Introduction to U-Pb geochronology

with a focus on “high-precision” ID-TIMS

Blair Schoene

Earthscope GSA geochronology shortcourse
Introduction to U-Pb geochronology, with a focus on “high-precision” ID-TIMS

Outline:

1. The basics – decay chains, dates, and data visualization

2. Geochemistry of U and Pb - what materials can we date?

3. Analytical techniques

4. Focus on high-precision U-Pb geochronology
   1. Methodology
   2. Case studies
Decay of U and Th to Pb

<table>
<thead>
<tr>
<th>U 92</th>
<th>238U</th>
<th>206Pb + 8α + 6β + Q; λ_{238} = 1.55125e-10 a⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pa 91</td>
<td>235U</td>
<td>207Pb + 7α + 4β + Q; λ_{235} = 9.8485e-10 a⁻¹</td>
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<tr>
<td>Th 90</td>
<td>232Th</td>
<td>208Pb + 6α + 4β + Q; λ_{232} = 4.9475e-11 a⁻¹</td>
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<tr>
<td>Ac 89</td>
<td>227Th</td>
<td>227Pb + 6α + 4β + Q; λ_{227} = 1.62e-11 a⁻¹</td>
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<tr>
<td>Ra 88</td>
<td>223Ra</td>
<td>223Pb + 5α + 3β + Q; λ_{223} = 8.0e-11 a⁻¹</td>
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<tr>
<td>Fr 87</td>
<td>222Ac</td>
<td>222Pb + 4α + 2β + Q; λ_{222} = 4.9475e-11 a⁻¹</td>
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<tr>
<td>Rn 86</td>
<td>218Po</td>
<td>218Pb + 3α + 1β + Q; λ_{218} = 4.9475e-11 a⁻¹</td>
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<tr>
<td>At 85</td>
<td>210Po</td>
<td>210Pb + 2α + 0β + Q; λ_{210} = 4.9475e-11 a⁻¹</td>
</tr>
<tr>
<td>Po 84</td>
<td>206Pb</td>
<td>206Pb + α + 0β + Q; λ_{206} = 4.9475e-11 a⁻¹</td>
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Neutron number (N)

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</thead>
<tbody>
<tr>
<td>Hg 80</td>
<td>206</td>
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<td>212</td>
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<td>238</td>
<td>239</td>
<td>240</td>
</tr>
</tbody>
</table>

indicates alpha decay
(to isotope diagonal in indicated direction and 4 a.m.u. less)

indicates beta decay
(to isotope diagonal in indicated direction and the same mass)

~Half-life
(only indicated if >10 a)
Three isochron equations for the three systems

\[
\left( \frac{^{206}\text{Pb}}{^{204}\text{Pb}} \right)_{\text{total}} = \left( \frac{^{206}\text{Pb}}{^{204}\text{Pb}} \right)_{\text{init.}} + \left( \frac{^{238}\text{U}}{^{204}\text{Pb}} \right)_{\text{now}} \cdot (e^{λ_{238}t} - 1) \tag{1}
\]

\[
\left( \frac{^{207}\text{Pb}}{^{204}\text{Pb}} \right)_{\text{total}} = \left( \frac{^{207}\text{Pb}}{^{204}\text{Pb}} \right)_{\text{init.}} + \left( \frac{^{235}\text{U}}{^{204}\text{Pb}} \right)_{\text{now}} \cdot (e^{λ_{235}t} - 1) \tag{2}
\]

\[
\left( \frac{^{208}\text{Pb}}{^{204}\text{Pb}} \right)_{\text{total}} = \left( \frac{^{208}\text{Pb}}{^{204}\text{Pb}} \right)_{\text{init.}} + \left( \frac{^{232}\text{Th}}{^{204}\text{Pb}} \right)_{\text{now}} \cdot (e^{λ_{232}t} - 1) \tag{3}
\]

plus one extra:

\[
\left( \frac{^{207}\text{Pb}}{^{204}\text{Pb}} \right)_{\text{total}} - \left( \frac{^{207}\text{Pb}}{^{204}\text{Pb}} \right)_{\text{init.}} = \frac{1}{137.82} \cdot \frac{(e^{λ_{235}t} - 1)}{(e^{λ_{238}t} - 1)} \tag{4}
\]

slope of the isochron: \[ \frac{1}{137.82} \cdot \frac{(e^{λ_{235}t} - 1)}{(e^{λ_{238}t} - 1)} \]
Correcting for initial daughter product (common Pb)

\[
\left( \frac{^{206}Pb}{^{204}Pb} \right)_{total} = \left( \frac{^{206}Pb}{^{204}Pb} \right)_{init.} + \left( \frac{^{238}U}{^{204}Pb} \right)_{now} \cdot \left( e^{\lambda^{238}t} - 1 \right)
\]

1) Ignore it because there is so much radiogenic Pb relative to Pb\(_c\) (either because the mineral is old or U-rich)

2) Use isochron methods to solve for the composition of Pb\(_c\) (if the minerals meet the requirements of an isochron)

3) Use a co-existing low-U phase to measure the composition of Pb\(_c\)

4) Estimate it using a “bulk earth” Pb evolution model (e.g. Stacey and Kramers)
testing closed-system behavior: the concordia diagram

\[ ^{238}U \rightarrow ^{206}Pb \quad t_{1/2} \approx 4.5 \text{Gyr} \]
\[ ^{235}U \rightarrow ^{207}Pb \quad t_{1/2} \approx 0.7 \text{Gyr} \]

\[ \frac{^{206}Pb}{^{238}U} = \exp(\lambda_{238} t) - 1 \]
\[ \frac{^{207}Pb}{^{235}U} = \exp(\lambda_{235} t) - 1 \]

note that common lead correction is already made!
Using the concordia diagram

The wetherhill concordia diagram

The Tera-Wasserburg concordia diagram
What materials can we date?
Chemistry of U, Th and Pb
Geochemistry of U, Th and Pb

$U^{4+}$: 1.05 Å

$Th^{4+}$: 1.10 Å

$Pb^{2+}$: 1.32 Å
# Minerals used in U-Th-Pb dating

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
<th>U content (ppm)</th>
<th>Th/U</th>
<th>Common Pb (ppm)</th>
<th>Rock Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zircon</td>
<td>Zr SiO$_4$</td>
<td>1 - &gt;10,000</td>
<td>0.1-2</td>
<td>&lt; 1</td>
<td>most</td>
</tr>
<tr>
<td>Titanite</td>
<td>CaTiOSiO$_4$</td>
<td>4 -500</td>
<td>0.5-20</td>
<td>5 -40</td>
<td>k,c,a,m,ig, gp, hv, gn, sk</td>
</tr>
<tr>
<td>Monazite</td>
<td>(Ce,La,Th)PO$_4$</td>
<td>282 - &gt;50,000</td>
<td>5-1000</td>
<td>&lt; 10</td>
<td>mp,sg, hv, gp</td>
</tr>
<tr>
<td>Xenotime</td>
<td>YPO$_4$</td>
<td>5,000 - 30,000</td>
<td>0.1-2</td>
<td>&lt; 5</td>
<td>gp, sg</td>
</tr>
<tr>
<td>Thorite</td>
<td>ThSiO$_4$</td>
<td>&gt; 50,000</td>
<td>huge</td>
<td>&lt; 2</td>
<td>gp, sg</td>
</tr>
<tr>
<td>Allanite</td>
<td>(Ca,Ce)$_2$(Fe$^{+2}$,Fe$^{+3}$)Al$_2$O•OH[Si$_2$O$_7$] [SiO$_4$]</td>
<td>130- 600</td>
<td>2-200</td>
<td>5 -30</td>
<td>ig, gp, sk</td>
</tr>
<tr>
<td>Perovskite</td>
<td>(Ca,Na,Fe$^{+2}$,Ce) (Ti,Nb)O$_3$</td>
<td>21 -348</td>
<td>&lt; 2- 90</td>
<td>k,c</td>
<td></td>
</tr>
<tr>
<td>Baddeleyite</td>
<td>ZrO$_2$</td>
<td>58 - 3410</td>
<td>&lt;0.2</td>
<td>&lt; 5</td>
<td>k,c,um, m,a</td>
</tr>
<tr>
<td>Rutile</td>
<td>TiO$_2$</td>
<td>&lt; 1 - 390</td>
<td>0.1-5</td>
<td>&lt; 2-10</td>
<td>gp, gn, hv</td>
</tr>
<tr>
<td>Apatite</td>
<td>Ca$_5$(PO$_4$)$_3$(OH,F,Cl)</td>
<td>8 -114</td>
<td>2-20</td>
<td>&lt; 5-30</td>
<td>most</td>
</tr>
</tbody>
</table>

k=kimberlite, c = carbonatite, a=alkaline, m = mafic, ig = I-type granitoids, sg = s-type granitoids, mp = metapelites, hv=hydrothermal veins, gp=granitic pegmatites, leucogranites, sk=skarn
U-Pb geochronology analytical techniques
Imaging of chemical zoning – important for guiding ID-TIMS geochronology

Zircon with inherited cores (to be avoided or microsampled)

Zircon without cores (to be dated or microsampled)

- Detection of age domains in complex zircon

Slide courtesy of J. Crowley
CA-ID-TIMS U-Pb on zircon

Zircon in grain mount

Separate U + Pb from other elements

Load onto filament, put into mass spectrometer

TIMS lab at Princeton
A thermal ionization mass spectrometer (TIMS)

An IsotopX Phoenix62 at Princeton University

Footprint is ~2 x 1 m
Why is precision so good with TIMS?

1. Stable ion beams for long periods of time: lots of data

~ 4 hrs
Why is precision so good with TIMS?

2. Isotope dilution allows us to measured Pb and U separately, and thus not worry about interelemental fractionation during measurements (which is a limiting factor in precision of other techniques).

How many red and blue balls are there in the grey box if you don’t know the size of the box?

Cartoon courtesy of D. Condon
What is isotope dilution?

Measure the ratio of the reds to blue – this is what mass spectrometers do well.

Answer:

$\text{Red/blue} = 1.00$

Problem: cannot measure U and Pb at the same time in a TIMS, so you need moles, not ratios.

Slide courtesy of D. Condon
What is isotope dilution?

Take 100 yellow balls and mix them into the box thoroughly then re-measure the ratios of all the balls measure:

Yellow/red = 0.05

So how many blue balls are there?

If you mix a tracer solution containing both “yellow” U and Pb into your sample, and measure them separately, then you know moles of each – accuracy of date then depends on how well you know the ratio of Pb and U in your tracer solution.
Application 1: calibration of the geologic timescale and earth history

Holmes - 1959
A Revised Geological Time-Scale

When precision and accuracy really matter....

Examples of ashbed geochronology from the stratigraphic record.
Why the need for higher precision?

Volcanism  extinction  environment

1. Fundy basin (Nova Scotia, Canada)
   - McCoy Brook Fm.
   - North Mtn. Basalt
   - 201.38±0.02 Ma

2. Pucara basin (N. Peru)
   - FO Nevadaphyllites
   - 201.29±0.16 Ma
   - LM4-100/101
   - NYC-N10
   - 201.33±0.13 Ma

3. New York canyon (Nevada, USA)
   - Sea level
   - Global warming
   - Cooling/glaciation
   - δ¹³Corg

Schoene et al., 2010a
Application 2: evolution of magmatic systems

What are the rates of mass and heat transport in the crust?

What are the rheological properties of the crust during orogenesis?

What are timescales of melt generation, storage and transport in the lithosphere?

How are batholiths made?

Why do super volcano eruptions occur?
Integration of ID-TIMS with mineral chemistry helps generate petrologic models

First do laser ablation for zircon geochemistry, then do ID-TIMS U-Pb geochron

Alder Creek Rhyolite

Huckleberry Ridge Tuff

Rivera et al (2013)

Rivera et al (2014)
Integration of ID-TIMS with mineral chemistry helps generate petrologic models

U-Pb TIMS-TEA (trace element analysis)

Wotzlaw et al., 2013

Schoene et al., 2010
Field observations, structural geology, and petrology of the same rocks have resulted in very different tectonic models for Archean terranes.

Application 3: calibrating the Archean

“There are many, many problems” that are coherent, but they come from different sources, and this is a great challenge for the Archean study. The challenge becomes even greater when we consider the diversity of Archean terranes. As a result, the Archean is full of surprises and puzzles that have yet to be explained. The Archean terranes have been studied extensively, and many of the geologic and geophysical data collected have been used to construct tectonic models. However, the models are often contradictory, and the interpretations of the data are often inconsistent. It is important to note that the Archean is a geological time period that spans from 4.54 to 2.52 billion years ago. The Archean is divided into two main periods: the Hadean and the Archean.

The Hadean is the oldest period of the Earth’s history, and it is characterized by the formation of the Earth’s crust and the development of the early Earth’s atmosphere. The Archean is the second period of the Earth’s history, and it is characterized by the formation of the first continents and the development of the first life on Earth. The Archean is divided into two main eras: the early Archean and the late Archean. The early Archean is characterized by the formation of the first continents and the development of the first life on Earth. The late Archean is characterized by the development of the first oceans and the development of more complex life forms.

The Archean is a period of significant geological and biological change. The Earth’s crust was forming, and the first continents were being formed. The first oceans were forming, and the first life forms were developing. The Archean is a time of great geological and biological diversity, and it is a time that has left a lasting imprint on the Earth’s history.

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Numerical modeling can make predictions for tectonics if one makes it hotter…

But can we test these models with only structural geometries, finite strain and geochronology with ±10-20 Myr uncertainties?

“vertical” tectonics in the Pilbara craton
Thebaud and Rey, 2013

Subduction/accretion
Van Hunen and Van der Berg., 2008
Reducing age uncertainties – using the \( ^{207}\text{Pb}/^{206}\text{Pb} \) chronometer

Mattinson 1987

\[
\begin{align*}
\text{PERCENTAGE ERROR IN AGE} \\
1\% \text{ in } ^{207}\text{Pb}/^{206}\text{Pb} \text{ ratio} \\
1\% \text{ in } ^{207}\text{Pb}/^{238}\text{U} \text{ ratio} \\
1\% \text{ in } ^{207}\text{Pb}/^{235}\text{U} \text{ ratio}
\end{align*}
\]
Reducing age uncertainties – using the $^{207}\text{Pb}/^{206}\text{Pb}$ chronometer

Using the $^{207}\text{Pb}/^{206}\text{Pb}$ date, uncertainties on low-N weighted-mean of 0.01-0.02% are possible!
Obtaining high-precision dates on Archean rocks is possible…and necessary!

Comparison between dates from Phanerozoic and Archean igneous rocks
Further reading (review papers) on ID-TIMS U-Pb geochronology:


Corfu
Mattinson
Schaltegger