Basics of Analysis with Antineutrinos From Heat Producing Elements - K, U, Th in the Earth

IAP 2010, January 5 - 22

Earth, Atmospheric
& Planetary Sciences
Massachusetts Institute of Technology

Session 1: January 5, 2010, 10 AM to Noon

Instructor *Dr. Ila Pillalamarri*

Course 12.091 Special Topics in Earth Sciences

Course Objectives

1) Relevance to antineutrino analysis of global concentration determination of radiogenic heat producing elements (HPE) by terrestrial heat flow studies and Bulk Silicate Earth (BSE) models, and unconventional models of the Earth's core.

2) Basic radiation characteristics of heat producing elements (HPE):

   Alpha, beta, gamma, neutrino and antineutrino radiations,

   Basics of radiation detection concepts,

   Special focus:

   Antineutrino radiation detection,

   Antineutrino radiation detection with directional sensitivity.

Course Objectives Continued

3) Relevance of existing large antineutrino detectors for probing the HPE in Earth's deep interior:

   Characteristics, research and contributions of the two existing antineutrino detectors – Sudbury Neutrino Observatory (SNO), Canada and Kamioka Liquid Scintillator Antineutrino Detector (KamLAND), Japan.

4) Proposed antineutrino detectors for probing the HPE in Earth's deep interior with directional sensitivity. Tomography of the whole Earth for the localization of the HPE in the deep interior of the Earth. Need for mobile antineutrino detectors for tomography.

5) Considerations for dedicated antineutrino detectors to probe the Earth's deep interior for the determination of concentrations of heat producing elements.

Course Schedule
January 5 – 22, 2010

Jan 05

Relevance to antineutrino analysis of global concentration determination of radiogenic heat producing elements (HPE) by terrestrial heat flow studies and Bulk Silicate Earth (BSE) models, and unconventional models of the Earth's core.

Jan 19

Basic radiation characteristics of heat producing elements (HPE):

Alpha, beta, gamma, neutrino and antineutrino radiations,

^{40}K decay characteristics, U and Th decay series

Basics of radiation detection concepts,

Special focus:

Antineutrino radiation detection,

Antineutrino radiation detection with directional sensitivity.

Course Schedule
January 5 – 22, 2010

Jan 20

Relevance of existing large antineutrino detectors for probing the HPE in Earth's deep interior:

Characteristics, research and contributions of the two existing antineutrino detectors – Sudbury Neutrino Observatory (SNO), Canada and Kamioka Liquid Scintillator Antineutrino Detector (KamLAND), Japan.

Jan 21

Proposed antineutrino detectors for probing the HPE in Earth's deep interior with directional sensitivity. Tomography of the whole Earth for the localization of the HPE in the deep interior of the Earth. Need for mobile antineutrino detectors for tomography.

Visit to Earth Atmospheric & Planetary Sciences – Radiometric/Neutron Activation Analysis Laboratory (NW13-263).

Jan 22

Considerations for dedicated antineutrino detectors to probe the Earth's deep interior for the determination of concentrations of heat producing elements.

Conclusions.

Student Presentations.

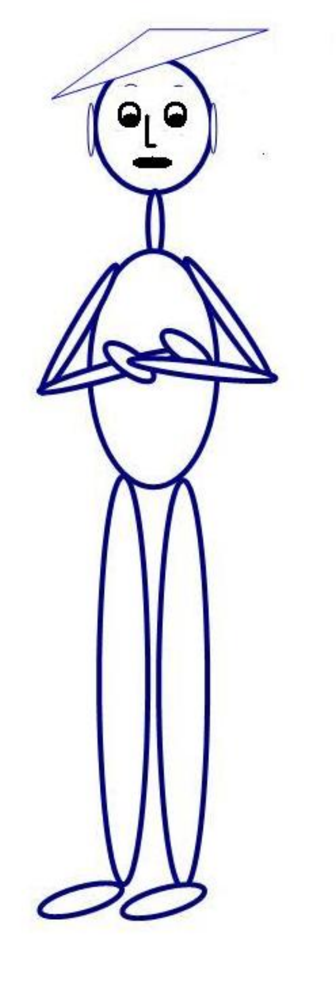
Details of course work

The course work involves the following:

1.	Class attendance and participation	25%
2.	Reading assignments	25%
3.	Homework assignments	15%
4.	Student report	15%
5.	Student presentation	15%

Required percentage to pass this course is 95%.

Course Overview



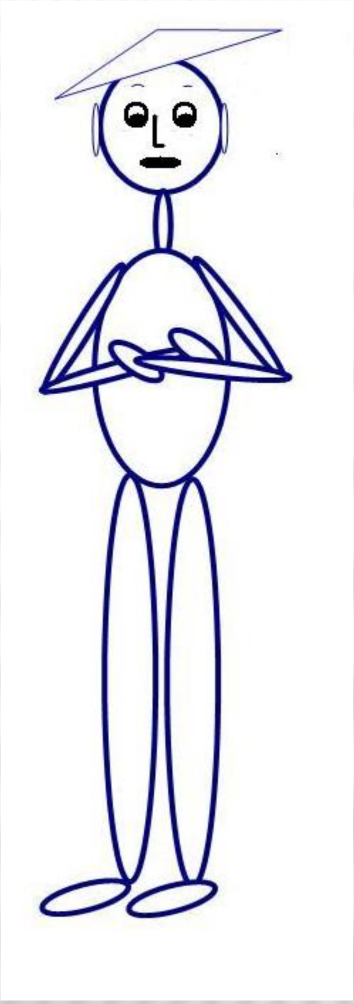
- Basics of
  - Analysis with
    - Antineutrinos from
      - Heat Producing Elements K, U, Th
        - In the Earth

Session 1 Objectives
January 05, 2010

By the end of this session we will learn about

- Radiogenic heat producing elements (HPE) – K, U, Th
- Basics of terrestrial heat flow concepts relevant to radiogenic HPE analysis by antineutrinos
- Basics of Bulk Silicate Earth (BSE) model concepts relevant to radiogenic heat producing elements (HPE) analysis by antineutrinos
- Neutrino parameters in the context of antineutrino analysis of concentration determination of HPE

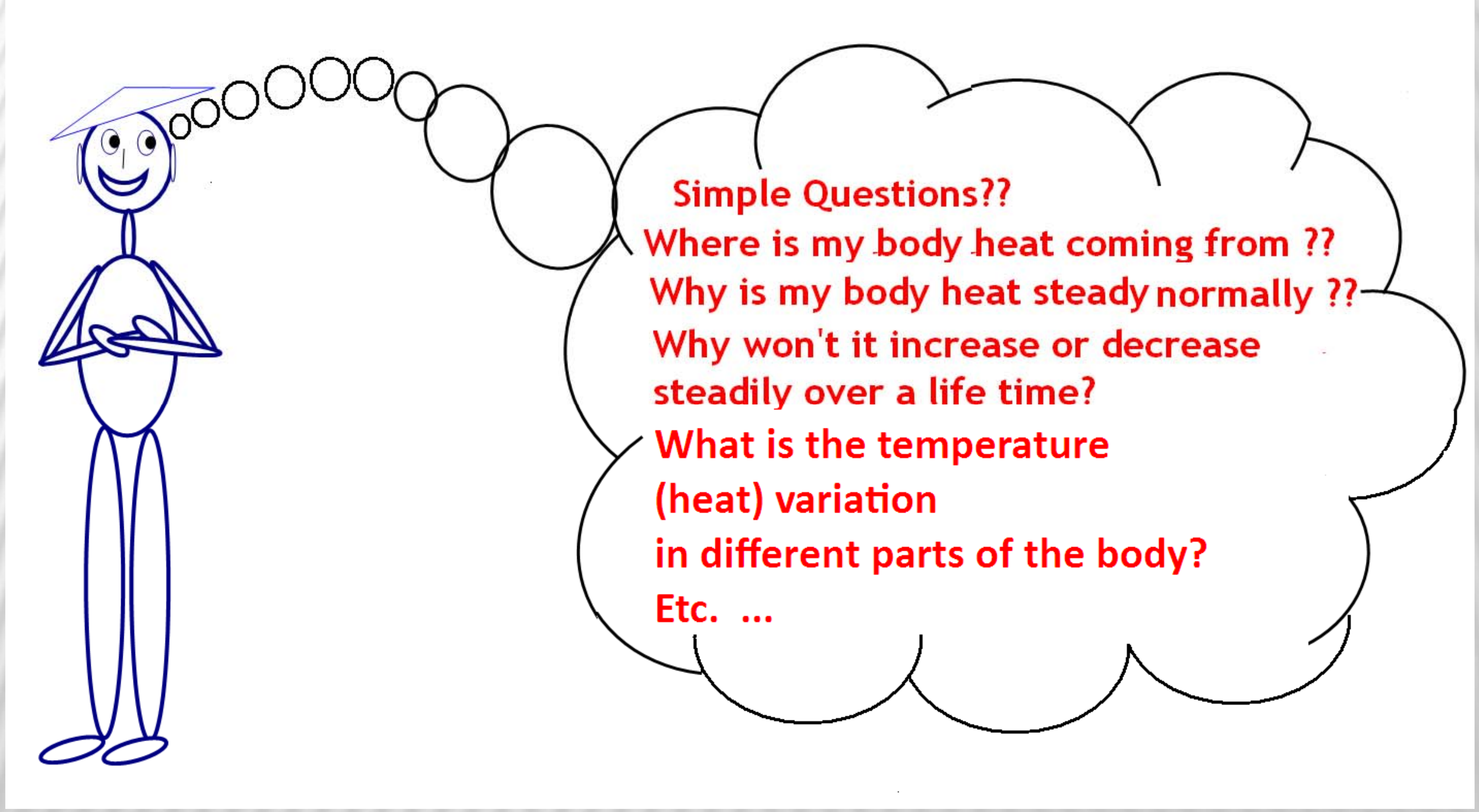
Session 1 Objectives



- **What am I going to talk about?**
  Basics of terrestrial heat concepts relevance.
- **Relevance to what?**
  Relevance to analysis of concentration determination of radiogenic heat producing elements (HPE) in the Earth
- **Analysis by what methodology?**
  By antineutrino detection .

Human Body & heat

Figure: Some heat related questions about human body



Earth Body heat

Simple heat related questions about the Earth body:

- **What are the sources of heat - external and internal?**
- **What are the mechanisms of heat distribution?**
- **What is the variation of heat with time?**
- **What is the variation of heat with depth?**

Etc. …

Figure. Earth Face

Terrestrial heat

In this course – the word "terrestrial" specifically refers to the planet Earth.

The word "terrestrial" is also currently referred to other planets such as Mars and Venus.

So a simple question is - What is terrestrial heat?

A simplistic answer is -

Terrestrial heat is the heat of the planet Earth.

But that is an incomplete answer for the incomplete question.

What further questions can we ask about terrestrial heat?

What are the fundamental questions unanswered still?

Terrestrial heat

We all know that the surface of the Earth gets heated externally by solar radiation, meaning by Sun's rays.
We also know that Earth is getting heated internally, from inside.
So there is heat production from inside and heat flow to the surface of the Earth.
So the next leading questions are:
How is that heat produced? How is it reaching the surface?
How much is needed? Currently sufficient?
Otherwise will the Earth cool off?
Thus the field of Terrestrial Heat has many important fundamental questions - on which fundamental research has been ongoing for decades.

Terrestrial heat variation with depth

The earth has a temperature around 7000 degrees Celsius in inner the core, on an average the temperature increases by 25-35 deg. C. per kilometer measured from the earth surface and inwards.

The temperature potential can be exploited as heat by pumping a fluid around in a circuit which takes the medium to depths of 2-5 kilometers. Depending on the depth and temperature profile, it is possible to achieve exit temperatures around 200 deg. C.

Knowledge of energy sources in the Earth is of increasing interest from many different points of view in the geosciences.

Why the heat is so high at the center of the Earth?

Terrestrial heat variation with depth

The Global Heat Flow Database of
The International Heat Flow Commission
is maintained currently by
Prof. Will Gosnold, Univ. of North Dakota
http://www.heatflow.und.edu/index.html

So where is the heat coming from in the center of the Earth?

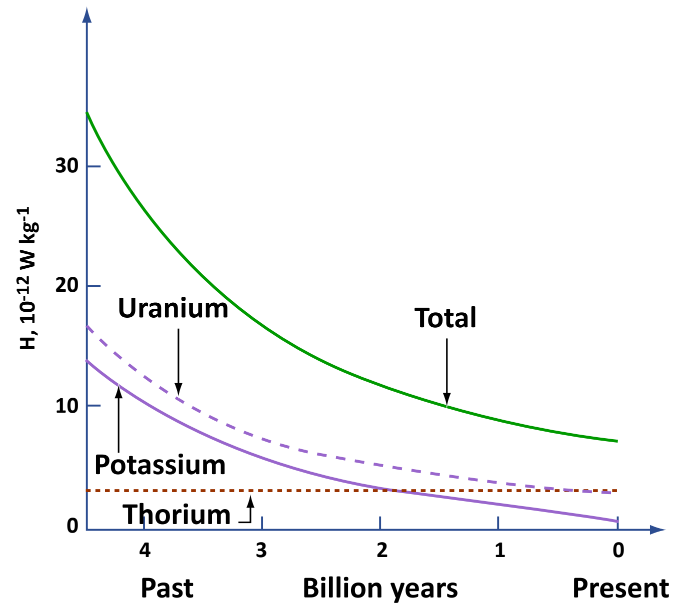
Terrestrial Heat–
Age of the Earth by Lord Kelvin

- In late 1800's, Lord Kelvin assumed that the Earth was originally as hot as the Sun and has been cooling ever since. He calculated that it would take between 20 and 400 million years for the earth to cool to its present state.
- This age estimate was not acceptable when compared to other evidence. This disagreement led to the searches for the identification of other sources of heat production within the Earth.
- To resolve this disagreement we need to know the sources of heat in the heat equilibrium equation.

Earth – Heat Generation Present – Past Estimate

Figure. Earth continuing to cool over its life time by current theory

- For example, heat production 3 billion years ago is twice heat production of present day.
- Thus, less and less heat is getting generated in the Earth through times, because of the radioactive decay of the heat producing elements .



Mean mantel heat production rates due to the decay of the radioactive isotopes of K, U and Th as functions of time from present to the past.

Figure by MIT OpenCourseWare.

Radioactivity – Radiogenic Heat

Natural radioactivity as a heat source in the Earth and Heat Producing Elements (HPE):

- Radioactivity as a heat source was quickly recognized soon after its discovery in 1895.
- Radiogenic heat is the heat generated by the decay of radioactive isotopes of the elements.
- Radiogenic heat was investigated as the source of heat flux over and above the primordial heat in the Earth. Abundances of heat producing elements (HPE) in the Earth were investigated extensively since then.

Terrestrial Heat

- Terrestrial heat - production
- Terrestrial heat - flow - dissipation
- Terrestrial heat - transport
- Terrestrial heat - energy usage
- Etc.

The focus of this course is the importance of antineutrino analysis for the concentration determination of the Heat Producing Elements for assaying the whole Earth – the knowledge of which is useful for identifying the radioactive sources of heat in such studies.

Terrestrial Heat

Refer to Quantitative geophysics and geology by Lliboutry, L., Chapter 9. Terrestrial Heat

9.11 Estimation of geothermal fluxes 180 – 181

9.12 Origins of Terrestrial heat 181-183

9.13 Concentrations of radioactivity in granitic terrain 183 – 185.

9.14 Lithospheric thickness and basin subsidence 185- 186

Quantitative geophysics and geology,
Springer- Praxis, New York, 2000.
ISBN 1-85233-115-1 Springer Verlag 2000

Terrestrial Heat

Refer to

Physics of the Earth, by Stacey, F. D., and Davis, P. M.,

Chapter 2. Composition of the Earth p. 29-47

Chapter 21 The global energy budget

Pages 348 – 352

Tables 21.1, 21.2, 21.3 and 21.4 are important

Physics of the Earth, 4th Edition,

Stacey, F. D., and Davis, P. M.,

Cambridge University Press, New York, 2008,

ISBN 978-0-521-87362-8 (hardback).

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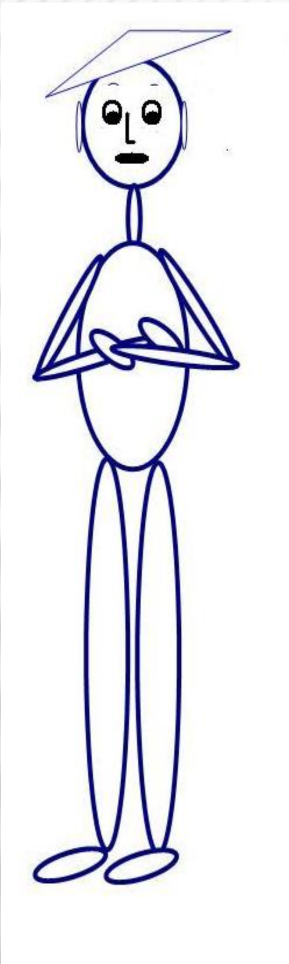

Radiogenic
Heat Producing Elements (HPE):
K, U, Th isotopes, half-lives

Radiogenic Heat Producing Elements

The Earth is still currently getting heated by the decay of radioactive elements.

Natural radioactive isotopes have existed billions of years ago to the present.

Only three radioactive elements occur within the Earth in sufficient abundance and generate enough heat to be significant contributors to radioactive heat production.

The most important are uranium, thorium, and potassium.

Their radioactive isotopes are Uranium-235, and Uranium-238, Thorium-232, and Potassium-40.

List of some long-lived naturally occurring radioactive nuclei and their half-lives:

Isotope	Half-life (billion years)
Potassium-40	1.28
Thorium-232	14.1
Uranium-235	0.7038
Uranium-238	4.468

However, there are many more heat producing radioactive isotopes of other elements.

This information is relevant to antineutrino analysis for the estimation of HPE in the Earth regions.

Radiogenic Heat Producing Elements

Four significant radioactive isotopes of HPE

- Two radioactive isotopes of Uranium

^{235}U	Uranium-235	(Half-life 0.7038 billion years)
^{238}U	Uranium-238	(Half-life 4.468 billion years)

- One radioactive isotope of Thorium

^{232}Th	Thorium-232	(Half-life 14.1 billion years)

- One radioactive isotope of Potassium

^{40}K	Potassium-40	(Half-life 1.28 billion years)

- Potassium-40 has remained the most important heat-producing isotope throughout the Earth's history.
- Uranium-235
  - has the fastest decay rate because of the shortest half-life of the four
  - is the smallest contributor of the four, to the terrestrial heat
  - was the second biggest contributor during the Earth's first half-billion years.

Radiogenic Heat Producing Elements

- Each so-called heat- producing isotope decays at a different rate
- The relative importance of each isotope has varied over time
- The total rate of radioactive heat generation has declined with time

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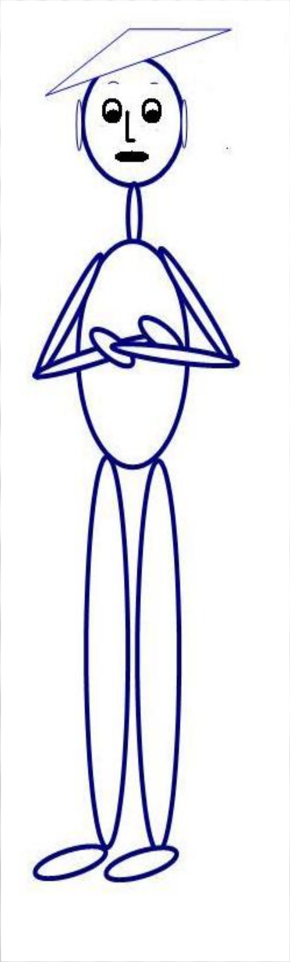


To provide a pictorial understanding of the Earth's regions, especially the dimensions of the Earth's interior relative to the radiation path length. This information provides the basic need for antineutrino analysis of heat producing elements (HPE) for assaying the whole Earth.

Earth Characteristics

Before proceeding further – let us look at the characteristics of the Earth, such as its parameters: size, density, mass; Earth's shells,

Tables and figures in the following slides are:

Table: Earth parameters

Table: Range-depth of Earth's shells; Figure. Earth's Shells
Ref.: United States Geological Survey (USGS)

Figure: Simplified Earth's Regions
Ref.: NORM Group Organization (Cambridge, USA)

All these parameters have relevance in the antineutrino analysis of heat producing elements. Used also in terrestrial heat flow calculations, Geochemical model estimates.

Table. Earth Parameters
Size, Area, Mass

Parameters	Value	Units
Polar Radius	6378.137	km
Equatorial Radius	6356.752	km
Equi-volume spherical radius	6371.0	km
Surface Area	5.10E+08	km^2
Mean density	5.51E+03	kg/m^3
Mean density	5.51E-06	kg/km^3
Total mass	5.97E+24	kg

Ref. New Theory of the Earth, D. L. Anderson, p. 379. Table A.5 Earth Parameters

All these parameters have relevance in the antineutrino analysis of heat producing elements.
Used also in terrestrial heat flow calculations, Geochemical model estimates.

Earth Shells

- Synonymous terminology
  - Earth's shells
  - Earth's layers
  - Earth's regions

Figure. Earth Shells
Ref.: United States Geological Survey (USGS)

Figure. Sectional view of the Earth shells:
Not drawn to scale.
Continental crust
oceanic crust,
lithosphere (crust + upper most solid mantle),
asthenosphere (portion of upper mantle which is below the lithosphere),
lower mantle,
outer core,
inner core.

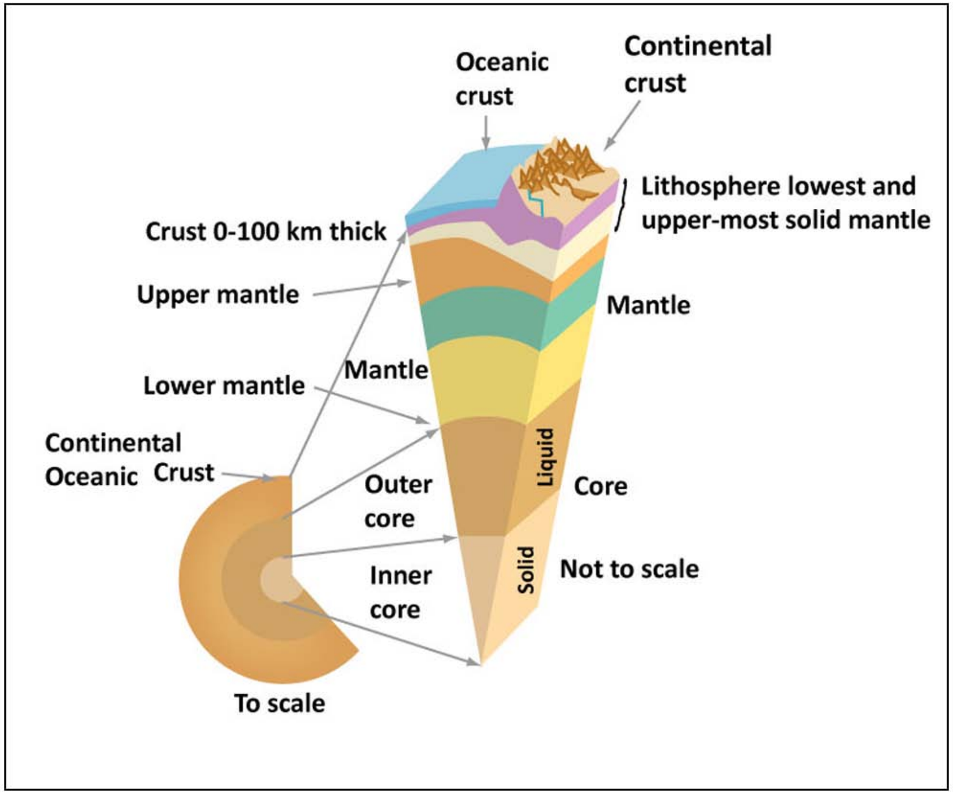


Figure by MIT OpenCourseWare.

This is for information purpose in this course in order to connect with studies in geosciences

Figure. Earth Shells Descriptive Text

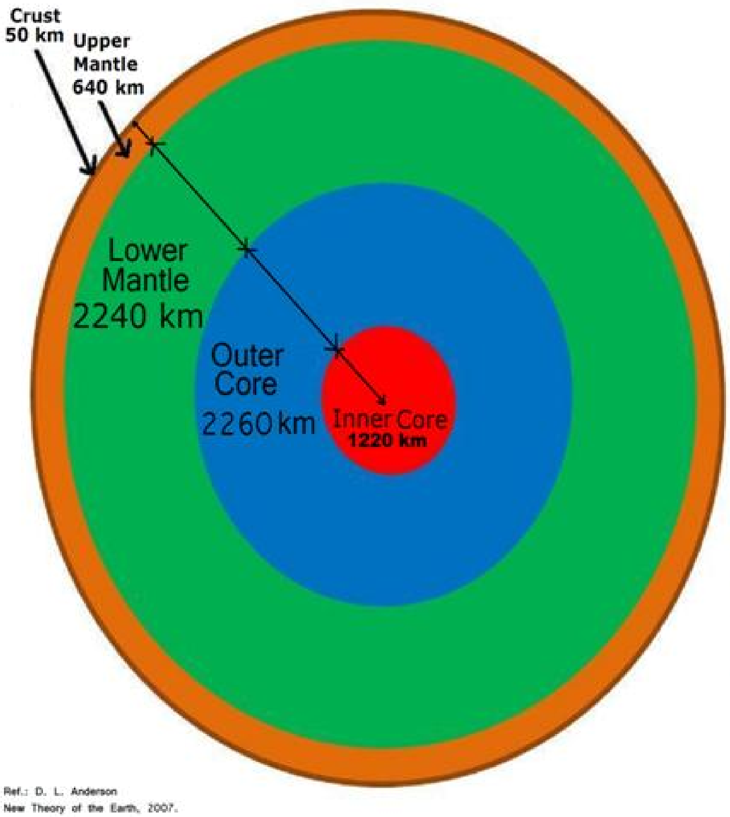
Earth's layers or shells or regions are shown pictorially in one dimensional concentric circles. Earth consists of basically three components, namely the crust on the surface, below the crust is the mantle and below the mantle is the core. The crust is further divided into oceanic crust and continental crust, the mantle is sub divided into the upper mantle which is below the crust, and the lower mantle is below the outer mantle going toward the center of the Earth. Similarly, the core is subdivided into the outer core and inner core. The outer core is below the lower mantle. The inner core is at the very center of the Earth. The approximate radial thicknesses are: oceanic crust 5 to 10 km, continental crust 50 to 65 km, upper mantle 640 km, lower mantle 2240 km, outer core 2260 km and inner core 1220 km. The radius of the Earth is 6370 km.

All this information provides basis for this course, in order to connect with studies in geosciences.

Ref: D. L. Anderson, The New Theory of the Earth, 2007, pp 92. Table 8.1

Figure: Courtesy of The NORM Group Organization, Copyright 2008.

Figure. Earth's Regions Radial Depth



Regions	Radial Thickness km
Crust	50
Upper Mantle	640
Lower Mantle	2240
Outer Core	2260
Inner Core	1220

Image courtesy of The NORM Group Organization

It can be seen from the figure that, these distances are so large , relative to the radiation path length, sample collection by current geophysical methods and geochemical analyses are not possible.

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d for antineutrino
ysis in-situ.

Image courtesy of NORM Group Organization, used with permission

Table. Mass of the Earth regions

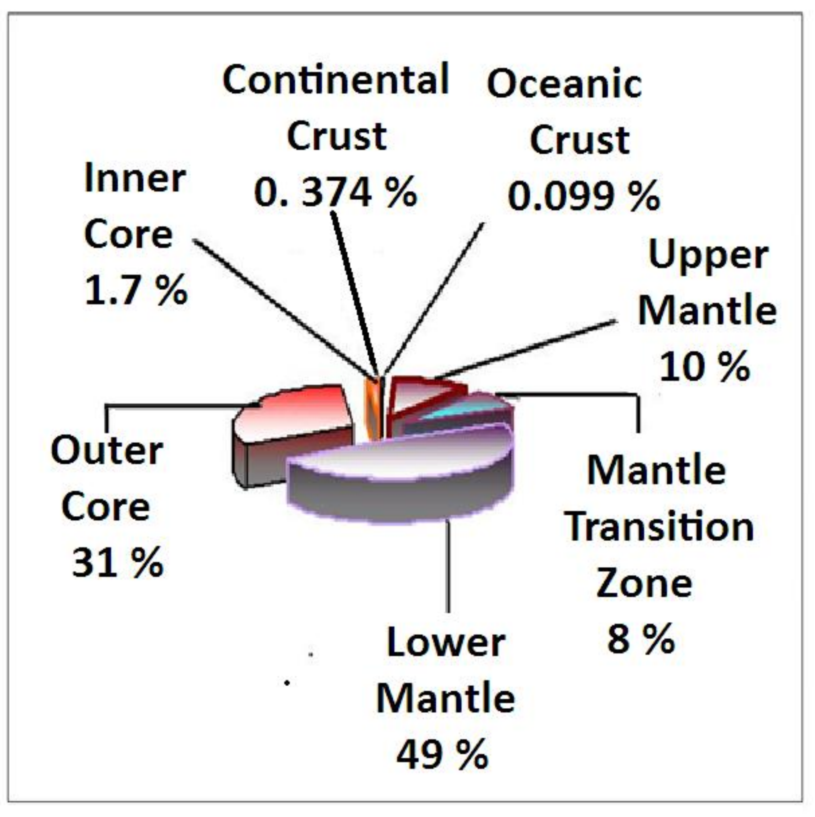
	Depth Km	Depth km	Fractional Earth Mass	Mass kg	Mass kg
	Anderson	USGS	Anderson	Anderson	Turcotte
Continental Crust	50	0-50	0.00374	2.234E+22	2.360E+22
Oceanic Crust	10		0.00099	5.914E+21	
Upper Mantle	390	720	0.103	6.153E+23	
Transition Zone	250		0.075	4.480E+23	
Lower Mantle	2240	2171	0.492	2.939E+24	Mantle Total 4.043E+24
Outer Core	2260	2259	0.308	1.840E+24	Core Total 1.883E+24
Inner Core	1220	1221	0.017	1.016E+23	
Earth Total Mass	6370	6421	1.00	5.972E+24	

Ref: New Theory of the Earth, D. L. Anderson, 2007, p. 92;
Geodynamics, D. L. Turcotte and G. S. Schubert, 2002, p. 433.

All these parameters have relevance in the antineutrino analysis of heat producing elements.
Used also in terrestrial heat flow calculations, Geochemical model estimates.

Figure. Fractional masses Of the Earth regions % of Earth's total mass

Figure.
The fractional masses of the Earth regions, expressed in % of the total mass of the Earth, (shown in pie diagram).
Continental crust 0.374%
Oceanic crust 0.099 %
Upper mantle 10%
Mantle transition zone 8%
Lower mantle 49%
Outer core 31%
Inner core 1.7%
5.972x 10^{24} kg is the total mass of the Earth.



Information of the Earth regions' masses is necessary for the estimation of HPE in the Earth regions.

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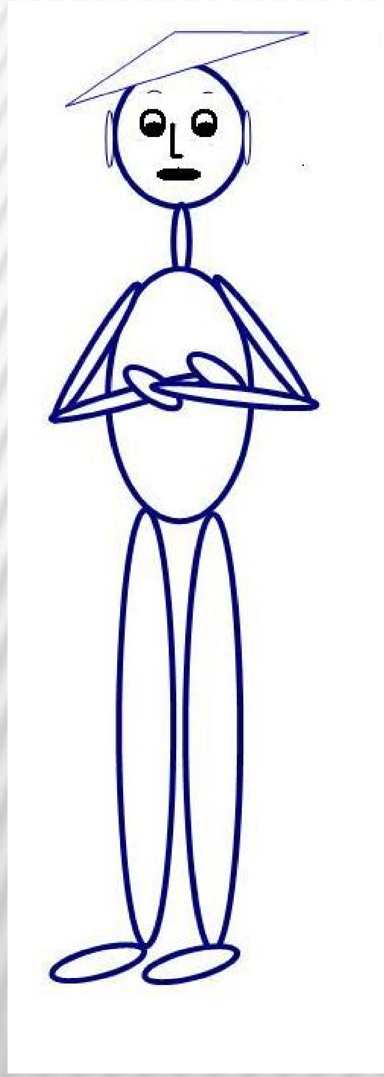


- **Terrestrial Heat**

  Heat Flow

  Heat production.

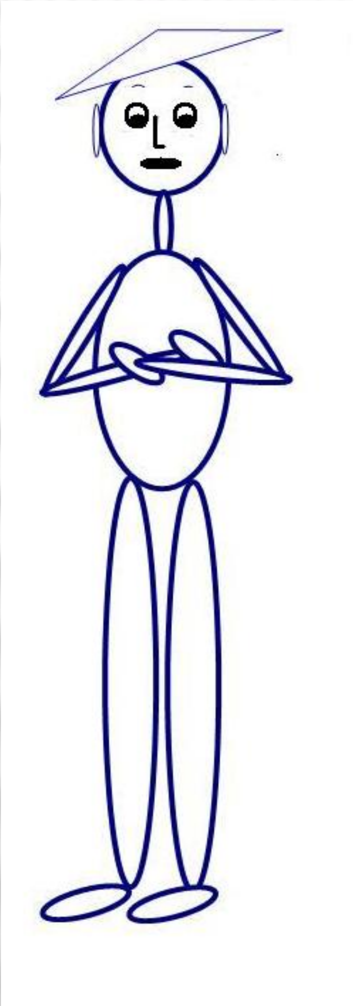
- **Relevance to what?**

  Relevance to analysis of concentration determination of radiogenic heat producing elements (HPE) for the assay of the whole Earth in-situ.

- **Analysis by what methodology?**

  By antineutrino analysis.

Next proceeding to



Geophysical Observations
Terrestrial Heat Flow

relevance to analysis of
concentration determination of
radiogenic heat producing elements
for the assay of the whole Earth
in-situ by antineutrino analysis.

Terrestrial heat flow

Current understanding of the heat flow from the studies in the geosciences:

- Knowing how the bulk of the Earth's heat is generated enables us to explain why the geothermal gradient is much greater in the crust than in the mantle.
- Uranium, thorium, and potassium are all much more abundant in the crust than in the mantle. They are all ‘incompatible’ elements that go preferentially into the magma when rock begins to melt.

Terrestrial heat flow

- The mantle-derived melts from which the Earth's crust formed were therefore greatly enriched in these elements.
- Consequently, about half the Earth's radioactive heat production takes place in the crust, although the volume of the mantle is hundred times greater than that of the crust.
- Penetration is required to measure beyond for example 15 km in –situ.

This information is relevant to antineutrino analysis
for the estimation of HPE in the Earth regions.

Terrestrial heat generation
Radiogenic sources

Ref.: Turcotte and Schubert, Geodynamics p. 136-137

A substantial part of the heat lost through the Earth's surface originates in the interior of the Earth by the decay of the radioactive elements uranium, thorium and potassium.

Some part of the surface heat loss must come from the overall cooling of the Earth through geologic time.

Terrestrial heat generation Radiogenic sources

Ref.: Turcotte and Schubert, Geodynamics p. 136-137.

- An upper limit to the concentration of radioactive elements can be derived by attributing all the surface heat loss to the radioactive heat generation.
- The mean heat generation per unit mass is

  $H = Q/M$

  $H_{Total} = H_{mantle} + H_{core}$

  where

  H = Heat generation per unit mass Wkg^{-1}

  Q = Heat W

  M= Mass of the Earth = 5.97E24 kg

Terrestrial heat generation
Radiogenic sources

Q = The total heat from the interior of the Earth

$= (A_c \times Q_c) + (A_o \times Q_o)$

A_c = area of the continents

Q_c = mean continental heat flow

A_o = area of the oceans mean oceanic heat flow

Q_o = mean oceanic heat flow

$Q = 4.43 \times 10^{13}$ W = 44.3 Tera Watts = 44.3 TW

Q_m = The mean surface heat flow

= Q/ Total surface area of the Earth

Q_m = Mean surface heat flow = 87mW m $^{-2}$

Ref.:Geodynamics, p.136, D. L. Turcotte and G.Schubert

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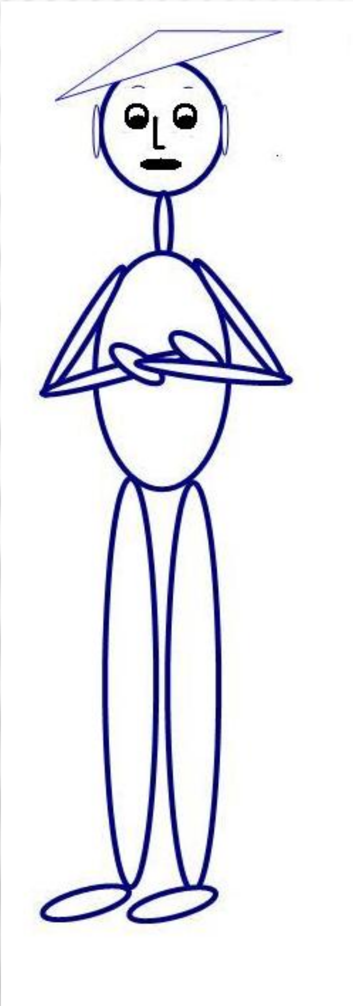

The following slides:

To provide a pictorial understanding of the Heat Flow on the surface of the Earth.

This knowledge is needed for an understanding of why antineutrino analysis of radiogenic heat producing elements is needed.

It is like an understanding pre-requisite.

The following presentation is by Heat Flow expert Prof. W. Gosnold of Univ. of North Dakota.

HPE & Terrestrial Heat Flow
-
Prof. Gosnold's studies

Terrestrial Heat Flow

Heat Flow in Young Oceanic Crust:

Is Earth's Heat Flux 44 TW or 31 TW ?

By W. Gosnold

American Geophysical Union

2008 Joint Assembly, Ft. Lauderdale

T-21A Thermotectonic Models of the Oceanic

Lithosphere and the

Problem of Hydrothermal Circulation: A New Look

http://www.heatflow.und.edu/Gosnold%20T21A-01.pdf

Terrestrial Heat Flow

A Mechanism to Explain the Exponential Model for Heat Production

By W. Gosnold

American Geophysical Union

December 11, 2007, Fall Meeting

T-22B Understanding the Earth's Deep Lithosphere II

HPE & Terrestrial Heat Flow

-

End of
Prof. Gosnold's studies

Some observations

- "An upper limit to the concentration of radioactive elements can be derived by attributing all the surface heat loss to the radioactive heat generation."

  - Turcotte & Schubert
- "The linear relation between heat flow and radioactive heat production applies at sites where both quantities are observed.
- It does not necessarily apply where heat production and heat flow are correlated geographically."-

  - Gosnold

Some more observations

"

- HPE content relates to lithology

  Lithosphere means – crust + solid upper mantle
- Most of the HPE, particularly U and Th, are in upper crust
- The vertical distribution is subject to many interpretations
- In orogenically related plutonic complexes, the exponential model appears to fit the data and

  there is a theoretical basis for an exponential vertical distribution. "

  \- Gosnold

Table. Heat release from the Heat Producing Elements in the Earth's interior

Rates of Heat release (H) and concentrations of the heat producing elements (C) in the Earth's interior			
	H W/kg	C kg kg^{-1}	Half-life yr
U-238	9.46E-05	3.08E-08	4.47E+09
U-235	5.69E-04	2.20E-10	7.04E+09
U	9.81E-05	3.10E-08	
Th-232	2.64E-05	1.24E-07	1.40E+10
K-40	2.92E-05	3.69E-08	1.25E+09
K	3.48E-09	3.10E-04	

Heat release is based on present mean mantle concentrations of the heat producing elements (HPE)

Ref.: Geodynamics - D. L. Turcotte and G. S. Schubert Table 4.2, p. 137

Total heat flow from the interior of the Earth

Total Heat flow

= Continental + Oceanic

Surface Heat

to the total surface of the Earth

44 $\pm$ 3 TW

Heat flow studies measure surface heat, not the total heat of the Earth. Where as, antineutrino analysis of concentration determination of the HPE of the entire Earth provides DIRECT measurement of TOTAL radiogenic heat of the Earth.

Terrestrial heat generation radiogenic sources

However, according to geochemical models, the core cannot contain significant fraction of heat producing elements HPE.

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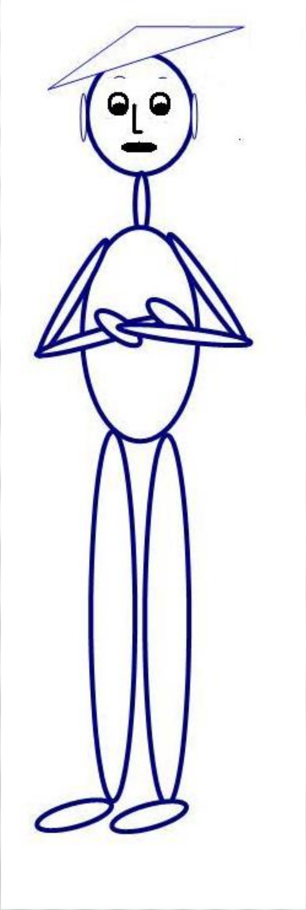

Bulk Silicate Earth (BSE) model

relevance to the antineutrino analysis of concentration determination of HPE for the assay of the whole Earth.

What is
Bulk Silicate Earth
(BSE) Model ?

Bulk Silicate Earth (BSE) Model

A global description of the crust-plus-mantle system is provided by the bulk silicate earth (BSE) model, a reconstruction of the primordial mantle of Earth, subsequent to the core separation and prior to crust differentiation, based on geochemical arguments.

In the BSE model :

- Uranium abundance $A(U) = 2\times10^{-8}$ = 20 ppb
- Th/U $\equiv A(Th)/A(U) = 3.9$
- K/U $\equiv A(K)/A(U) = 1.14\ \times10^{4}$

For comprehensive information about the derivation of these values, and understanding of geochemical reference models , in the context of antineutrino analysis, a list of references is provided in the Reference section of this presentation.

Bulk Silicate Earth (BSE) Model Limitations

As Fiorentini et al [2005] aptly explained,

"In our modelling we assumed that the Earth's core does not contain a significant

amount of radioactive elements. We are aware that some authors proposed

that the core is hosting some radioactive elements and particularly K, in order to offer

an alternative explanation either for the energy needed to run the geodynamo

or as a way to explain Earth's volatile elements inventory [McDonough , TOG 2003].

However, the proposed models of the core's energy budget imply a variety of

assumptions and are vastly different, thus reaching in cases opposite conclusions,

whereas geochemical evidence is in favour of a general absence of radioactive heating

in the core.

We want to stress here that this point is not crucial for our modelling.

Comparison of predictions of geo-neutrino production with experimental results at

Radiogenic Heat Components Pie Diagram

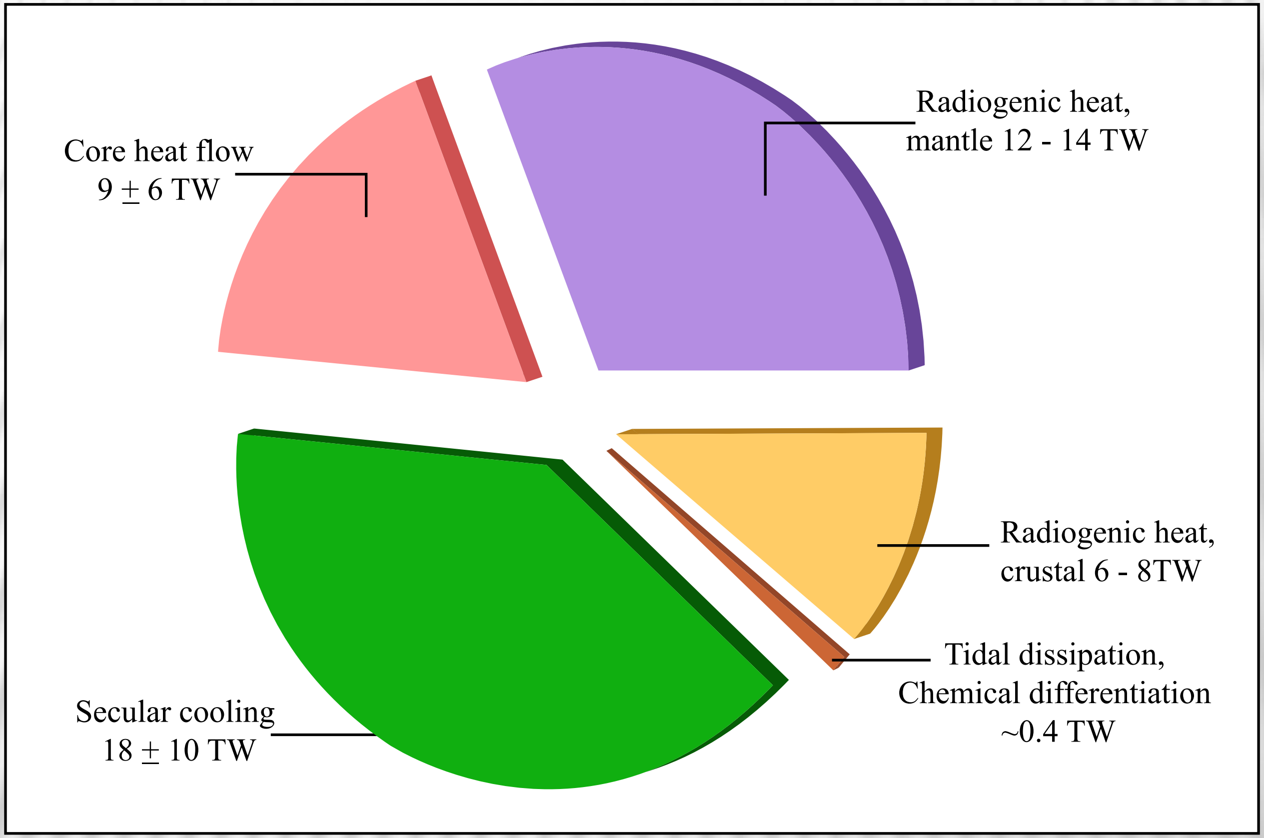

Figure by MIT OpenCourseWare.

Open questions about radiogenic heat producing elements in the Earth

1 - What is the radiogenic contribution to terrestrial heat production?

2 - How much U and Th in the crust?

3 - How much U and Th in the mantle?

4 - What is hidden in the Earth's core? (^{40}K, …)

5 - Is the standard geochemical model Bulk Silicate Earth (BSE) satisfactory in providing the terrestrial radiogenic heat estimates?

Energetics of the Earth and The heat source paradox

- Heat from the Earth is the equivalent of some 10000 nuclear power plants

  H_{Earth} = (30 - 44)TW

- The BSE canonical model, based on **cosmochemical** arguments, predicts a radiogenic heat production ~ 19 TW:
  ~ 9 TW **estimated** from radioactivity in the (continental) crust
  ~ 10 TW **supposed** from radioactivity in the mantle
  ~ 0 TW **assumed** from the core

- Unorthodox or even heretical models have been advanced…

D. L. Anderson (2005),Technical Report, www.MantlePlume.org

Radioactivity in the core?

Conventional understanding:

Radioactive heat production is exclusively in the Crust and Mantle of the Earth

(Bulk Silicate Earth - BSE).

Core cannot contain significant fraction of heat producing elements HPE.

Radioactivity in the core Suggestions

- Elsasser [1950] suggested the radioactive decay energy of uranium and thorium concentrated at the center of the Earth as the source for thermal convection in the fluid core.

  W. M. Elsasser, The Earth's interior and geomagnetism, Rev. Mod. Phys, 1950, 22, 1-35.
- Ferber et al [1984] again supported that concept by an experiment showing the tendency of uranium to alloy with iron at high temperatures.
- R. C. Ferber, T. C. Wallace and L. M. Libby, Uranium in the Earth's core, EOS, 1984, 785-786.
- Source: J. M. Herndon

Radioactivity in the core
Suggestions & Estimates

Herndon provided alternate possibilities for uranium to exist in the core by considering enstatite chondrites.

- Herndon, J. M., The nickel silicide inner core of the Earth. Proceedings of the Royal Society of London, 1979, A368, 495-500.
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Radioactivity in the core Suggestions & Estimates

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  Sub-structure of the inner core of the Earth.

  Proceedings of the National Academy of Sciences USA, 1996, 93, 646-648.

  http://www.pnas.org/content/93/2/646.full.pdf
- Herndon , J. M., and Edgerley , D. A., [2005] provided preliminary estimates of the abundances and distribution of fissionable and nonfissionable radionuclides within the deep interior of the Earth.

  Ref.: Background for Terrestrial Antineutrino Investigations: Radionuclide Distribution, Georeactor Fission Events, and Boundary Conditions on Fission Power Production
- http://arxiv.org/ftp/hep-ph/papers/0501/0501216.pdf

Potassium radioactivity in the core Suggestions & Investigations

Earth's core: Special K

"The nature of the heat sources in the Earth's core has long been debated. Potassium-40 decay was suggested as one candidate on theoretical grounds over 30 years ago, but data on potassium solubility in iron have proved inconclusive. Experiments performed at high temperatures (up to 1,800 °C) and pressures (30 kilobars) now show that ^{40}K could be a substantial heat source in the cores of Earth and Mars."

Ref. Experimental evidence that potassium is a substantial radioactive heat source in planetary cores."
V. R. Murthy, W. V. Westrenen and Y. W. Fei
Nature , 2003, 423, 163–165; doi:10.1038/nature 01560

Potassium radioactivity in the core
Suggestions & Investigations

- The maximum possible amounts of potassium in Earth's core suggested by the experiments range from 60-130 ppm [Murthy etal 2003], to 1200 ppm [Gessman etal 2002], to as high as 7000 ppm [Lee at al 2003], 29 ppm [Stacey and Davis, 2008].

- Fields and Hochmuth [2004] did simulation study of antineutrino intensities from 130 ppm, 1200 ppm and 7000 ppm of core K.

Conclusions
Terrestrial Heat

Geophysical heat flow studies measure the surface heat flow, hence provide the Earth's surface heat measurements.
They provide a lower limit constraint on the Earth's total heat.

Heat flow studies, currently cannot measure the concentrations of the heat producing elements upto depths of about 15 km.

Geochemical analyses might have been done on some mantle rocks, but not from deep interior of the Earth.

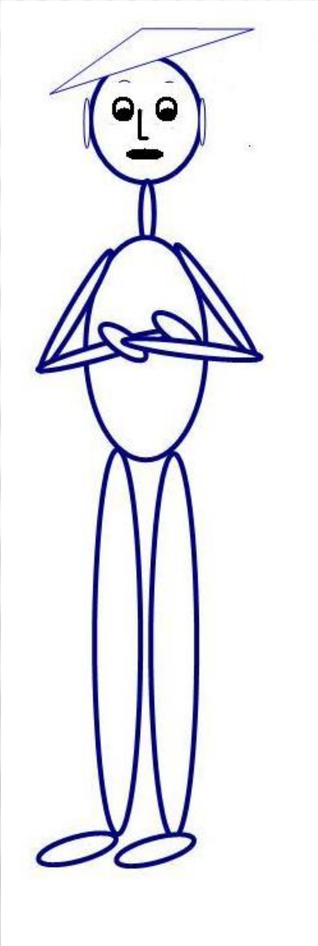
Geochemical modelling, based on cosmochemical arguments, currently predict that core cannot contain significant fraction of heat producing elements K, U and Th.

Conclusions
Terrestrial Heat

So, there is a strong geo-scientific need to investigate the deep interior of the Earth for the accurate and direct determination of HPE concentrations.

Since, Earth's deep interior is inaccessible, in-situ direct measurements have to be performed.

Next proceeding to

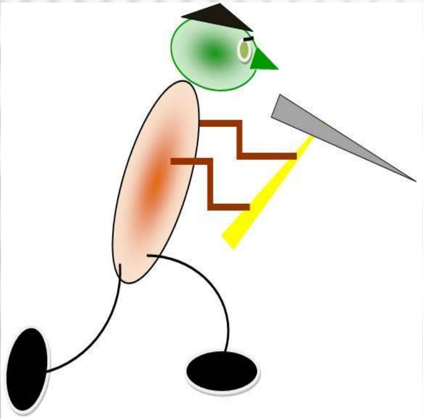


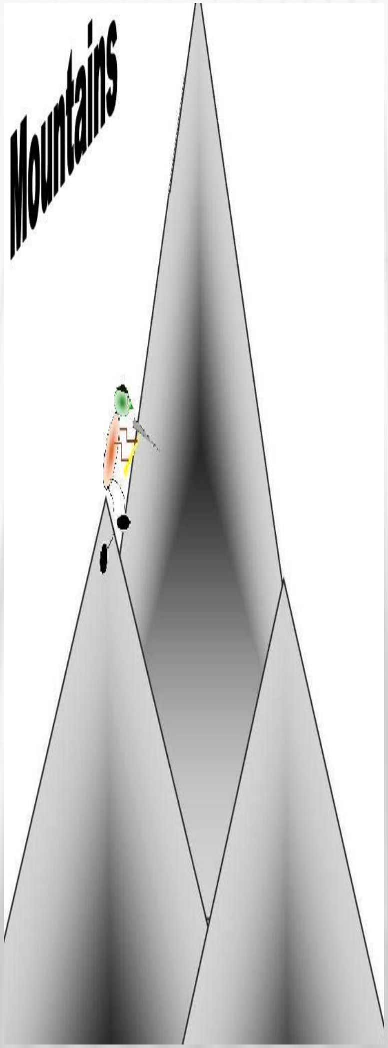
- **Limitations of current analytical techniques** for assaying the HPE in the deep interior of the Earth
- **Importance of antineutrino analysis** to estimate/determine the HPE activity in the deep interior of the Earth.

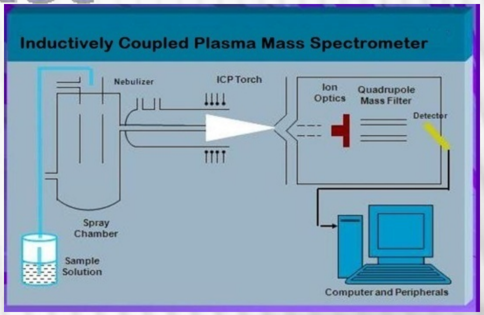
Conventional field sampling of crust

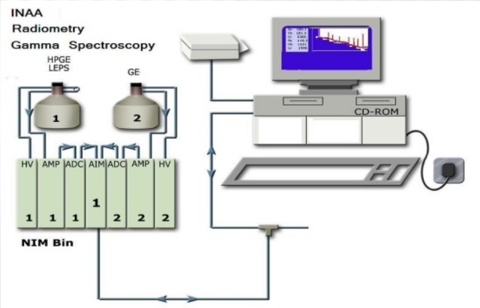
Geophysical and Geochemical

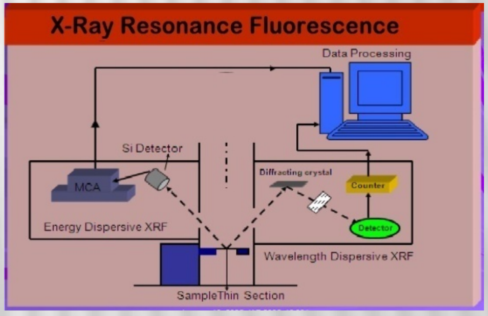
HPE analyses

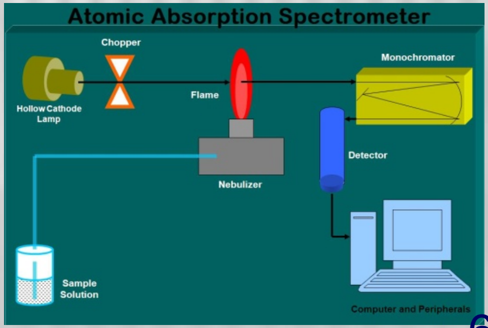










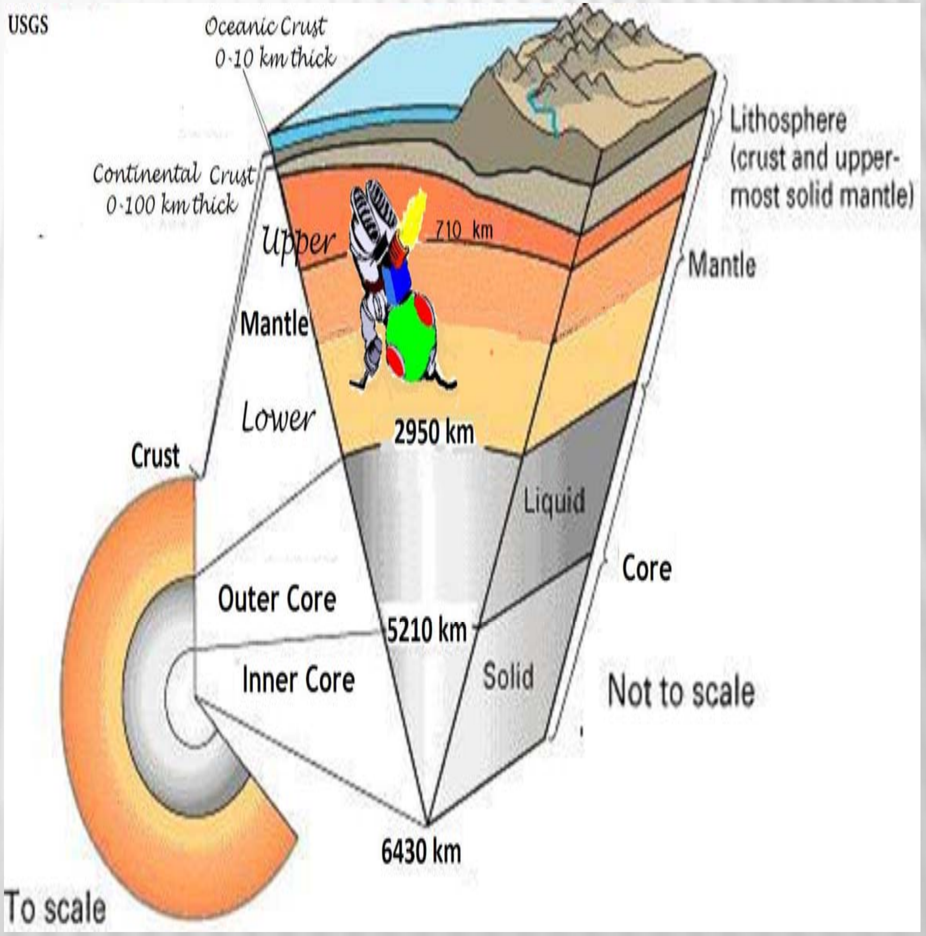


Descriptive text of the Figure

Figure describes:

Heat Producing Elements namely K, U, Th concentrations are determined in crustal rock samples, later in deep sea drilled core samples etc., say, in 1960's predominantly by radiometric gamma spectroscopy, bore-hole logging, and other chemical techniques, later in the 1980's through 90's with the advent of computers and solid state detector technology, neutron activation analysis became popular; which is followed by currently popular technique called ICPMS inductively coupled plasma mass spectrometry. But these techniques are not useful any more because of the inaccessible distances in the deep interior of the Earth.

Analytical techniques to probe the Earth's deep interior



Antineutrino concept

- The Earth emanates about 40 TW of heat at the surface coming from the interior.

Ref. : Zharkov V. N., Interior Structure of the Earth and Planets, Harwood Acad. Publ., Switzerland, 1986.

It is believed that considerable part of this heat originates from radioactive decay of Uranium, Thorium and Potassium hidden in the Earth. Antineutrinos , "geoneutrinos" as they are referred to by particle physicists, generated in the radioactive decays provide information on the abundances and radiogenic heat sources inside the Earth. This information is of key importance for understanding of the formation and subsequent evolution of our planet.

- The antineutrino concept is now 45 years old. A short overview of this concept is provided by Domogatsky et al .

Ref: Domogatsky, G., V. Kopeikin, L. Mikaelyan, V. Sinev, arXiv:hep-ph/0409069, submitted to Phys. Atom. Nucl.

Dependence of investigations for assaying the Earth's interior

Investigations for assaying HPE were dependent on:

- Geological sampling & Geochemical assay techniques.
- Radiometric and X-ray techniques evolved rapidly with developments in instrumental analysis based on radioactive radiations exploited the signals generated by characteristic alpha, beta, gamma and x-rays from the heat producing elements,
- High resolution and high sensitivity radiation detectors.

Requirements of investigations for assaying the Earth's interior

- In-situ sampling is required in order to investigate the interior regions of the Earth, at ever increasing depths, all the way to the core.
- In-situ sampling reduces the cost of field sampling.
- Penetrating power of the radiation used in the assay technique plays a major role, for in-situ assaying in the field, or in the context of assaying the whole Earth.

What are antineutrinos?

- Antineutrinos are neutrino radiation emanating during the beta decay from the long lived radioactive isotopes in the entire Earth.
- Antineutrinos could be neutrinos or antineutrinos, but usually antineutrinos generated in the Earth are specifically referred to as “geo-neutrinos” by particle physicists.

Ref. Kobayashi and Fukao, 1991

Favorable characteristics of antineutrino radiation for HPE analysis

- 1. Penetration power > Diameter of the Earth. Hence sample the whole earth.
- 2. Travel in straight lines from point A to B. Hence can provide directionality.
- 3. Identification of K, Th and U concentrations from antineutrinos' characteristic signature each element.

Ref. Jagam, P. AGU 2009

Conclusions

Currently, both geophysical and geochemical analyses are not providing a satisfactory measurement of the total terrestrial radiogenic heat from the deep interior of the Earth.

So, there is a strong geo-scientific need to investigate the deep interior of the Earth for the accurate determination of HPE concentrations of the entire Earth.

Antineutrinos – Earth's deep interior

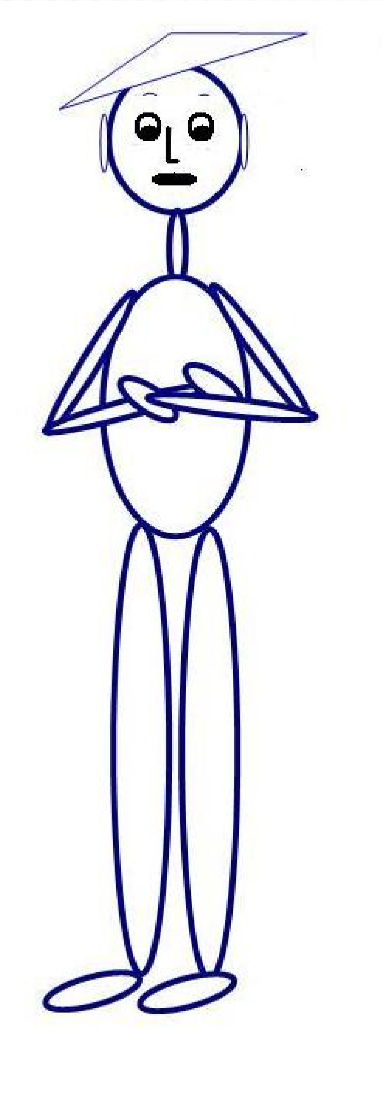
Time is ripe for utilizing antineutrino detectors to probe Earth's deep interior.

Session 1 Review

For antineutrino analysis of concentration determination of Heat Producing Elements in the Earth's deep interior, the following are reviewed

- Terrestrial heat variation with radial depth of the Earth
- Heat producing elements - radiogenic heat
- Earth parameters
- Terrestrial heat paradox
- Radioactivity in the Earth's core
- Importance of antineutrino analysis relative to conventional geophysical and geochemical techniques
- Earth - an antineutrino star

Session 1 Overview



- Basically antineutrino analysis for concentration determination of the Heat Producing Elements (HPE) in the entire Earth, is for the purpose of determining the global radioactivity.
- Currently available geophysical methods and geochemical models are not sufficient.
- This session provides an understanding of
  - 1) the relevance of those models with reference to the analysis of HPE concentrations in the Earth
  - 2) the need for antineutrino analysis compared to the conventional analytical techniques

Session 1 : Student Assignments January 5, 2010

I.

Read:

From the following text books.

New Theory of the Earth by D. L. Anderson

i. Planetary perspective, pages 1- 11.

ii. Let's take it from the top:
the crust and upper mantle, pages 92-108.

iii. The bowels of the Earth, pages 116- 123.

Geodynamics by D. L. Turcotte and G. Schubert

iv. Heat transfer, pages 132-138.

Write:

Your understanding, at least 2 full pages length summary of the four parts.

Session 1 : Student Assignments
January 5, 2010

II. Answer the following review questions.

1. What are the fundamental questions unanswered in terrestrial heat for geoscience?
2. What is the purpose of studying the HPE concentration determination in deep interior of the Earth?
3. Why are new techniques needed to determine the concentrations of HPE ?
4. What are the predominant radiogenic HPE and their radioactive isotopes?

Session 1 : Student Assignments
January 5, 2010

II.

5. Find the Half lives of the following long lived isotopes.

Express them in units of billion years.

Suggested reading: Table of isotopes, by C. M. Lederer and V. S. Shirley

Chart of Nuclides by Knolls or GE.

- Rubidium-87
- Indium-115
- Lanthanum-138
- Neodymium-144
- Samarium-147
- Gadolinium-152
- Lutetium-176
- Hafnium-174
- Rhenium-187
- Platinum-190
- Platinum-192

Explain the characteristics of the elements, such as refractory …

Do the above radioactive isotopes contribute to heat generation in the Earth?

Session 1 : Student Assignments
January 5, 2010

III.

Calculate the radiogenic heat released in different regions of the Earth, using the heat release Table (Turcotte and Schubert) and Fiorentini, and Earth's characteristics of this presentation.

IV. What are the sources of terrestrial heat?

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END of FIrst SESSION

12.091 Basics of Analysis with Antineutrinos from Heat Producing Elements – K, U, Th in the Earth
January (IAP) 2010