Uranium-series Crystal Ages

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Introduction to decay series

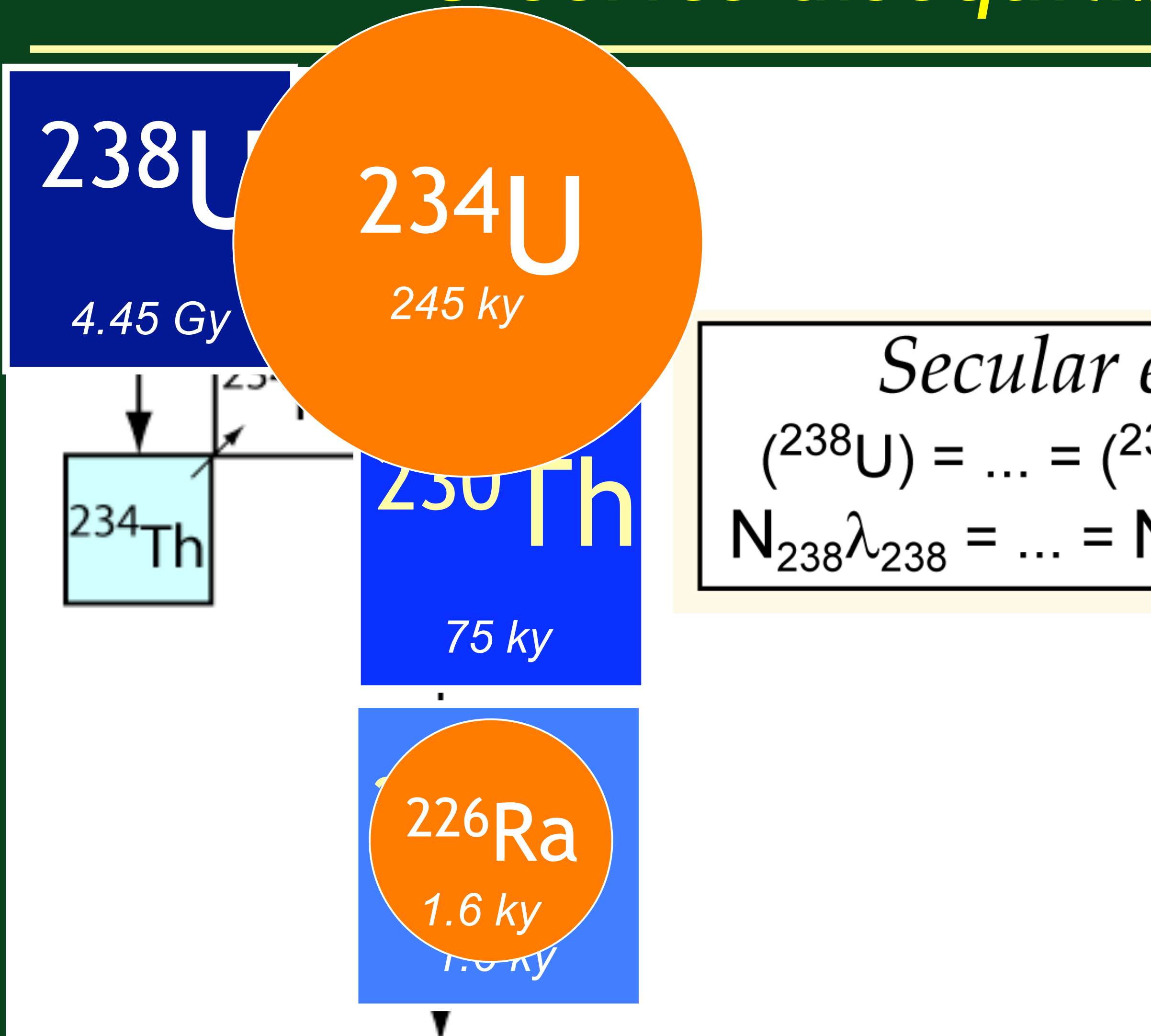
Our focus for this session:

- How to visualize decay series dynamics
- How you'll see these data presented
- How you can obtain these data
- How decay series data can be interpreted

Motivation:
Why would I obtain these ages?

- You want to date an eruption
- You want to learn when in a volcano’s history the crystals formed
- You want to determine whether there are multiple crystal populations
- You want to construct time-temperature-composition paths for magma evolution from crystal records

U-series disequilibria



Secular equilibrium:

$(^{238}U) = \ldots = (^{230}Th) = (^{226}Ra) = \ldots$

$N_{238}\lambda_{238} = \ldots = N_{230}\lambda_{230} = N_{226}\lambda_{226} = \ldots$

to ^{206}Pb

Decay series equation

Reflects balance between decay and in-growth:

$$N_2 = N_2^0 e^{-\lambda_2 t} + \frac{\lambda_1}{\lambda_2 - \lambda_1} N_1^0 \left(e^{-\lambda_1 t} - e^{-\lambda_2 t}\right)$$

" Amt daughter present "

"Daughter remaining from that present initially "

" Balance between daughter produced and that which has subsequently decayed "

Useful approximation:

$$(N_2) = (N_2)^0 e^{-\lambda_2 t} + (N_1)^0 (1 - e^{-\lambda_2 t})$$

At $t >> t_{1/2}$ of N_2:

$$(N_2) = (N_1)^0$$

Nuclides:

1: parent

2: daughter

0: initial amount

U-series disequilibria

QuickTime™ and a
decompressor
are needed to see this picture.

^{238}U-^{230}Th isochron equation

$$\frac{(^{230}Th)}{(^{232}Th)} = \frac{(^{230}Th)_0}{(^{232}Th)} e^{-\lambda_{230}t} + \frac{(^{238}U)_0}{(^{232}Th)} (1 - e^{-\lambda_{230}t})$$

" Activity of ^{230}Th present "

" Activity of ^{230}Th remaining of that present initially "

" Balance between ^{230}Th produced and that which has subsequently decayed "

Age defined by isochron slope (m):

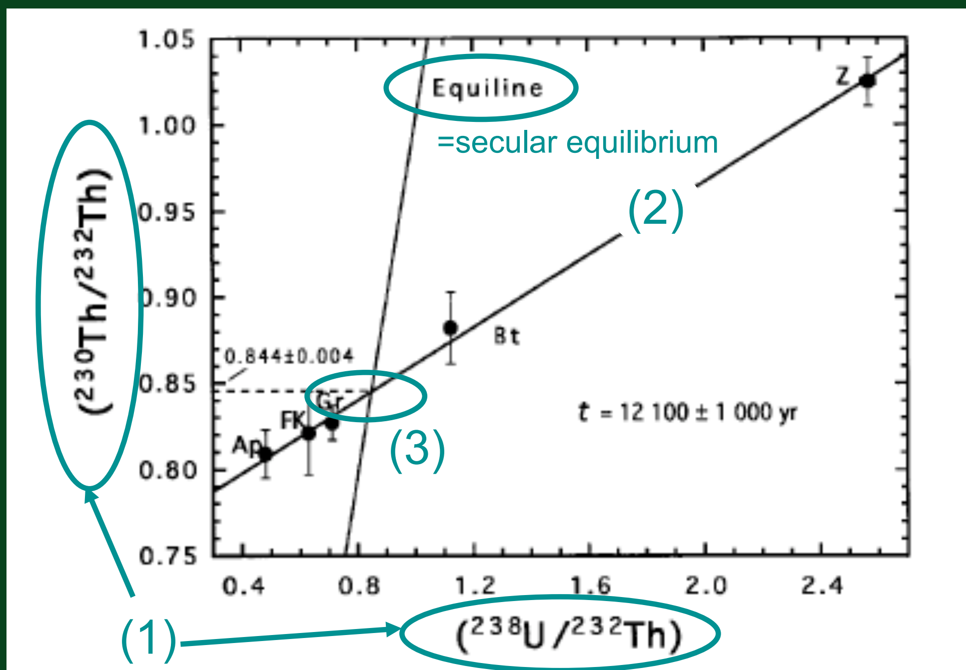
$$t = - \frac{1}{\lambda_{230}} \ln (m - 1)$$

ISOCHRON EQUATION

At $t \gg t_{1/2}$ of ^{230}Th:

$$\frac{(^{230}Th)}{(^{232}Th)} = \frac{(^{238}U)}{(^{232}Th)}$$

^{238}U-^{230}Th isochron diagram



Puy du Dome, France

Data for 4 minerals and groundmass:

Ap: apatite

FK: K-fsp

Bt: biotite

Z: zircon

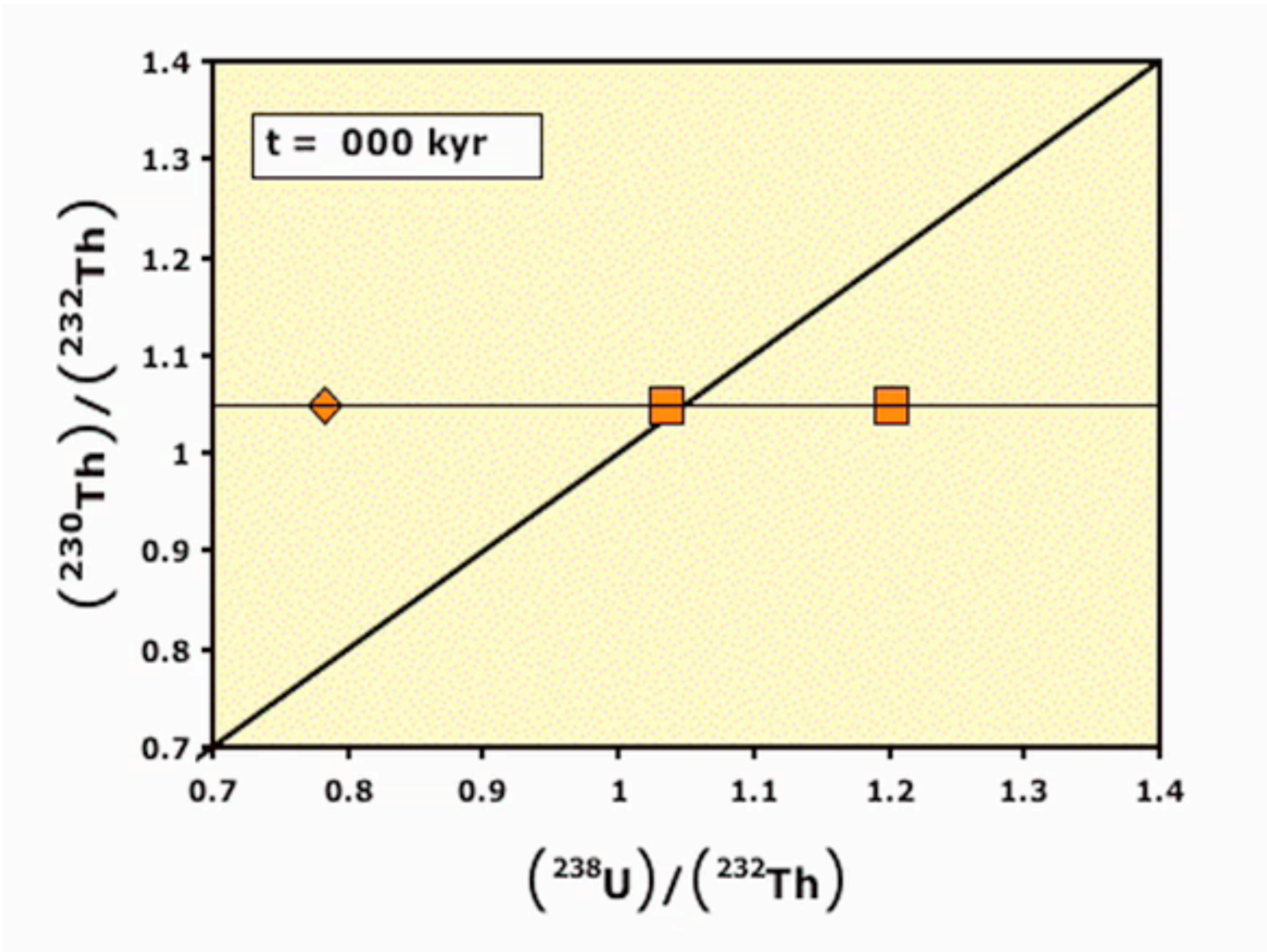
Gr: groundmass

Condomines, 1997

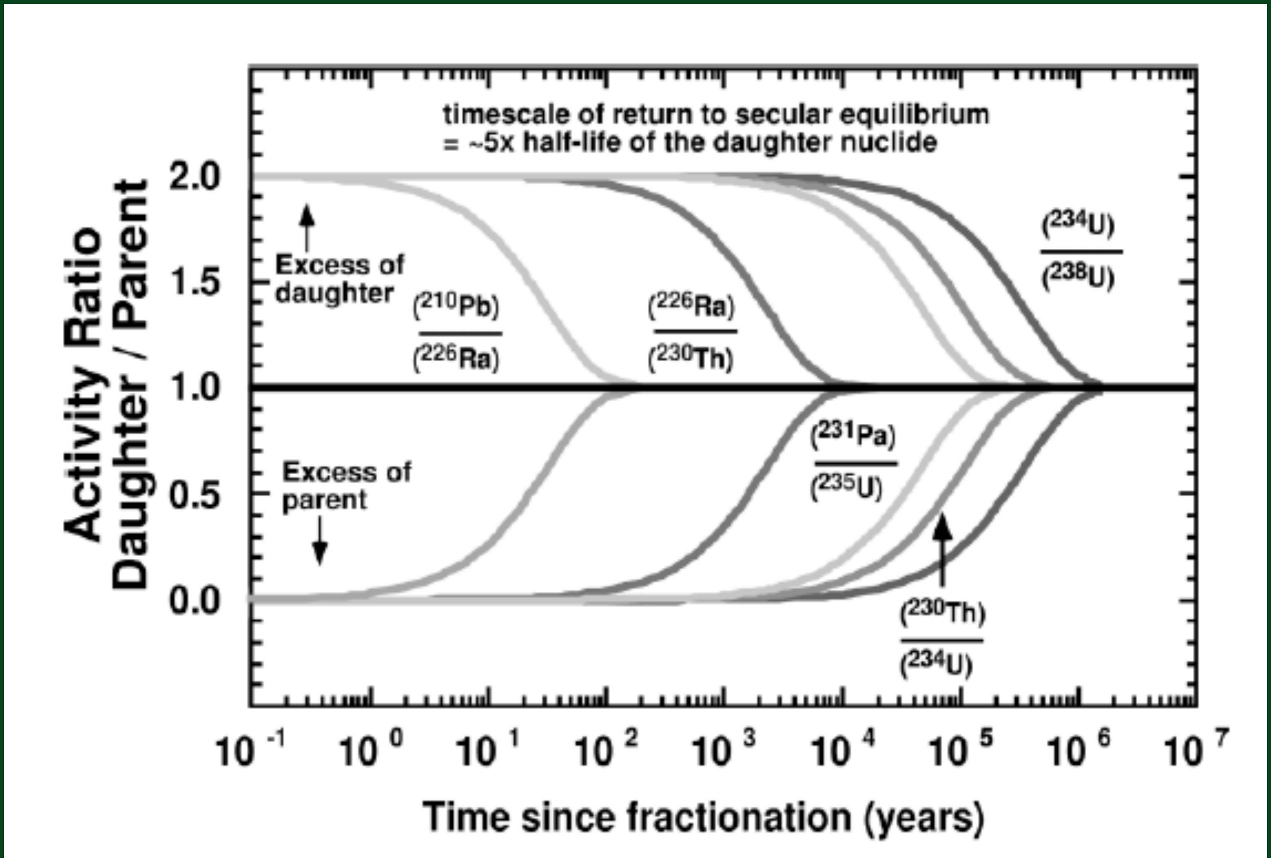
Different from isochron diagram with stable radiogenic daughter:

1. Activities rather than atomic ratios plotted (proportional to amounts)
2. Rather than quasi-linear changes in slope with age, slope increases at an exponentially decrease rate (next illustration)
3. Initial ratio is preserved by intercept with equiline

^{238}U-^{230}Th isochron



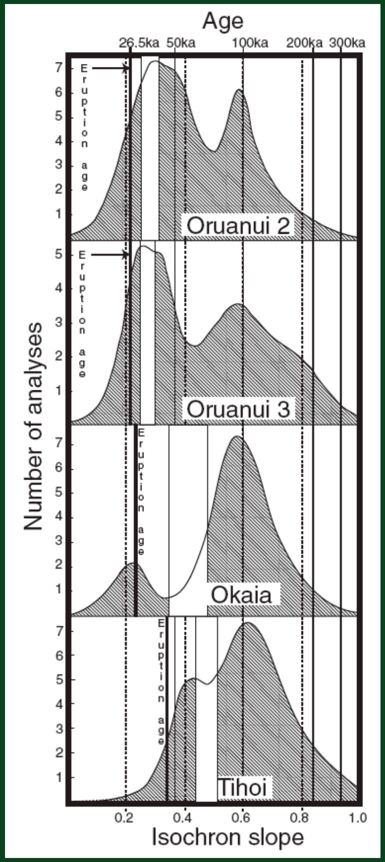
Useful age ranges



from Bourdon et al., 2003

Effects of mixing on U-Th isochrons

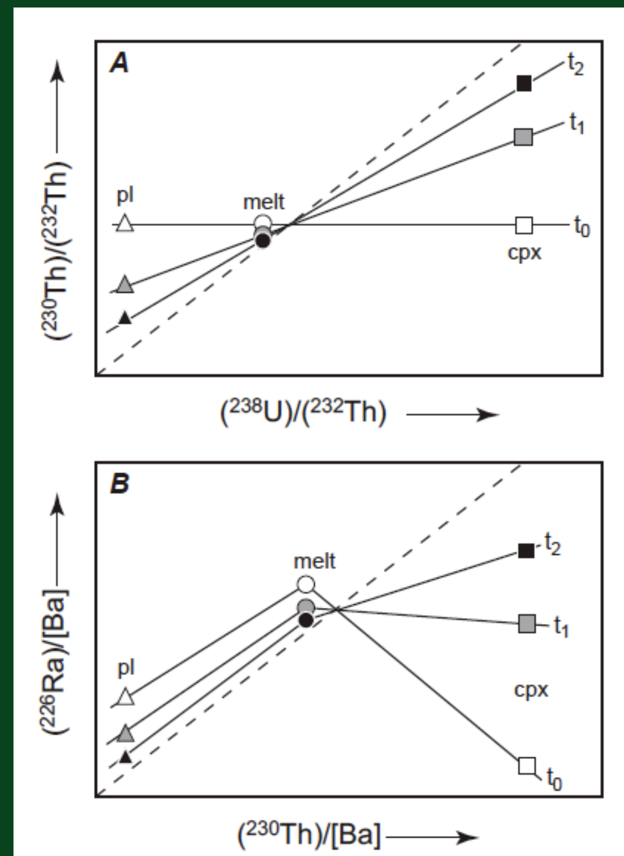
- Mixing of different same-aged phases will not modify the apparent age
- Mixing of different populations of a single phase produces mixed ages that must be interpreted carefully
- For in situ ^{238}U-^{230}Th analyses (e.g., zircon, allanite, etc.), can calculate model ages (mineral-glass or mineral-whole rock) and identify episodes of crystallization



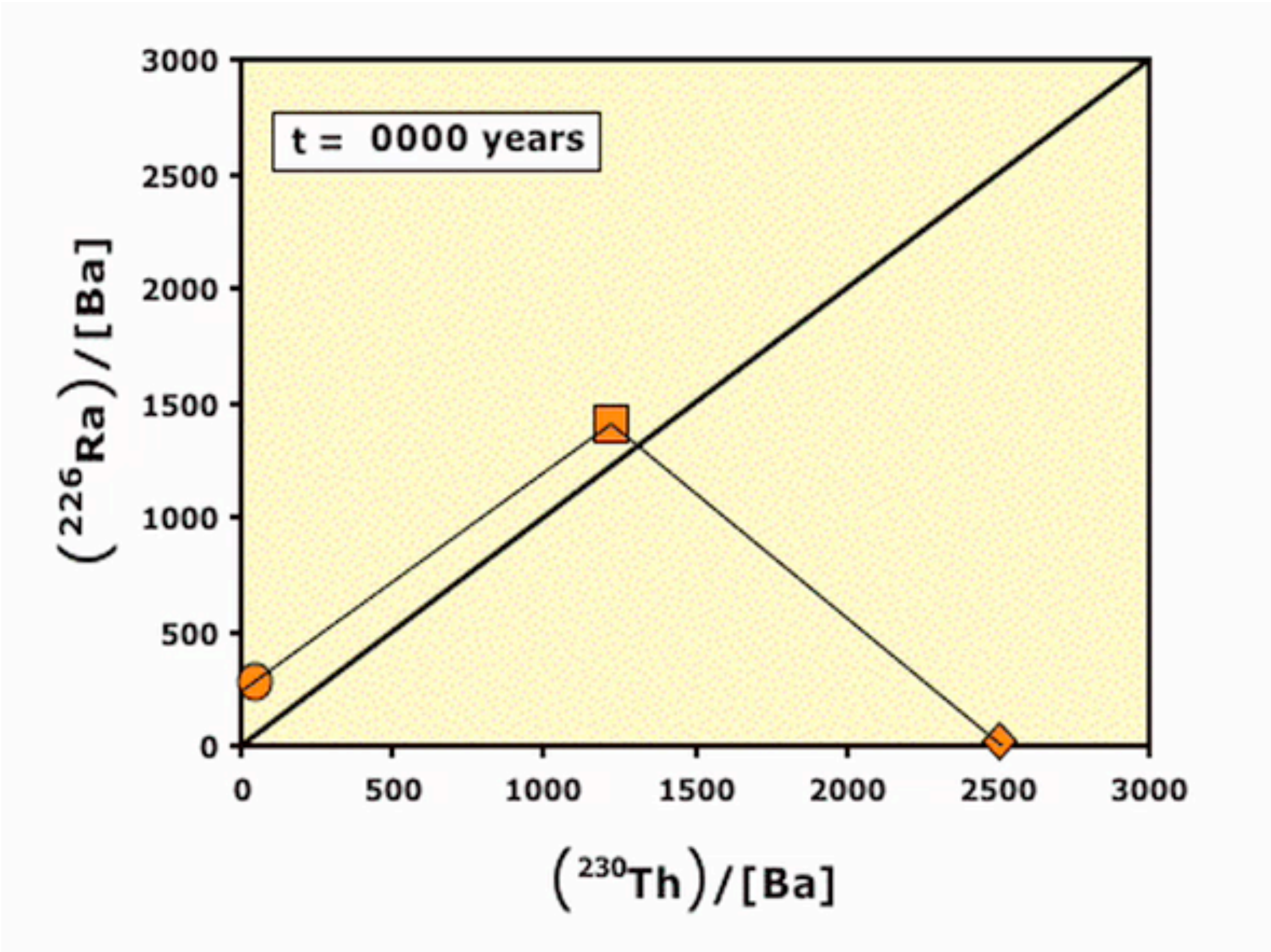
from Charlier et al., 2005

Th-Ra model ages: partitioning matters

- No long-lived reference isotope
- Ra and Ba have different chemical behavior
- Ra-Ba fractionation must be accounted for

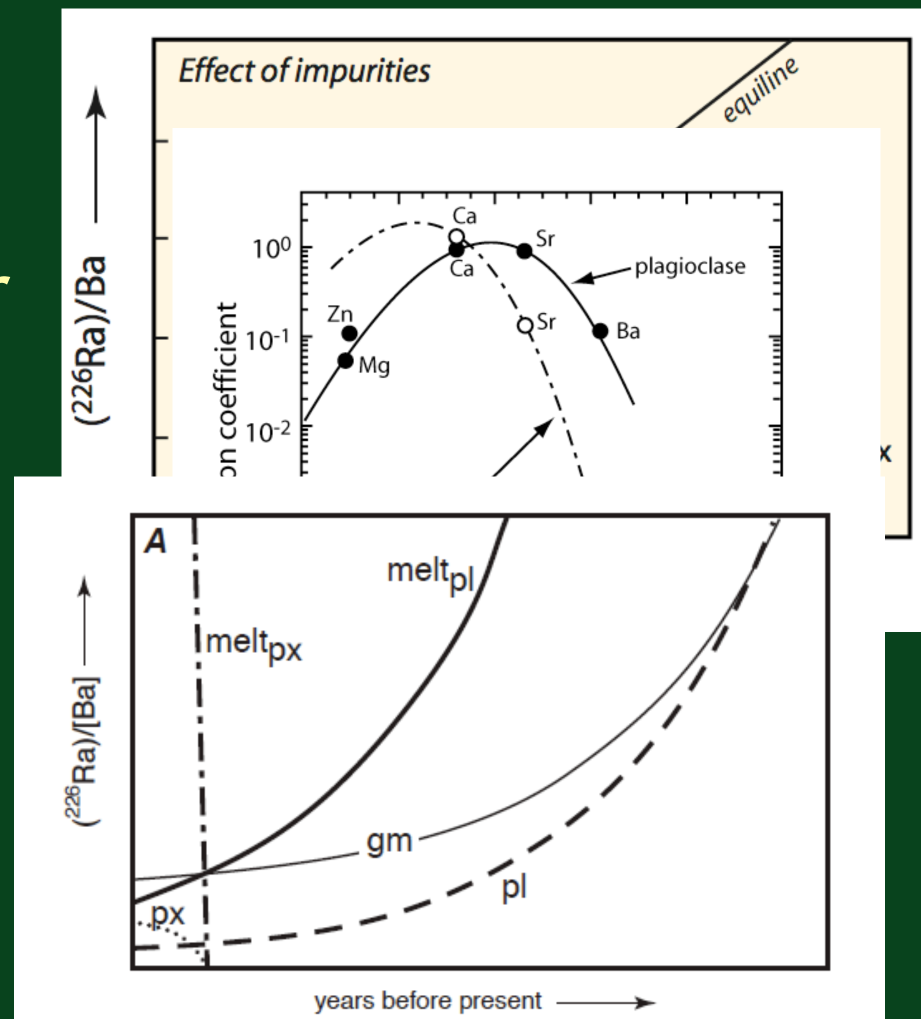


^{230}Th-^{226}Ra isochron



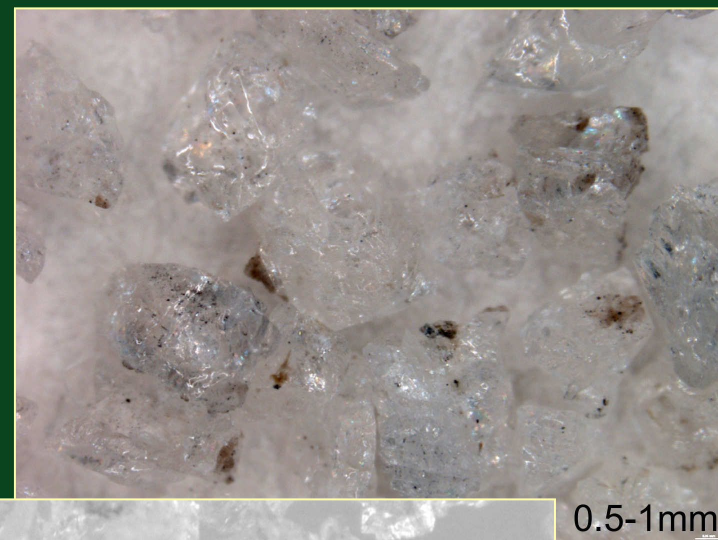
Calculating ^{230}Th-^{226}Ra model ages

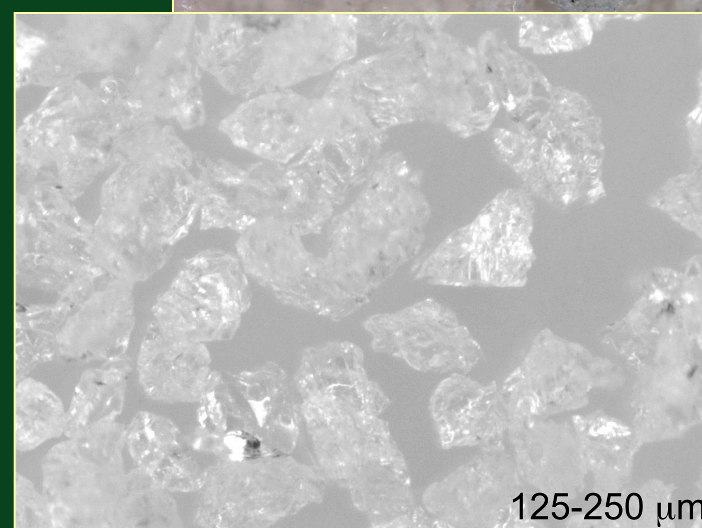
1. Correct for impurities
2. Determine D’s for appropriate conditions
3. Calculate model ages (evolution diagram and/or mathematically)



Calculating ^{230}Th-^{226}Ra model ages

1. Correct for impurities
   - Minimize impurities through careful separation
   - Mass balance calculations: solution ICP-MS vs. LA-ICP-MS or SIMS

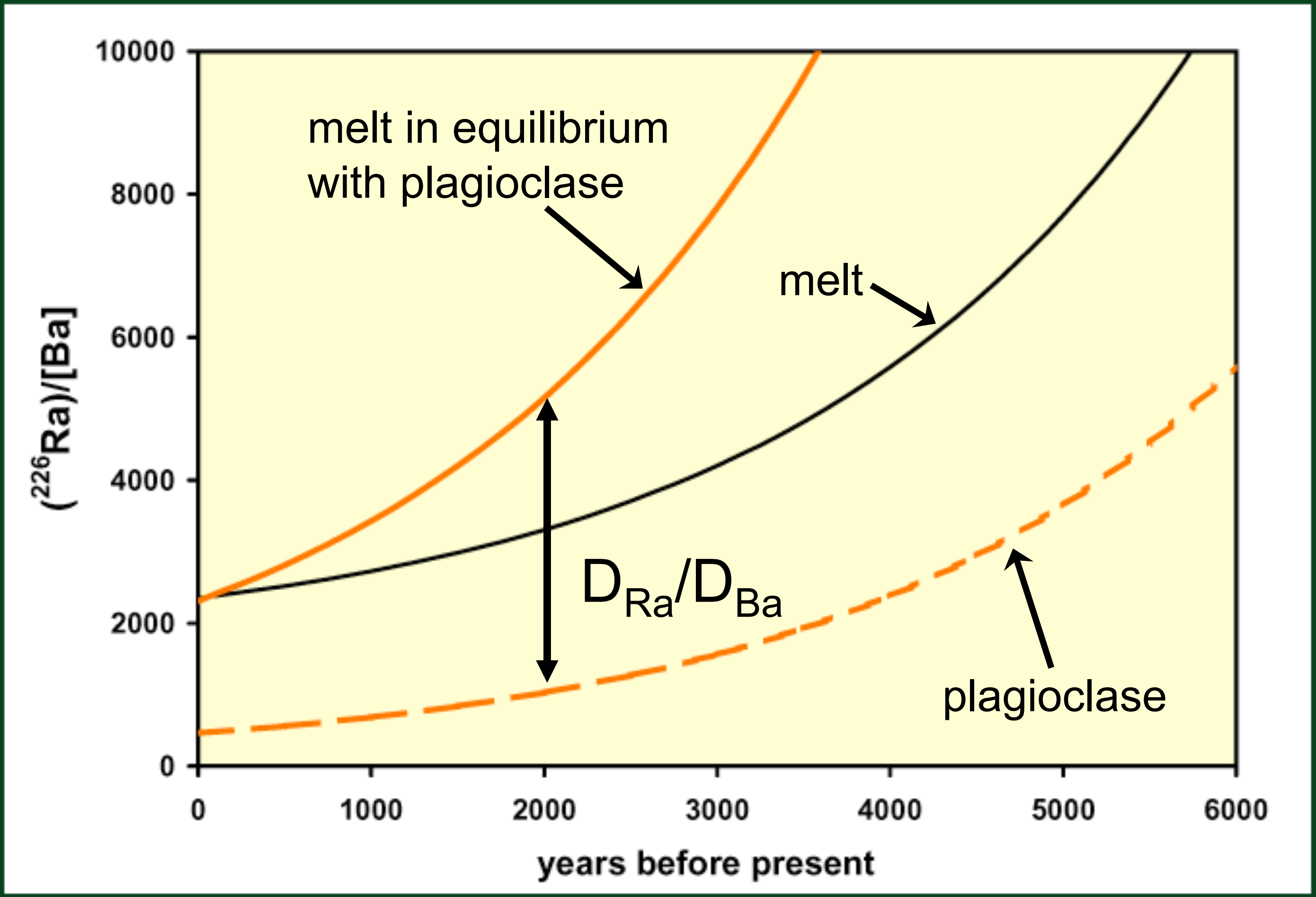




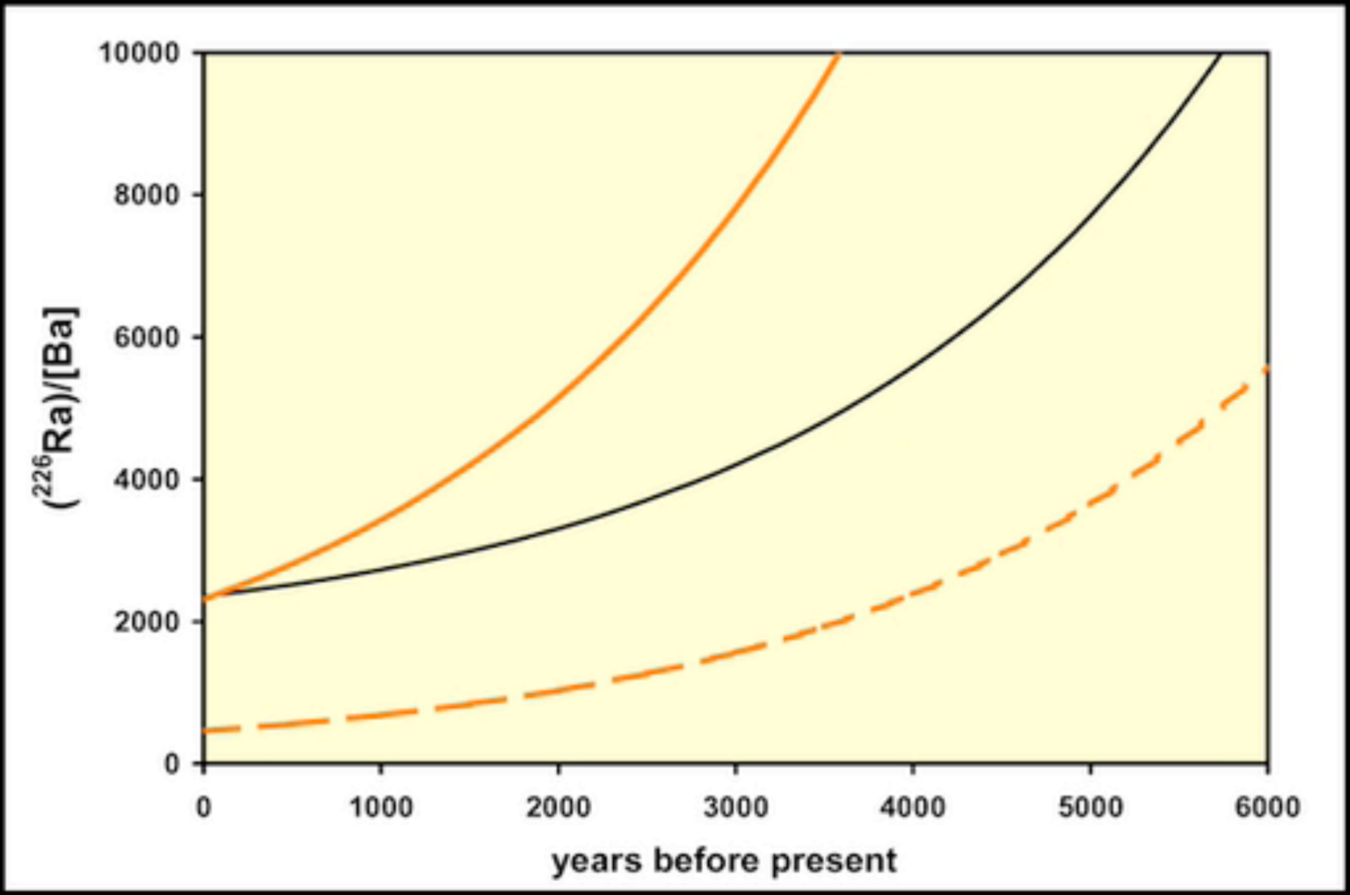
Calculating ^{230}Th-^{226}Ra model ages

2. Determine D's for appropriate conditions
   - Calculate partition coefficients (e.g., Blundy and Wood, 2003)
   - Use experimentally-derived partition coefficients (e.g., Miller et al., 2007; Fabbrizio et al., 2008 and in press)
   - In almost all mineral phases, $D_{Ra}<<1$ and $D_{Ra}<D_{Ba}$
     - Exceptions: Leucite ($D_{Ra}>1$, $D_{Ra}>D_{Ba}$); K-feldspar ($D_{Ra}>1$, $D_{Ra}<D_{Ba}$); phlogopite ($D_{Ra}\sim D_{Ba}$)
   - Most important variables: mineral composition, temperature

Evolution diagrams



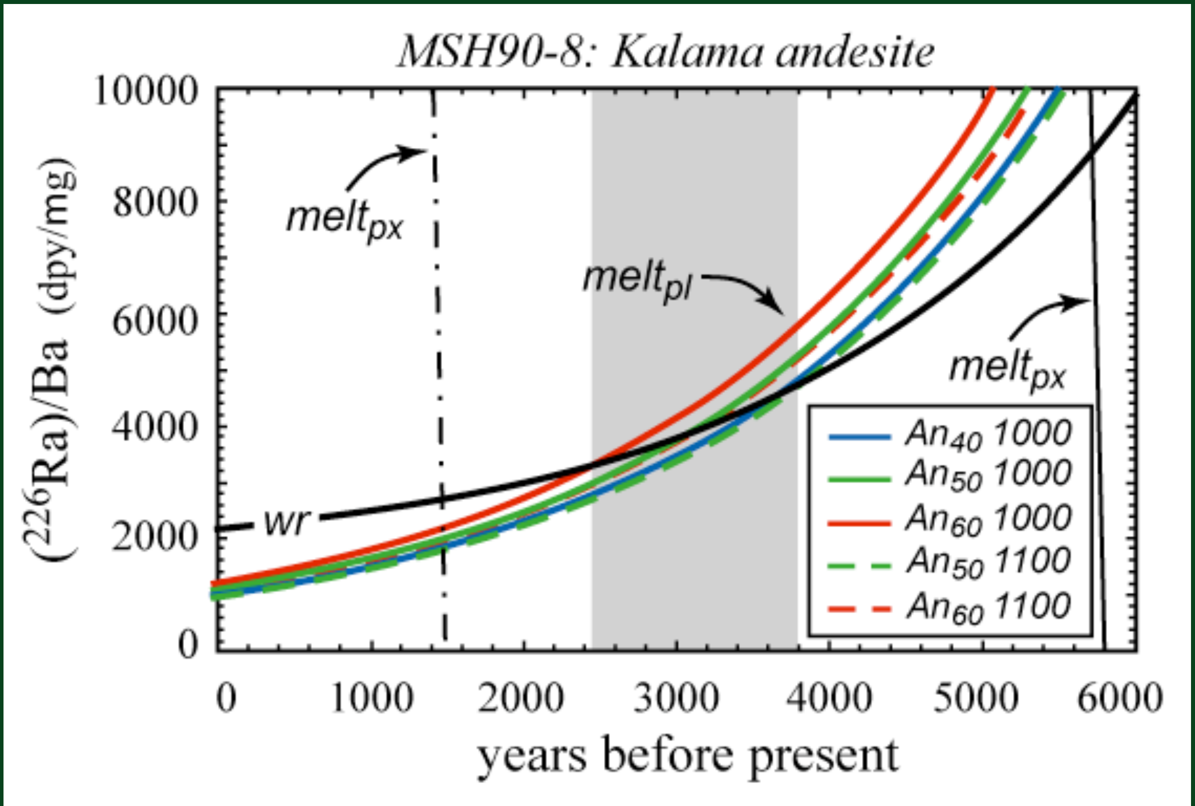
Evolution diagrams



Calculating ^{230}Th-^{226}Ra model ages

'Geological uncertainty'

- Crystal composition
- Crystallization T
- Correction for impurities
- Melt-crystal relations



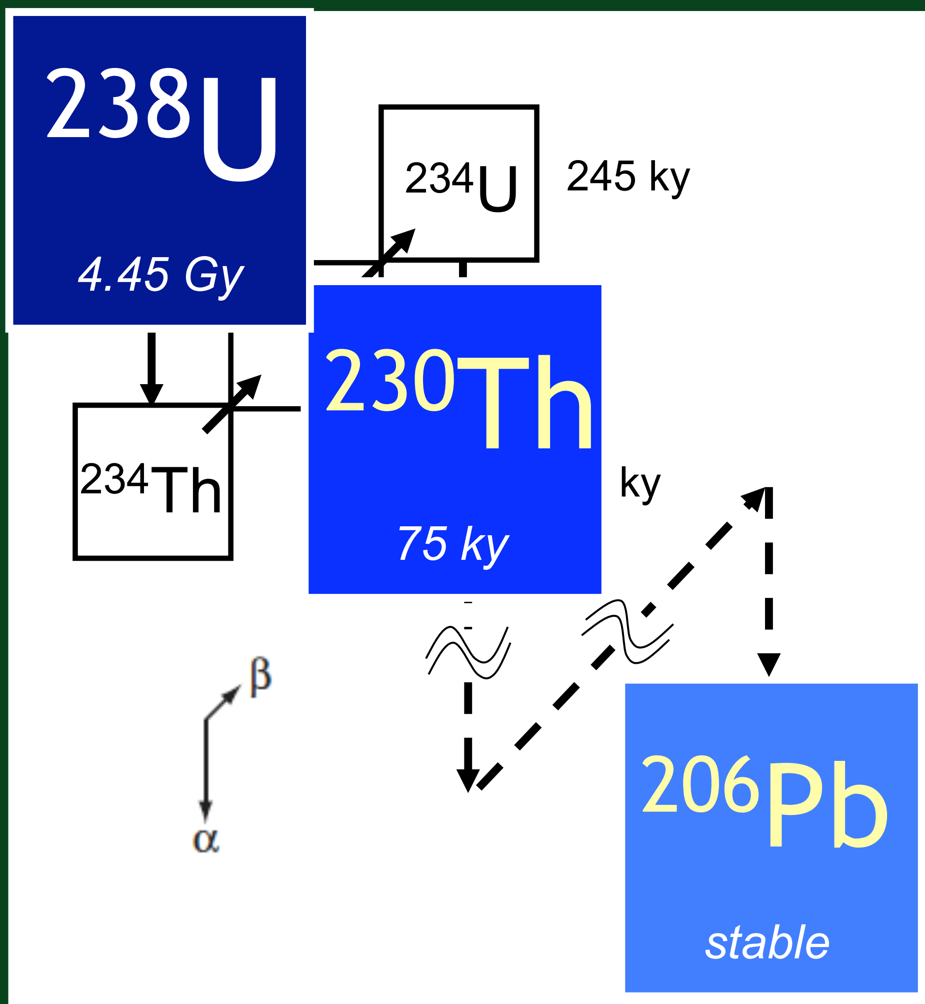
Example spreadsheet available on request

Cooper&Reid, 2003

Effects of mixing on Th-Ra isochrons

- Mixing of different phases will generally produce erroneous ages
- Mixing of different populations of a single phase:
  - Can produce intermediate ages that must be interpreted carefully
  - Can lead to discordant ages between different parent-daughter pairs

The ultimate daughter: ^{206}Pb

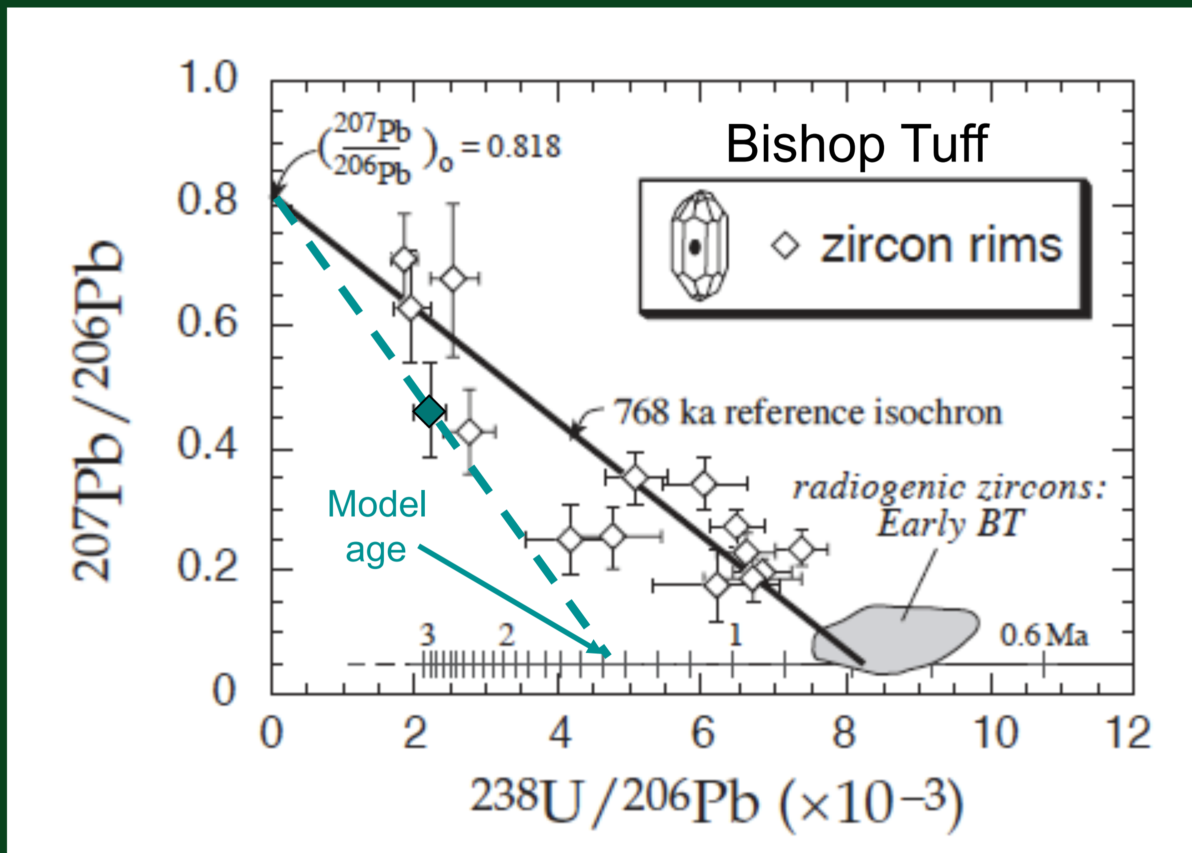


Decay equation:

$$^{206}Pb = {}^{238}U(e^{\lambda_{238} t} - 1)$$

- Long-standing means of dating igneous rocks via dating of zircon and other accessory phases
- Means of dating domains within individual crystals
- For young rocks, effect of U-series disruptions on ages is significant

Tera-Wasserburg diagram



Reid & Coath, 2000

Corrections for ^{230}Th deficit in zircon

Can essentially define a compound partition coefficient:

$$D(Th/U)_{crystal/melt} = \left[\frac{(Th/U)_{crystal}}{(Th/U)_{melt}^{*}} \right]_{measured} = f$$

$$^{206}Pb^{*}/^{238}U = \left(e^{\lambda_{238}t} - 1\right) + \frac{\lambda_{238}}{\lambda_{232}}\left(f - 1\right)$$

" Measured ratio of parent:daughter " — " In-growth at secular equilibrium " — " Reduction due to ^{230}Th deficit "

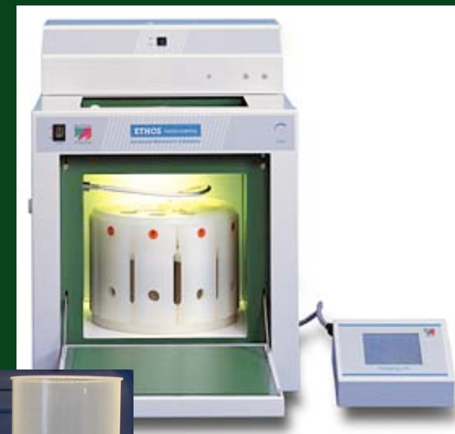
$^{*}(Th/U)_{melt}$ can be estimated from whole rock and/or glass

So - you want to date crystals…

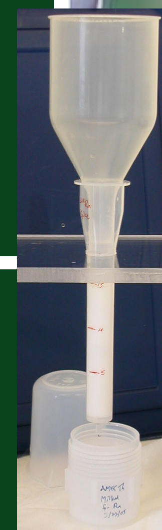
- How do you get from sample to data?
- What do you need to do to prepare samples?
- How much sample will you need?
- How are the samples analyzed?
- How long will this all take?

Collection & min sep

Analytical issues - bulk separates



Dissolution & chemistry



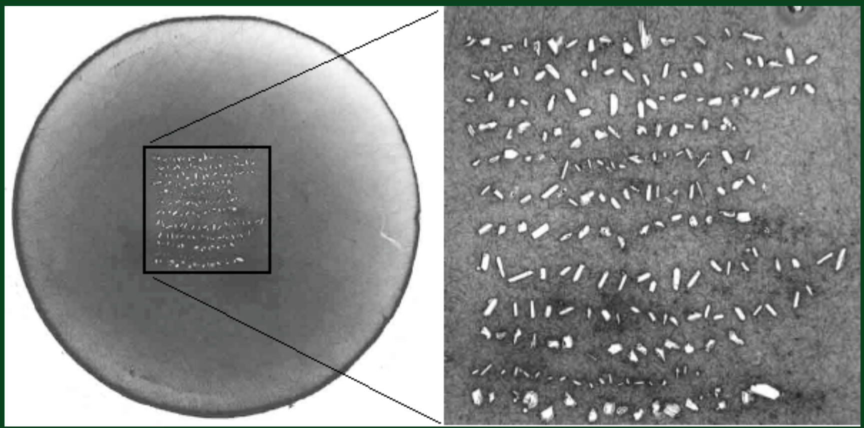
Th, U, Ra, Ba concentrations
Th, U isotopic compositions

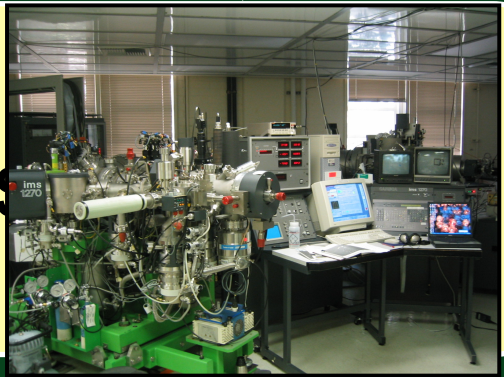
Analytical issues - in situ

Collection & min sep

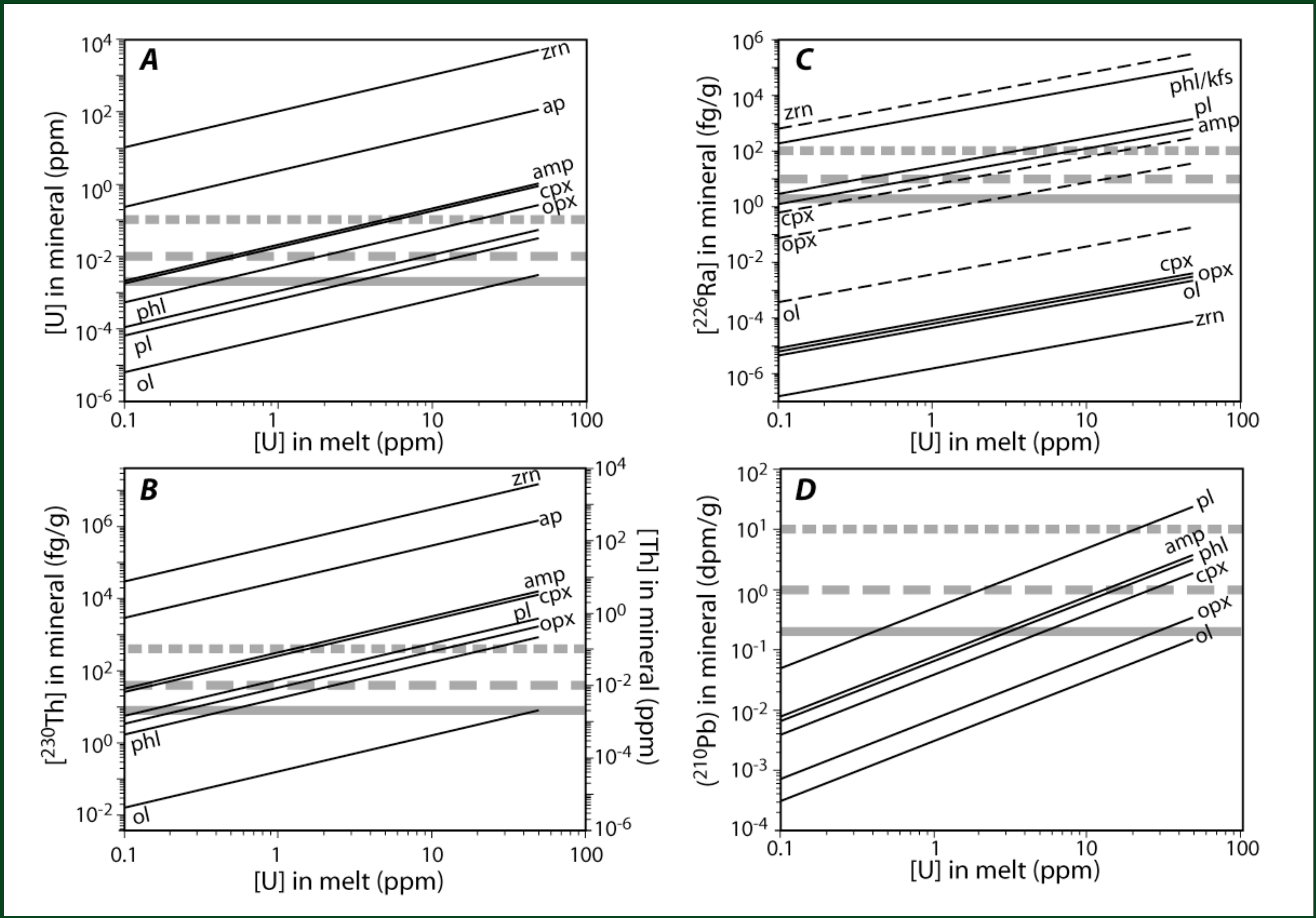
Grain mount (no dissolution)

Th, U, Pb isotopic compositions

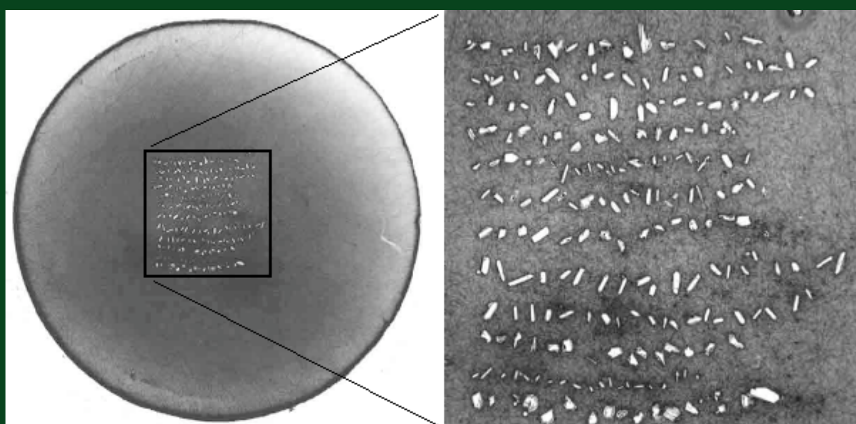




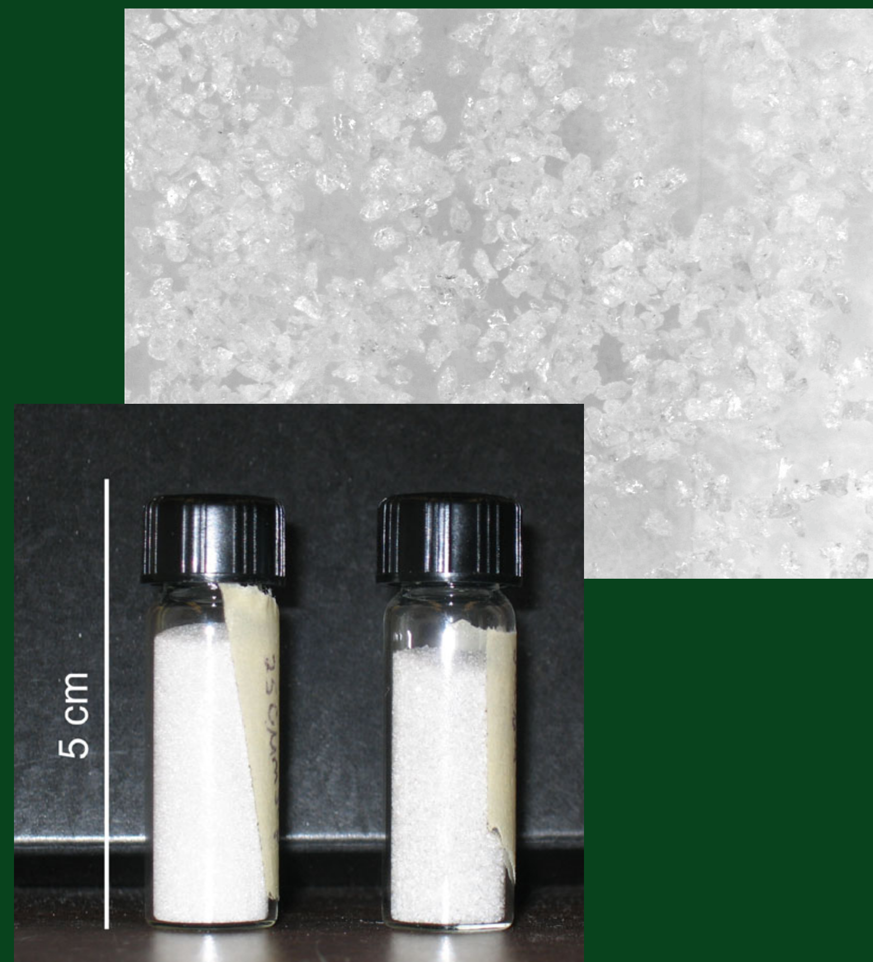
Practical matters: how much sample do you need?



Practical matters: how much sample do you need?



10s of grains



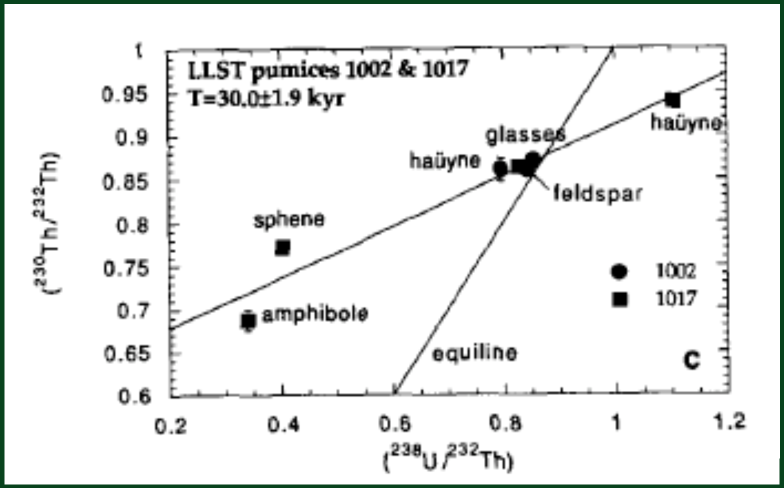
~5 g separate

How can I interpret these ages once I have them?

- Is the age an eruption age?
- What can I say about when in a volcano's history the crystals formed?
- Are there multiple crystal populations?
- How do the ages relate to the time-temperature-composition paths for magma evolution from crystal records

Laacher See Volcano, Germany: Dating Mineral Separates

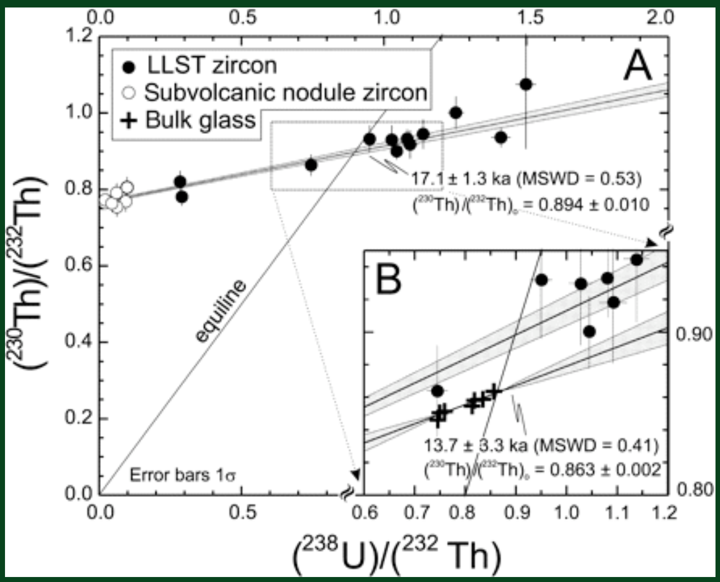
Lower Laacher See tephra



Bourdon et al., 1994

- Eruption from compositionally zoned magma body at 12.9 ka
- ^{238}U-^{230}Th mineral isochron ages:
  - Similar to eruption age for material erupted later
  - 30 ka for material erupted from the top of magma chamber
- Difference between crystal ages and eruption:
  - Residence of magma for ~17 k.y. before eruption?
  - Entrainment of cumulate material?

Laacher See Volcano, Germany: In Situ Age Dating

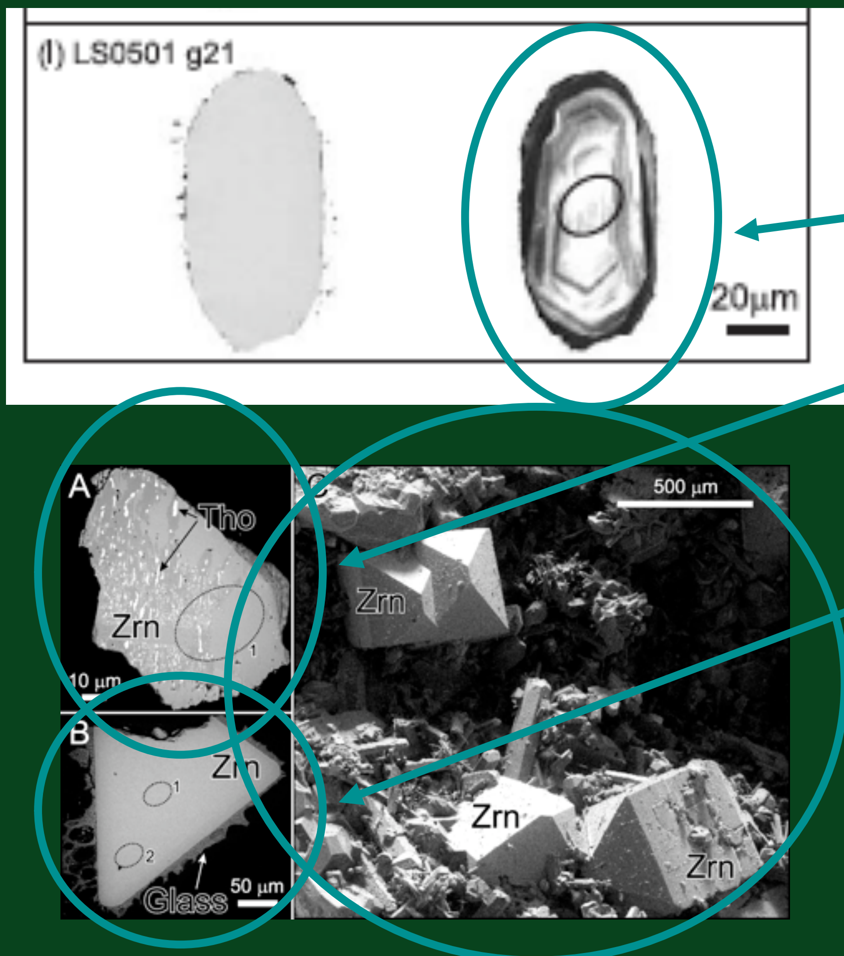


Schmitt, 2006

(xenoliths data not shown)

- Isochron age for zircons separated from tephra zircons is 18 ka
- Data for zircons from subvolcanic nodules lie on same isochron and collectively define an age of 17 ka
- Initial ratio higher than host glass (i.e., zircons not in Th isotope equilibrium with host)

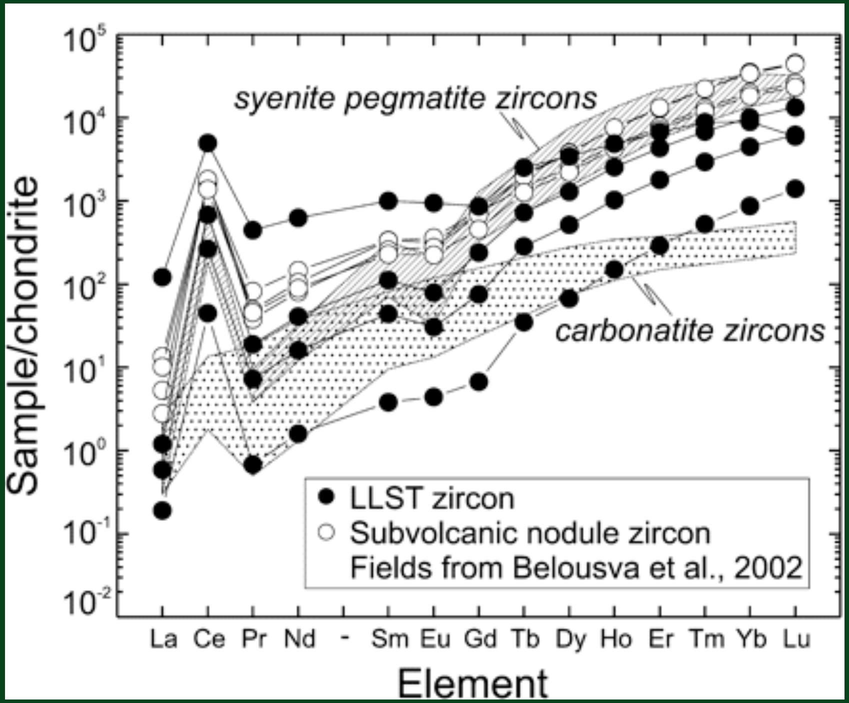
Laacher See Volcano, Germany: Zircon-Scale Observations



Schmitt, 2006

- Petrographic observations:
  - Igneous zoning patterns
  - Thorite rods in zircon provide provide evidence of exsolution
  - Glass selvages on crystals demonstrate immersion in liquid
  - Zircons found in nodule vesicles

Laacher See Volcano, Germany: In Situ Chemical Observations



Schmitt, 2006

- In situ REE data:
  - similarities between subvolcanic and LLST zircons (HREE enrichment; Ce and Eu anomalies)
  - Patterns more characteristics of syenite than carbonatites
- In situ O isotope data:
  - Overlap between $\delta^{18}O$ range of nodule zircons (5.0-5.7 ‰) and tephra zircons (5.3-7.1 ‰)
  - Oxygen isotope disequilibrium between zircons and pumice

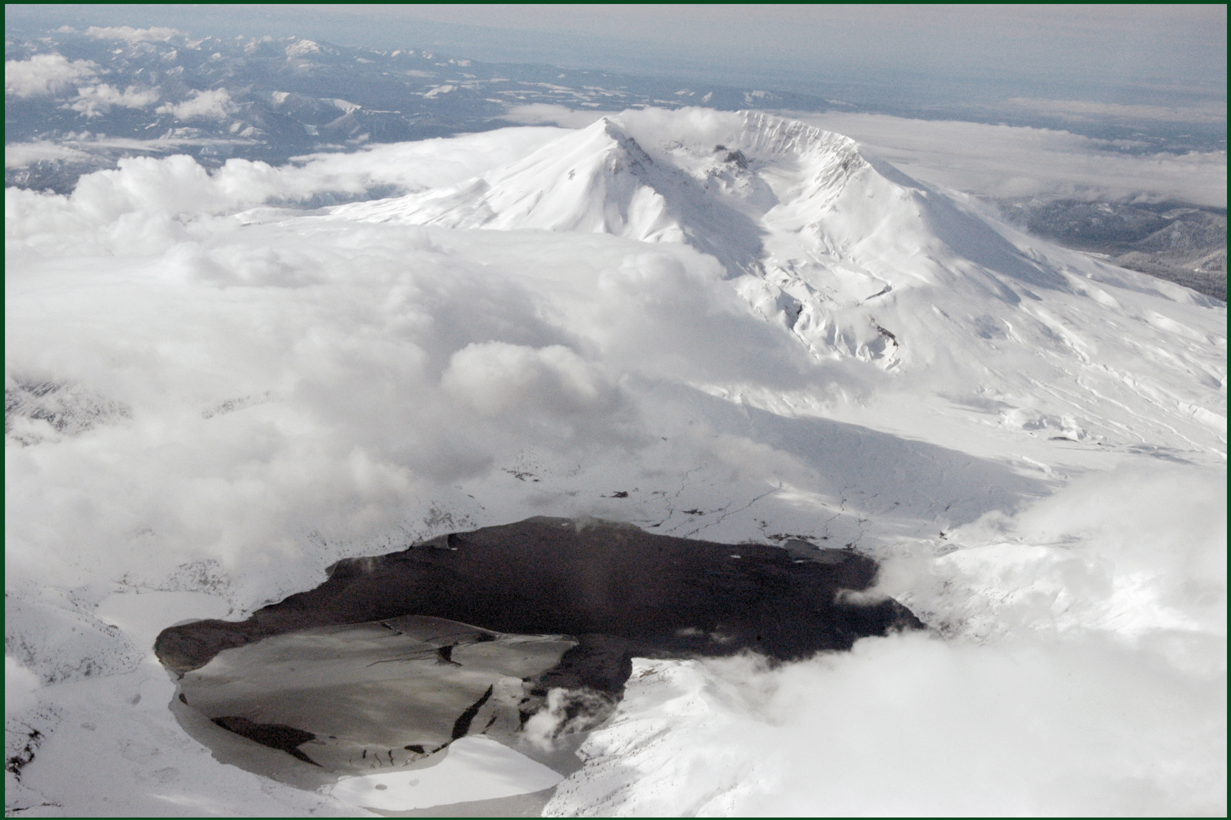
Laacher See Volcano, Germany: Redux

- Zircons and likely other crystals were scavenged from marginal apophyses of the Laacher See magma chamber
- All units could have differentiated within a few k.y. of eruption

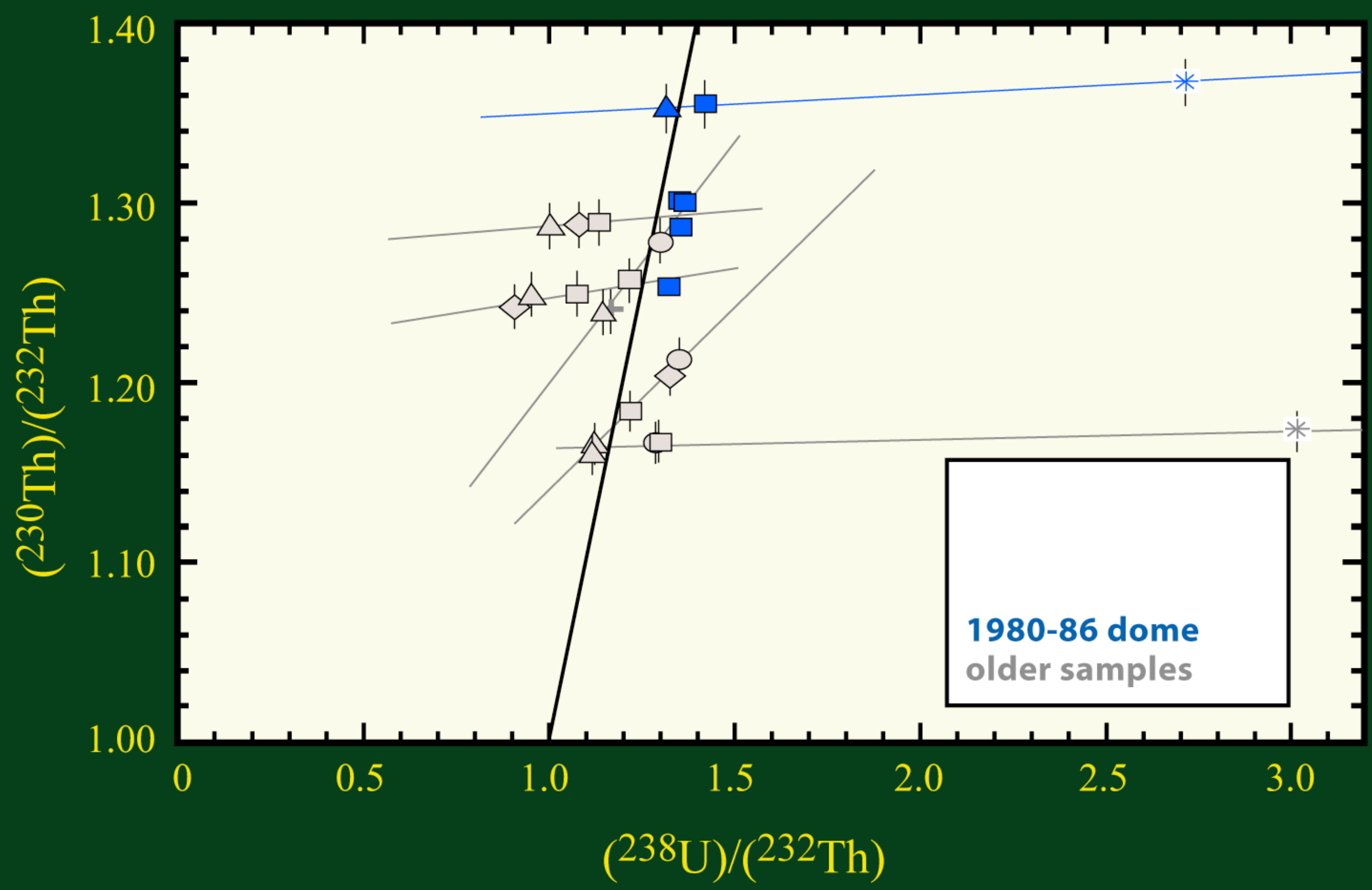
How can I interpret these ages once I have them?

- Is the age an eruption age?
- What can I say about when in a volcano’s history the crystals formed?
- Are there multiple crystal populations?
- How do the ages relate to the time-temperature-composition paths for magma evolution from crystal records

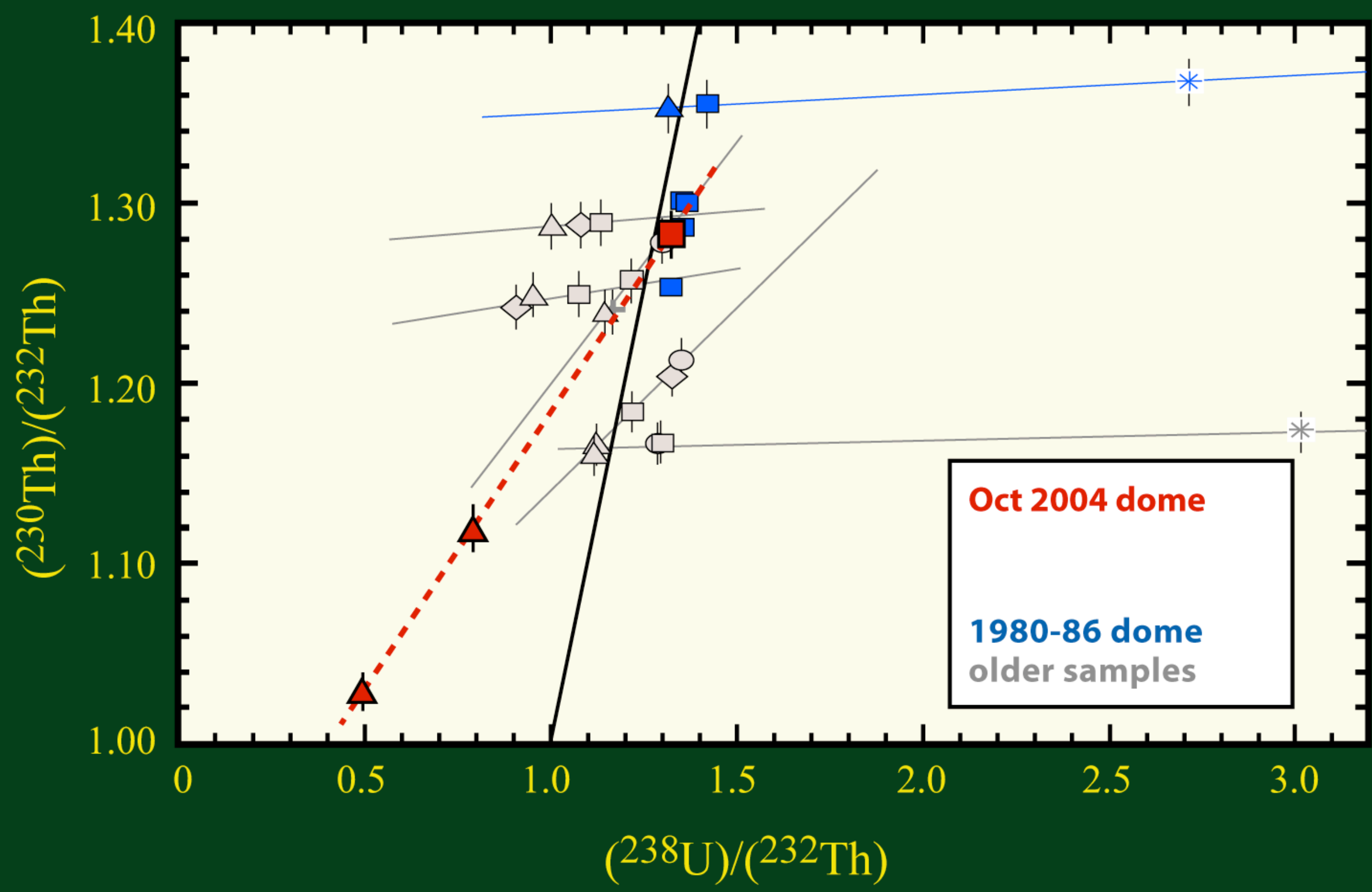
Mount St Helens: 2004-2008 eruption



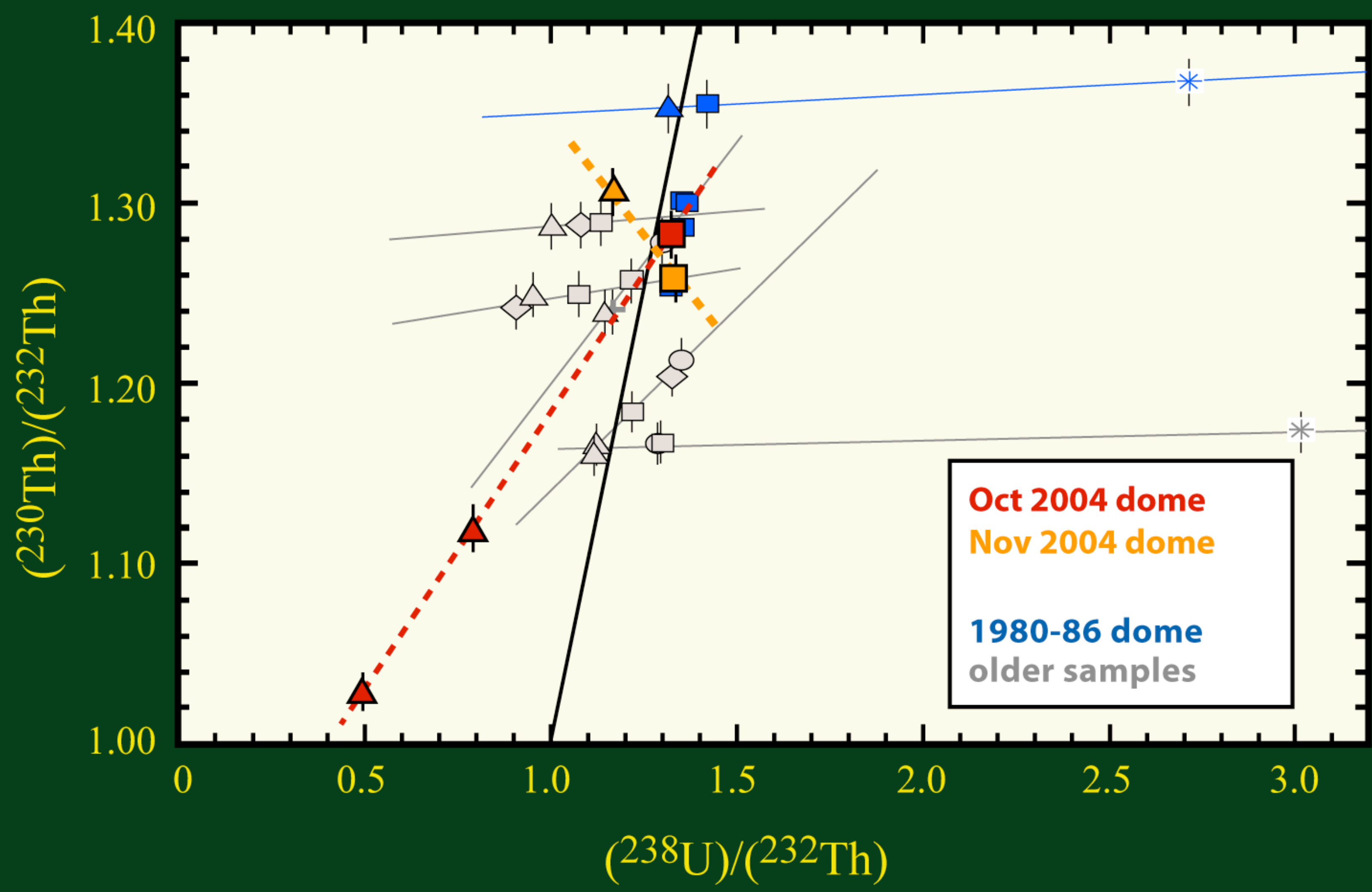
MSH 2004-2005: Th-U



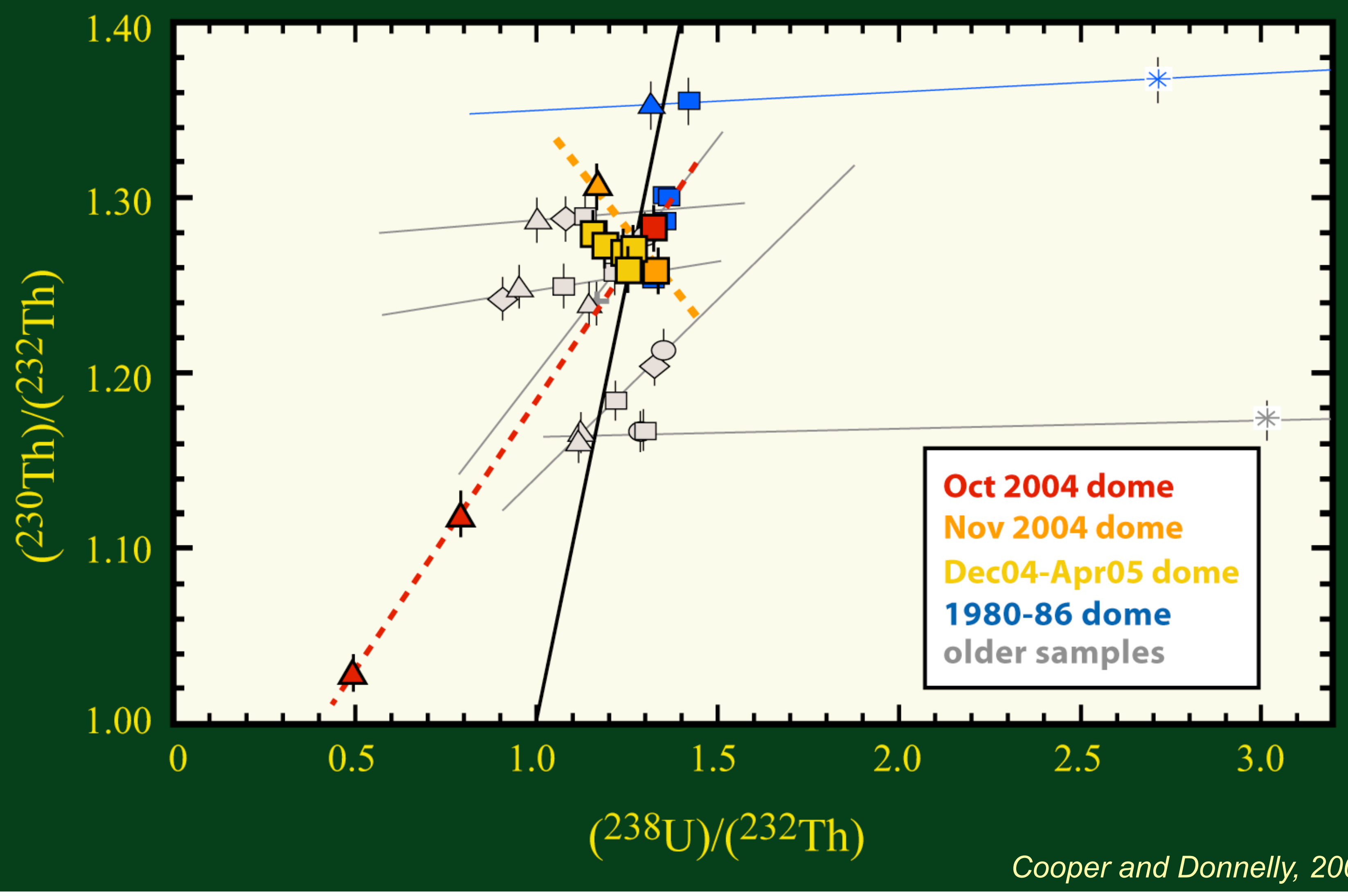
MSH 2004-2005: Th-U



MSH 2004-2005: Th-U

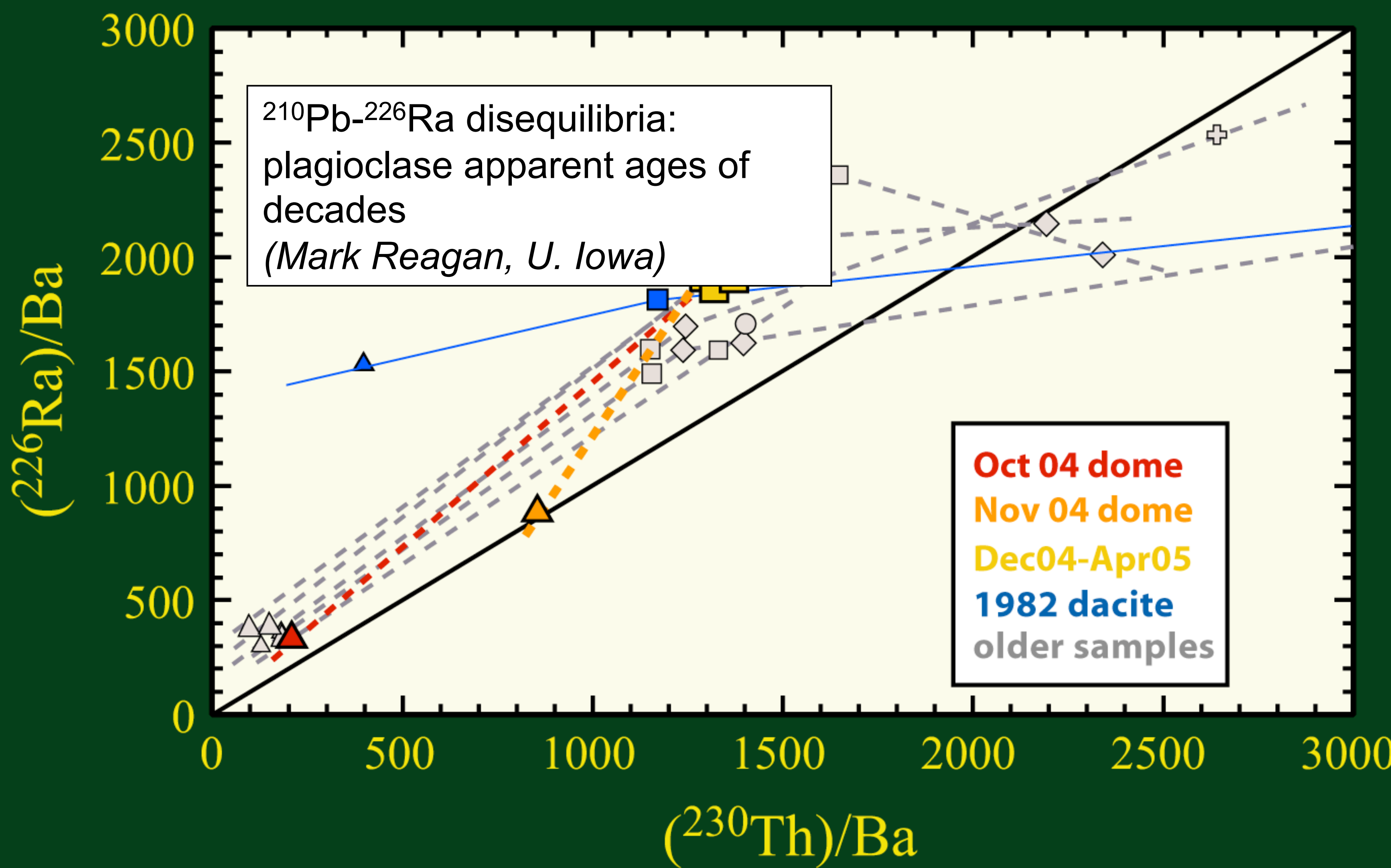


MSH 2004-2005: Th-U

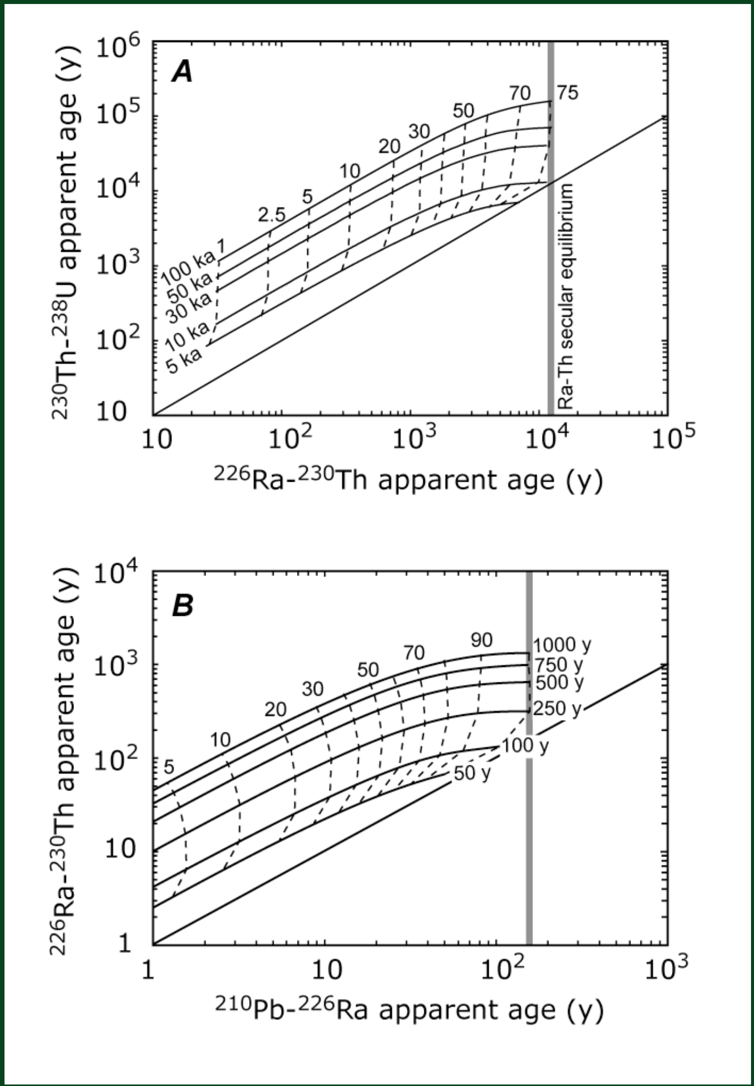


Cooper and Donnelly, 2008

MSH 2004-2005: Ra-Th



Recognizing multiple crystal populations



- Discordant ^{238}U-^{230}Th-^{226}Ra-^{210}Pb ages reflect protracted crystal histories (decades to 10's of ky)
- 2004-05 dome contains new and diverse plagioclase components compared to 1980's

More examples of crystal age results and new directions for research in the volume and AGU sessions!

- You want to date an eruption
- You want to learn when in a volcano’s history the crystals formed
- You want to determine whether there are multiple crystal populations
- You want to construct time-temperature-composition paths for magma evolution from crystal records