Lecture 8: Geological Clocks and the Nuclear History of the Earth: Outline

CBE 30235: Introduction to Nuclear Engineering — D. T. Leighton

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1 Uranium-Lead (U-Pb) Dating: The "Gold Standard"

The U-Pb system is the most robust and reliable geochronometer for dating the early solar system and the age of the Earth. It relies on two parallel decay chains within the same mineral matrix. Due to the long half-lives of the uranium parents (10^8 to 10^9 years), this method is primarily used to date samples older than 1 million years, though its extreme precision makes it the definitive tool for establishing the 4.54 billion-year age of the Earth.

1.1 The Double-Clock Mechanism

The power of U-Pb dating comes from having two independent clocks ticking at different rates in the same sample:

1. **The ^{238}U Clock:** $^{238}\text{U} \rightarrow ^{206}\text{Pb}$ $\quad (T_{1/2} = 4.47 \times 10^9$ years)
2. **The ^{235}U Clock:** $^{235}\text{U} \rightarrow ^{207}\text{Pb}$ $\quad (T_{1/2} = 0.704 \times 10^9$ years)

1.2 The Zircon Crystal: A Perfect Pressure Vessel

The mineral of choice for this method is **Zircon** ($ZrSiO_4$). From a materials engineering perspective, Zircon is the ideal container:

- **Cation Substitution:** During crystallization, U^{4+} and Th^{4+} ions can easily substitute for Zr^{4+} in the lattice.
- **Lead Exclusion:** The crystal structure strongly rejects Lead (Pb) during formation. Thus, any Lead found in a pristine zircon is almost certainly **radiogenic** (produced by decay in-situ).
- **Thermal Robustness:** Zircon has a very high "closure temperature" ($> 900°$C), meaning it locks in its isotopic ratio and resists the "leakage" of daughter products even under extreme geological heating.

1.3 The Concordia Diagram

Because we have two ratios ($^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$), we can determine if a sample has remained a "closed system."

- **The Concordia Line:** A curve representing all points where the ages calculated from both clocks agree perfectly.
- **Discordance:** If a rock underwent a heating event (e.g., a metamorphic event or an impact on the Moon), some Lead may have escaped. These points fall on a straight line (the **Discordia**) that intersects the Concordia at two points: the time of original crystallization and the time of the lead-loss event.

1.3.1 Mathematical Basis of the Concordia

The Concordia curve is the locus of points (x, y) in the $\mathbb{R}^2$ plane where:

$$x = \frac{^{207}\text{Pb}}{^{235}\text{U}} = e^{\lambda_{235}t} - 1, \quad y = \frac{^{206}\text{Pb}}{^{238}\text{U}} = e^{\lambda_{238}t} - 1 \tag{1}$$

As t increases, the curve traces a path that is slightly concave downward because ^{235}U decays significantly faster than ^{238}U.

1.3.2 Discordia and Lead Loss

If a Zircon crystal formed at time t_{start} and remained closed, it sits on the Concordia. However, if a metamorphic event (like a moon impact) occurred at t_{event}, the crystal may lose a fraction of its Lead.

- **The Linear Property:** Because the loss of Lead isotopes (^{206}Pb and ^{207}Pb) is chemically non-fractionating (they are both Lead), the ratio of the loss is constant.
- **The Chord:** This causes the data points to move off the Concordia along a straight line (a **chord**) connecting the point t_{start} to the point t_{event}.
- **Solving for Two Ages:** By measuring several Zircons with varying degrees of Lead loss, we can perform a linear regression. The **Upper Intercept** tells us when the rock first crystallized; the **Lower Intercept** tells us exactly when the "catastrophe" occurred.

1.4 The Physics of Discordance: Why Points Move

Discordance is not random; it is a function of the mineral's internal transport properties. Within a single rock sample, different zircon grains will plot at different positions along the Discordia based on:

1. **Grain Size (a):** Smaller grains have a higher S/V ratio. According to the diffusion equation, the fractional loss of Lead is proportional to $\sqrt{Dt/a^2}$.
2. **Radiation Dosage:** Grains with higher initial ^{238}U concentrations sustain more alpha-recoil damage (metamictization), which increases the effective diffusion coefficient D_{Pb} by several orders of magnitude.

Engineering Takeaway: The Discordia is a "Linear Regression of Failure." We use the fact that some crystals "failed" (lost Lead) more than others to project back to the time when they all successfully "started" (the Upper Intercept).

1.5 Multiple Failure Events and Complex Discordance

When a sample undergoes two or more thermal disturbances at different times (t_1, t_2), the simple linear Discordia relationship is lost.

- **The Geometric Envelope:** Points will scatter within a triangular region on the Concordia plot, where the vertices represent the original crystallization and the subsequent "catastrophes."
- **Zonal Analysis:** Using *in-situ* micro-sampling (Laser Ablation), geochemists can separate the "Inherited Core" (the original age) from the "Metamorphic Rim" (the failure age), effectively resolving two separate Concordia points from a single crystal.
- **Continuous vs. Episodic:** A curved Discordia is indicative of continuous diffusive loss over geological timescales, whereas a straight chord indicates a short-lived, high-energy event (e.g., the Late Heavy Bombardment on the Moon).

1.6 Case Study: Interpreting Lunar U–Pb Ages (Apollo Era, 1969–1972)

During the Apollo era, researchers at the USGS and collaborating laboratories applied U–Pb geochronology to individual mineral grains extracted from Apollo samples to unravel the Moon's complex thermal and impact history. Ages were determined by dissolving each grain, adding a calibrated U–Pb isotope tracer, and measuring isotopic ratios using thermal ionization mass spectrometry (ID-TIMS).

- **The Observation:** Individual accessory mineral grains (e.g., zircon and related U-bearing phases) from Apollo samples often exhibited strong discordance, meaning that the $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages did not agree.
- **The Geometric Interpretation:** When isotopic data from multiple discordant grains were plotted on a Concordia diagram, the results commonly defined linear arrays (*discordia lines*), rather than clustering on the Concordia curve.
- **The Geological Interpretation:**
  1. **Upper Intercept ($\sim$ 4.4–4.5 Ga):** Interpreted as recording early lunar differentiation and crystallization events, broadly consistent with formation of the lunar crust following magma ocean solidification.
  2. **Lower Intercept ($\sim$ 3.8–4.0 Ga):** Interpreted as evidence for later thermal or impact-related Pb loss events, consistent with intense impact processing of the lunar surface during early lunar history.

Note for Students: In U–Pb geochronology, isotopic discordance is not simply "bad data." When interpreted carefully, discordant ages from individual mineral grains can preserve a record of multiple geological events, providing insight into the timing and sequence of crust formation, metamorphism, and impact-related resetting.

2 Potassium-Argon (K-Ar) Dating: The Volcanic Clock

While U-Pb is the "Gold Standard" for ancient rocks, the K-Ar system is the primary tool for dating volcanic events and the cooling history of the crust. Because of the 1.25 billion-year half-life of ^{40}K, this method is effective for samples ranging from approximately 100,000 years old to the age of the solar system.

2.1 The Branching Decay of ^{40}K

Potassium-40 is a unique radionuclide because it decays via two different modes:

- **Beta Minus (β^-):** ∼89% of decays result in stable ^{40}Ca. (This is rarely used for dating because ^{40}Ca is already ubiquitous in nature).
- **Electron Capture (EC):** ∼11% of decays result in stable ^{40}Ar. This is the "clock" isotope.

2.2 The "Reset Button" and Gas Diffusion

From a transport perspective, K-Ar dating is brilliant because the daughter product is a noble gas.

- **Zeroing the Clock:** In a molten state (magma), any existing Argon gas escapes to the atmosphere. When the lava solidifies, the concentration of ^{40}Ar is effectively zero.
- **Closure Temperature:** As the rock cools, it reaches a "closure temperature" where the crystal lattice becomes tight enough to trap the newly produced Argon atoms.
- **Engineering Limitation:** If a rock is reheated (metamorphism), the Argon can diffuse out, "resetting" the clock. Geologists use this "leakage" to determine the thermal history of mountain ranges.

2.3 The Kinetic Theory of the K-Ar Clock

The loss of Argon gas from a mineral is governed by the diffusion coefficient D:

$$D(T) = D_0 \exp\left(-\frac{E_a}{RT}\right)$$

The Dodson Equation: The closure temperature T_c (where the clock "starts") is defined by:

$$\frac{E_a}{RT_c} = \ln\left(\frac{A \cdot R \cdot T_c^2 \cdot D_0/a^2}{E_a \cdot dT/dt}\right)$$

Variables:

- A: Geometric factor (sphere vs. cylinder).
- a: Diffusion length (size of the crystal).
- dT/dt: The cooling rate of the magma.

Key takeaway: A slow-cooling granite in the deep crust will stay "open" (leaking Ar) for millions of years longer than a lava flow that hits the ocean and "quenches" instantly.

3 Rubidium-Strontium (Rb-Sr) Dating: The Isochron Method

The Rb-Sr system ($^{87}\text{Rb} \rightarrow ^{87}\text{Sr}$, $T_{1/2} = 48.1$ Ga) is used when a rock already contains some of the daughter isotope (^{87}Sr) at the time of formation, making simple "clocks" impossible. Due to the extremely slow decay of ^{87}Rb, this method is effective for dating very old geological features, typically ranging from 10 million years to the age of the solar system.

3.1 The Isochron Equation

To solve for the age, we normalize the radioactive species to a stable, non-radiogenic isotope of the same element: ^{86}Sr. The growth of ^{87}Sr is described by:

$$\left(\frac{^{87}\text{Sr}}{^{86}\text{Sr}}\right)_{now} = \left(\frac{^{87}\text{Sr}}{^{86}\text{Sr}}\right)_{initial} + \left(\frac{^{87}\text{Rb}}{^{86}\text{Sr}}\right)_{now} (e^{\lambda t} - 1) \tag{2}$$

3.2 Linear Regression as a Solution

This equation is in the form $y = b + mx$.

- **The Slope (m):** By measuring different minerals within the same rock (which have different Rb/Sr ratios), we can plot them on a graph. The slope of the resulting line (the **Isochron**) is $(e^{\lambda t} - 1)$.
- **The Intercept (b):** The y-intercept gives us the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the magma when it first crystallized.

4 Summary of Geochronological Methods

The choice of a radioactive "clock" depends on the age of the sample and its chemical composition. For a dating method to be valid, the mineral must remain a **closed system** from the time of formation until the time of measurement.

Table 1: Comparison of Primary Geochronological Clocks

Method	Parent Isotope	Effective Range	Primary Application
U-Pb	$^{238}\text{U}, ^{235}\text{U}$	1 Ma – 4.5 Ga	Zircons, Moon rocks, Age of Earth
K-Ar	^{40}K	0.1 Ma – 4.5 Ga	Volcanic layers, thermal history
Rb-Sr	^{87}Rb	10 Ma – 4.5 Ga	Igneous and metamorphic bulk rocks

4.1 The "Closure" Concept

In all these methods, the "age" actually measures the time since the rock cooled below a specific **closure temperature**.

- Above this temperature, ions and gases diffuse freely, and the "clock" is reset.
- Below this temperature, the crystal lattice "freezes," trapping the daughter products inside.

This thermal sensitivity brings us to a fundamental question of geophysics: Why is the interior of the Earth still hot enough to melt rock 4.5 billion years after its formation?

5 Radioactive Decay and the Earth's Heat Budget

5.1 Radiogenic vs. Primordial Heat

The total heat flux from the Earth's surface is approximately **47 TW**. Current consensus suggests this is split roughly 50/50 between two sources:

1. **Primordial Heat:** Residual kinetic energy from the original accretion of the planet and the gravitational potential energy released during core formation.
2. **Radiogenic Heat:** Heat generated by the constant "frictional" energy of alpha and beta particles slowing down in the mantle and crust.

5.2 The Dominant Isotopes

Over the history of the Earth, four isotopes have provided the bulk of the nuclear heating.

Isotope	Half-life (Ga)	Mean Heat Release (W/kg)	Current Contribution
^{238}U	4.47	9.4×10^{-5}	∼40%
^{232}Th	14.0	2.6×10^{-5}	∼45%
^{40}K	1.25	2.9×10^{-5}	∼15%
^{235}U	0.70	5.7×10^{-4}	<1% (now)

5.3 The Cumulative Energy Balance

The total radiogenic heat released since the Earth's formation is approximately 1.5×10^{31} J. To put this in perspective:

- This is roughly **equal** to the total gravitational potential energy released during the Earth's initial formation.
- Without this "nuclear furnace," the Earth would have cooled and solidified billions of years ago, halting plate tectonics and likely ending the geodynamo (our protective magnetic field).

5.4 The Geoneutrino "Telescope": Probing the Global Reactor

While Alpha particles generate the heat (Q_{total}), they cannot escape the Earth's interior. To verify our heat models, we measure the flux of **antineutrinos** ($\bar{\nu}_e$) produced during the beta-decay steps of the U and Th chains.

- **Beta-Heat Correlation:** Under the assumption of **Secular Equilibrium**, the rate of neutrino emission is directly proportional to the total rate of alpha decay on each decay path (and thus total heat production).
- **Flux to Wattage:** By measuring the antineutrino flux at the surface, we can integrate over the Earth's volume to determine the total radiogenic power.
- **Experimental Confirmation:** Results from the KamLAND (Japan) and Borexino (Italy) detectors have confirmed a radiogenic heat flux of 20 ± 8 TW, providing the first direct experimental proof that nuclear decay remains a significant source of Earth's internal heat and therefore an important contributor to the energy driving plate tectonics.

CBE Insight: This is a classic "Non-Invasive Process Monitoring" problem. We cannot put a sensor in the Earth's core, so we monitor the "exhaust" (neutrinos) of the reaction to calculate the "fuel consumption" (U/Th concentration).

6 Conclusion: The Nuclear Earth

Nuclear Engineering is not just about human-made reactors; we live on a planet that is powered by a distributed, deep-crustal nuclear furnace. The same decay laws we use to date a Zircon crystal explain why our planet has a protective magnetic field and active volcanoes.

References

- **Radiogenic Heat (Primary Source):** Arevalo Jr, R., McDonough, W. F., & Luong, M. (2009). "The K/U ratio of the silicate Earth: Insights into mantle composition, radioactive heat, and secular cooling." *Earth and Planetary Science Letters*, 278(3-4), 361-369. (Source for the 50/50 heat split and total energy integrals).

- **Total Heat Budget (Geoneutrino Data):** The KamLAND Collaboration (2011). "Partial radiogenic heat model for Earth revealed by geoneutrino measurements." *Nature Geoscience*, 4(9), 647-651. (The definitive experiment using antineutrinos to measure U and Th decay inside the Earth).

- **U-Pb and Zircon Physics:** Valley, J. W., et al. (2014). "Hadean age for a post-magma-ocean zircon confirmed by atom-probe tomography." *Nature Geoscience*, 7(3), 219-223. (Validates the "Closed System" behavior of Zircons over 4.4 billion years).

- **U-Pb Dating Methods:** Wikipedia: Uranium-Lead Dating. (Excellent summary of Concordia/Discordia geometry).

- **K-Ar Dating Methods:** Wikipedia: Potassium-Argon Dating. (Details on branching ratios and Argon gas trapping).

- **Rb-Sr Dating Methods:** Wikipedia: Rubidium-Strontium Dating. (Summary of the Isochron math and ^{86}Sr normalization).