12}C$
relative to atmosphere
Numbers in **brown**: % of $^{14}C$
Applications: Estimation of air-sea exchange rate

Air $\Delta^{14}$C

Surface water $\Delta^{14}$C

12 mol m$^{-2}$ yr$^{-1}$
Applications: Estimation of air-sea exchange rate

For $^{12}$C

$$F_{12} + wC_S = F_{12} + wC_G + B$$

$$wC_S = B + wC_G$$

For $^{14}$C

$$D_G = F_{12}(R_A - R_G) + w(C_S R_S - C_G R_G)$$

$w =$ advective velocity
$C_S =$ total DIC in surface water
$D_G =$ mean depth of the gulf of Kutch

$R_A$ : comes from tree ring analysis
$R_G$ : comes from coral band analysis (of $^{14}$C)
How the organisms control oceanic $\delta^{13}C$

$$\delta^{13}C = \frac{^{13}C/^{12}C}_{\text{sample}} - \frac{^{13}C/^{12}C}_{\text{reference}} \times 1000 \, (‰)$$
Control mechanism of oceanic $\Delta^{14}C$

Radiocarbon dating: Chakraborty – IITM
Sub: Earth System Science and Climate
Very salty and dense sea water sinks thereby creating thermohaline circulation

Understanding the cause of this motion and the specific route is important. These currents disperse energy around our planet and are a huge influence on the world’s climate and, therefore, on the economies of nations.
Rates of ocean mixing characterizing the abyssal circulation are intimately linked to climate change.

Deep ocean contains more than 95% of carbon so the mixing rate between the atmosphere equilibrated surface ocean and the deep ocean exert an important force via the greenhouse connection.

Changes in ocean mixing rate are thought to have played a key role in deriving climate change on glacial to interglacial time scale.

Determination of ocean mixing rate during the last glacial period have relied on the comparison of the planktonic and benthic foraminifera shells.
Ventilation Age: Knowledge of ventilation age helps estimate the CO$_2$ transfer rate to the deep sea.

Definition: In radiocarbon years, the deep ocean is older than the surface water, because deep waters have been isolated from the surface water. This time interval of isolation is referred to as the ventilation age & can be measured by radiocarbon decay.

Tools: Analysis of foraminifera
Analysis of deep sea coral
The difference indicates that the ventilation of circumpolar deep water, the water mass that fills the Drake passage was significantly older at the LGM.
Applications: Estimation of ventilation age

705m water depth
Atmospheric $\Delta^{14}C$

Intermediate water $\Delta^{14}C$ (Baja California)

Atmospheric $pCO_2$ (ppmv)

Year Before Present

Radiocarbon dating: Chakraborty – IITM
Marchitto et al. 20087
ventilation was suppressed by ice cap

Cross section of the Pacific Ocean showing the state of ventilation

Glacial state

- Poorly ventilated deep water
- Low $^{14}$C
- Core site

Early deglacial state

- CO$_2$ release
- Low $^{14}$C intermediate water
- Poorly ventilated deep water

Radiocarbon dating: Chakraborty – IITM

Keeling 2007
Lowering of atmospheric CO2 in the southern ocean

Glacial state

South

North

Poorly ventilated deep water: low $^{14}$C

Interglacial

Water column stratification

Radiocarbon dating: Chakraborty – IITM

Froncois et al. 1997
Hypothesis: a positive feedback that shoots atmospheric CO$_2$ from glacial extremes to interglacial extremes and back again. It is an internal to the climate system. An interaction between the ocean’s circulation, atmospheric winds, and atmospheric CO$_2$ pushes the atmospheric pCO$_2$ up and down, not the biogeochemistry or the orbital forcing.
Modern near bottom $\Delta^{14}C$ values
Atmospheric $^{14}\text{C}$ Variability

$\Delta^{14}\text{C}$

Year AD

Variability
Temporal and spatial variability of tropospheric $\Delta^{14}C$ depends on

- Fossil fuel emission
- Ocean-atmospheric exchange
- Stratosphere-troposphere mixing
- Terrestrial ecosystem fluxes

Radiocarbon dating: Chakraborty – IITM

Sub: Earth System Science and Climate
Atmospheric $\Delta^{14}C$ is useful

SOURCE

AGE

MAGNITUDE

OF REGIONAL FLUXES
Atmospheric $\Delta^{14}C$ variability at Schauinsland (48°N, 8°E, 1205m asl)

Levin & Kromer 1997
Atmospheric $\Delta^{14}$C variability

Stuiver et al. 1998

Radiocarbon dating: Chakraborty – IITM

Sub: Earth System Science and Climate
Applications: Estimation of fossil fuel component
Applications: Estimation of fossil fuel component

Radiocarbon dating: Chakraborty – IITM

Chakraborty et al. 2008
Applications: Estimation of fossil fuel component

Possible causes of reduced $\Delta^{14}C$ peak

- Dilution by fossil fuel CO$_2$
- Evasion of CO$_2$ from the upwelling areas of the Arabian Sea, depleted in $^{14}CO_2$
- Root respired CO$_2$
- Transport of southern hemispheric air

Fossil fuel component appears to be the most likely candidate.

\[ C_{fossil} = C_{bkg} \frac{^{14}C_{bkg} - ^{14}C_{ms}}{^{14}C_{bkg}} \]
Wegener’s hypothesized the theory of **continental drift**: continents had once been joined to form a single supercontinent.

He proposed that the supercontinent, **Pangaea**, began to break apart ~200 million years ago and form the present landmasses.
Breakup of Pangaea

250 Million Years Ago
Pangaea consisted of all the major continents.

200 Million Years Ago
The rifting that eventually resulted in the Atlantic Ocean occurred over an extended period of time. The first rift developed between North America and Africa.

100 Million Years Ago
Continued rifting of the southern landmasses sent India on a northward journey.

50 Million Years Ago
Australia began to separate from Antarctica.

Present
A modern map shows that India has collided with Asia, creating the Himalayas.
- The Continental Puzzle

- Matching Fossils
  - Fossil evidence for continental drift includes several fossil organisms found on different landmasses.

- Rock Types and Structures
  - Rock evidence for continental exists in the form of several mountain belts that end at one coastline, only to reappear on a landmass across the ocean.

- Ancient Climates
Matching Mountain Ranges

North America

Appalachian Mountains

Caledonian Mountains

British Isles

Scandinavia

Africa

Greenland

Europe

North America

South America
Wegener could not provide an explanation of exactly what made the continents move. New technology lead to findings which then lead to a new theory called **plate tectonics**.
• **Seismology - the study of earthquakes**

Earthquake – produces seismic waves - generated by the movement of the rocks along a fault.
The waves emanate from the “source” or earthquake, and travel through the body of the Earth

- 1. Body waves and 2. Surface waves
- Body wave:
  a) P-wave – compression of material in Earth’s interior
  b) S-wave – also called shear wave and transverse in nature
Seismometer – measures the horizontal and vertical displacement of the earth surface
Outer core: The Earth's rotation makes this ocean flow and swirl, and the moving metal generates the planet's magnetic field.

Crust is hard and thin, 10 to 100 kilometers thick

The mantle is a highly viscous layer between the crust and the outer core. It is a rocky shell about 2,900 km thick that constitutes about 84% of Earth's volume. It is predominantly solid and encloses the iron-rich hot core, which occupies about 15% of Earth's volume.

Outer core: The Earth's rotation makes this ocean flow and swirl, and the moving metal generates the planet's magnetic field.

What is the importance of the core?

Source of Earth’s magnetic field
According to the **plate tectonics** theory, the uppermost mantle, along with the overlying crust, behaves as a strong, rigid layer. This layer is known as the lithosphere.

A **plate** is one of numerous rigid sections of the lithosphere that move as a unit over the material of the asthenosphere.
Plate Tectonics
Divergent boundaries (also called spreading centers) are the place where two plates move apart.

Convergent boundaries form where two plates move together.

Transform fault boundaries are margins where two plates grind past each other without the production or destruction of the lithosphere.
Divergent Boundaries

- Oceanic Ridges and Seafloor Spreading
  - **Oceanic ridges** are continuous elevated zones on the floor of all major ocean basins. The rifts at the crest of ridges represent divergent plate boundaries.

  - **Rift valleys** are deep faulted structures found along the axes of divergent plate boundaries. They can develop on the seafloor or on land.

  - **Seafloor spreading** produces new oceanic lithosphere.
Spreading Center

- Upwarming
- Rift valley
- Linear sea
- Oceanic ridge
- Rift
- Continental crust
- Oceanic crust
Continental Rifts

• When spreading centers develop within a continent, the landmass may split into two or more smaller segments, forming a rift.
A subduction zone occurs when one oceanic plate is forced down into the mantle beneath a second plate.

- **Oceanic-Continental**
  - Denser oceanic slab sinks into the asthenosphere.
  - Pockets of magma develop and rise.
  - **Continental volcanic arcs** form in part by volcanic activity caused by the subduction of oceanic lithosphere beneath a continent.
  - Examples include the Andes, Cascades, and the Sierra Nevadas.
Oceanic-Continental Convergent Boundary

- Trench
- Continental volcanic arc
- Subducting oceanic lithosphere
- Melting
- Continental crust
- Asthenosphere
Oceanic-Oceanic

- Two oceanic slabs converge and one descends beneath the other.
- This kind of boundary often forms volcanoes on the ocean floor.
- **Volcanic island arcs** form as volcanoes emerge from the sea.
- Examples include the Aleutian, Mariana, and Tonga islands.
Oceanic-Oceanic Convergent Boundaries

- Volcanic island arc
- Trench
- Oceanic crust
- Continental crust
- Oceanic lithosphere
- Asthenosphere
- Subducting oceanic lithosphere
- Melting

Dimensions:
- 100 km
- 200 km
• When subducting plates contain continental material, two continents collide.

• This kind of boundary can produce new mountain ranges, such as the Himalayas.
Continental-Continental Convergent Boundary
Collision of India and Asia

[Diagram showing the collision of India and Asia, including tectonic plates, volcanic arcs, and geological features.]
Paleomagnetism is the natural remnant magnetism in rock bodies; this permanent magnetization acquired by rock can be used to determine the location of the magnetic poles at the time the rock became magnetized.

- **Normal polarity**—when rocks show the same magnetism as the present magnetism field

- **Reverse polarity**—when rocks show the opposite magnetism as the present magnetism field
The discovery of strips of alternating polarity, which lie as mirror images across the ocean ridges, is among the strongest evidence of seafloor spreading.
Polarity of the Ocean Crust

- Period of normal magnetism
- Period of reverse magnetism
- Period of normal magnetism
It is believed that convection occurring in the mantle is the basic driving force for plate movement.

- Convective flow is the motion of matter resulting from changes in temperature.

Mantle Convection

- Mantle plumes are masses of hotter-than-normal mantle material that ascend toward the surface, where they may lead to igneous activity.
- The unequal distribution of heat within Earth causes the thermal convection in the mantle that ultimately drives plate motion.
Sources of Heat

Radioactive decay

Residual heat from the Earth’s interior

Growth of the inner core
Effect on Climate

How tectonic motion affects the climate?

Location of continents determines ice sheet formation
   Example: opening of Drake Passage ~30 My ago.

Regulation of atmospheric pCO$_2$ through chemical weathering

Change in rainfall pattern and expose new rocks to the atmosphere
   Example: formation of Himalaya ~40 My ago.
   Changes of wind pattern caused heavy rainfall

   increased chemical weathering

   Drew down atmospheric CO$_2$ over a period of tens of millions of years

   Results in cooling