Radiogenic Isotopes and Geochronology

- **Rb-Sr system**
  - $^{87}$Rb decays to $^{87}$Sr via $\beta$- decay
  - Half-life of $48.8 \times 10^9$ y
  - $\lambda = 1.42 \times 10^{-11}$/yr
  - $^{87}$Sr, is insignificant and must be corrected for
  - $^{86}$Sr stable, not created from radioactive decay
  - Rb behaves like K; $D < 1$; concentrated into K-feldspar, mica
  - Sr behaves like Ca; $D > 1$; concentrated into plagioclase and apatite
  - Amount of $^{87}$Sr in mineral today = radiogenic $^{87}$Sr + $^{87}$Sr$_o$
  - Thus single sample cannot give unambiguous age

- **Isochron approach**
  - normalize to stable $^{86}$Sr (mainly it is easier to measure isotopic ratios):
    \[
    \frac{^{87}Sr}{^{86}Sr} = \left( \frac{^{87}Sr}{^{86}Sr} \right)_o + \frac{^{87}Rb}{^{86}Sr} \left( e^{\lambda t} - 1 \right)
    \]
    \[y = b + x(m)\]

- Equation of straight line in plot of $^{87}$Rb/$^{86}$Sr vs $^{87}$Sr/$^{86}$Sr
  - Different minerals (or rocks) will have fractionated Rb from Sr in varying proportions, generating spread along the x axis
  - $^{87}$Rb decay moves samples toward upper left in diagram
  - Slope of isochron array gives t; see meteorite isochrons

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Figure 5-11: Schematic Rb-Sr isochron diagram showing the isotopic evolution over time of three ends or minerals, A, B, and C, with different Rb/Sr ratios after Rb-Sr derivation from a heterogeneous source at time $t_o$. The isochron diagram is plotted in a log-log scale.
Radiogenic Isotopes and Geochronology

- **U-Th-Pb Concordia/Discordia diagram**
  - For minerals that exclude Pb at time of formation (zircon, monazite, sphene)
  - Overcome the problems of open-system behavior, principally small degrees of Pb loss or inheritance of older grains, using Wetherill’s (1956) concordia method.

  - Simple radioisotopic decay equations
    \[ {^{207}\text{Pb}} = {^{235}\text{U}} (e^{2.5t} - 1) \]
    \[ {^{206}\text{Pb}} = {^{238}\text{U}} (e^{2.8t} - 1) \]

  - Rearrange to express relationships between daughters and parents as ratios:
    \[ \frac{{^{207}\text{Pb}}}{{^{235}\text{U}}} = e^{2.5t} - 1 \]
    \[ \frac{{^{206}\text{Pb}}}{{^{238}\text{U}}} = e^{2.8t} - 1 \]

- Substituting various values of \( t \) into these equations, we can graph resulting ratios of \( ^{206}\text{Pb}/^{238}\text{U} \) and \( ^{207}\text{Pb}/^{235}\text{U} \)
  - Values plot on a single curve called **concordia**, the locus of all concordant U-Pb ages.
  - Curvature reflects different decay rates of \( ^{238}\text{U} \) and \( ^{235}\text{U} \) and relative rates of production of \( ^{206}\text{Pb} \) and \( ^{207}\text{Pb} \) (Fig. 3.13, Dalrymple, 1991).

- **Power of the method is to address open-systems that have experienced Pb loss**

  **Discordia:**
  - Pb loss does not fractionate Pb isotopes from one another
  - Pb loss results in linear decrease from concordia curve toward the origin
  - As time passes, system evolves such that chord along which Pb-loss took place connects age of sample to time at which Pb loss event (e.g., metamorphism) took place
  - **discordia** cannot be defined by a single datum—requires at least 2 or 3 or more points to regress

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**Figure 9-16** Concordia diagram illustrating the Pb isotopic development of a 3.5 Ga old rock with a single episode of Pb loss. (a) Radiogenic \( ^{206}\text{Pb}^{*} \) and \( ^{207}\text{Pb}^{*} \) evolve simultaneously along the concordia curve for the first 2.5 Ga, at which time a thermal or fluid infiltration event causes lead to be lost. Both isotopes of Pb are lost in the proportions that they exist in the rock at the time, so that the isotopic compositions of the depleted rocks trend along the discordia directly toward the origin (arrow). The filled circles represent hypothetical rocks with variable degrees of depletion due to the event. (b) Continued evolution of the Pb system for a further 1 Ga causes undepleted rocks to follow the concordia for a total of 3.5 Ga of evolution. Depleted rocks follow separate concordia-type curves (dashed) to the new positions shown. The final discordia intersects the undepleted concordia at two points, one yielding the total age of the rocks, and the other yielding the age of the depletion event. After Faure (1986).
Pb-Pb Isochron and the Age of the Earth

- To avoid Pb loss problems and examine U-poor ancient systems
- Develop system in terms of ratios of daughter Pb isotopes to nonradiogenic $^{204}\text{Pb}$

$$\frac{^{207}\text{Pb}}{^{206}\text{Pb}} = 5 \left( e^{165t} - 1 \right)$$
$$\frac{^{206}\text{Pb}}{^{204}\text{Pb}} = 8 \left( e^{168t} - 1 \right)$$
$$\frac{^{207}\text{Pb}}{^{206}\text{Pb}} = \frac{1}{137.88} \left( e^{175t} - 1 \right)$$

- Equation of a family of straight lines
  - slope = right side, proportional to age $t$
  - lines pass through common point
  - gives composition of initial Pb in the system
  - cannot determine $P_e$ from y-axis intersection
- Used to determine age of systems where composition or amount of initial Pb unknown

Figure 9-17 Concordia diagram for three discordant zircons separated from an Archean gneiss at Morton and Granite Falls, Minnesota. The discordia intersects the concordia at 3.55 Ga, yielding the U-Pb age of the gneiss, and at 1.85 Ga, yielding the U-Pb age of the depletion event. From Faure (1986). Copyright © reprinted by permission of John Wiley & Sons, Inc.
Claire Patterson (1956) Geochimica Cosmochimica Acta

Measured Pb isotope composition of 5 chondritic meteorites, plus composite sample of Pacific Ocean sediment to represent bulk Earth

- All 6 samples fall along single P-Pb isochron
- The isochron was 4.55 ± 0.07 Ga
- Established firm connection between origin of Earth, meteorites, solar nebula.

Variations in isotopic composition
- Reflect isotopic decay
  - Rb-Sr; Sm-Nd; U-Pb, Th-Pb parent-daughter isotope systems
  - Isotopes of these elements are not fractionated from one another during melting or crystallization
  - Hence, radiogenic isotope ratios of magmas retain a “memory” of their source materials
  - Viewed over long periods, isotopic composition of magmas give a “time-integrated” picture of evolving sources, mainly in the upper mantle

Examples:
- Rb-Sr
  - $^{87}$Rb decays to $^{87}$Sr via $\beta$-decay; $t_{1/2} = 48$ G.y.
  - Isotopic composition of Sr in mineral/rock containing Rb a function of:
    - 1. Age
    - 2. Rb/Sr ratio
      - Reflects partitioning of these trace elements during melting or crystallization
      - Rb strongly incompatible, partitions into melt phase
      - Rb/Sr ratio increases with increasing amount of crystallization
      - Rb/Sr ratio high for small % partial melts

Radiogenic Isotopes as Petrogenetic Tracers
Radiogenic Isotopes as Petrogenetic Tracers

- **Rb-Sr**
  - Meteorites and Lunar materials 4.55 Ga
    - Primordial Sr (BABI) gives initial solar system ratio:
      \[
      \frac{\text{Sr}^{87}}{\text{Sr}^{86}} = 0.69907 \pm 0.00003
      \]
  - Earth’s mantle evolved through extraction of granitic melts that formed the continental crust we live on
    - Granitic/rhyolitic melts strongly enriched in Rb over Sr
    - These rocks are “reservoirs” that evolve much faster to high $^{87}$Sr/$^{86}$Sr
    - Complementary evolution of “depleted” upper mantle to low $^{87}$Sr/$^{86}$Sr

- **Modern MORB, OIB**
  - Reveal composition of upper mantle, uncontaminated by continental crust

Oceanic basalts have heterogeneous $^{87}$Sr/$^{86}$Sr
- Mantle = variable Rb/Sr
  - Depleted domains (partial melt extracted) = lower Rb/Sr
  - Enriched domains = higher Rb/Sr
- Crust = extremely variable, but high Rb/Sr
  - Elevated $^{87}$Sr/$^{86}$Sr
- Subduction zone basalt = larger range in $^{87}$Sr/$^{86}$Sr, higher values than MORB, OIB
Radiogenic Isotopes as Petrogenetic Tracers

- Sm-Nd system
  - Rare Earth system—well understood behavior
  - $^{147}$Sm decays to $^{144}$Nd via alpha decay; $t_{\frac{1}{2}} = 106$ G.y.
  - Isotopic composition of Nd in mineral/rock containing Sm a function of:
    - 1. Age
    - 2. Sm/Nd ratio
      - Reflects partitioning of these trace elements during melting or xennt
      - Nd slightly more incompatible, partitions into melt phase
      - Sm/Nd ratio decreases with increasing amount of xennt
      - Sm/Nd ratio low for small % partial melts
  - Meteorites and Lunar materials 4.55 Ga
    - Primordial Nd (CHUR) give initial ratio in solar nebula
      \[
      \left( \frac{^{143}Nd}{^{144}Nd} \right)_{\text{o}} = 0.512638 = \text{CHUR}
      \]

Radiogenic Isotopes as Petrogenetic Tracers

- Earth’s mantle evolved through extraction of “granitic” melts that formed the continental crusts that we live on.
  - Granitic/rhyolitic melts strongly enriched in Nd over Sm
  - These rocks (“reservoirs”) evolve much faster to low $^{143}$Nd/$^{144}$Nd
  - Complementary evolution of “depleted” upper mantle to high $^{143}$Nd/$^{144}$Nd

- Today’s Nd isotopic composition of the mantle deduced from modern MORB and OIB, uncontaminated by continental crust
  - Oceanic basalts have heterogenous $^{143}$Nd/$^{144}$Nd
    - Mantle = variable Sm/Nd
      - Depleted domains = higher Sm/Nd
      - Enriched domains = higher Nd/Sm
    - Crust = extremely variable, but low Sm/Nd, low $^{143}$Nd/$^{144}$Nd
    - Note large ranges in $^{143}$Nd/$^{144}$Nd of subduction basalts compared to MORB, OIB
Radiogenic Isotope Domains in Mantle and Crust

- U-Th-Pb systems
  - \( ^{238}\text{U} > ^{234}\text{U} > ^{206}\text{Pb} \) via chain of alpha decays; \( t_{1/2} = 0.704 \) G.y.
  - \( ^{235}\text{U} > ^{207}\text{Pb} \) \( t_{1/2} = 4.47 \) G.y.
  - \( ^{232}\text{Th} > ^{208}\text{Pb} \) \( t_{1/2} = 14.0 \) G.y.

- Isotopic composition of Pb in mineral/rock containing U is function of:
  - Age
  - U/Pb ratio (called \( \mu \))
    - Reflects partitioning of these elements during melting or crystallization
      - U & Th more incompatible, lower D than Pb; partition more strongly into melt
  - Meteorites and Lunar Materials 4.55 Ga
    - Primordial Pb in troilite (FeS) in Canyon Diablo Meteorite (Meteor Crater, Arizona):
      \[
      \left( \frac{^{206}\text{Pb}}{^{204}\text{Pb}} \right) = 9.3066 \quad \left( \frac{^{207}\text{Pb}}{^{204}\text{Pb}} \right) = 10.293 \quad \left( \frac{^{208}\text{Pb}}{^{204}\text{Pb}} \right) = 29.475
      \]
    - Primordial Pb removed from sources define isochrons in plots of \( ^{207}\text{Pb}/^{204}\text{Pb} \) vs. \( ^{206}\text{Pb}/^{204}\text{Pb} \)

- Geochron
  - All modern Pb evolved in single stage since 4.55 Ga from sources with variable \( \mu \)
  - Mantle evolved through extraction of "grantitic" melts and MORB
    - Granites enriched in U+Th over Pb; evolve faster to highly radiogenic Pb ratios
    - Complementary evolution of "depleted" upper mantle
Radiogenic Isotope Domains in Mantle and Crust

Pb isotopes in modern MORB & OIB
- Suboceanic mantle is:
  - extremely heterogeneous
  - defines mixing lines between primitive and evolved/crustal compositions
- Pb paradox - mantle is not complementary to crust that has been extracted from it
- Also delineates:
  - Ancient mantle domains
  - Crustal contamination of basalt