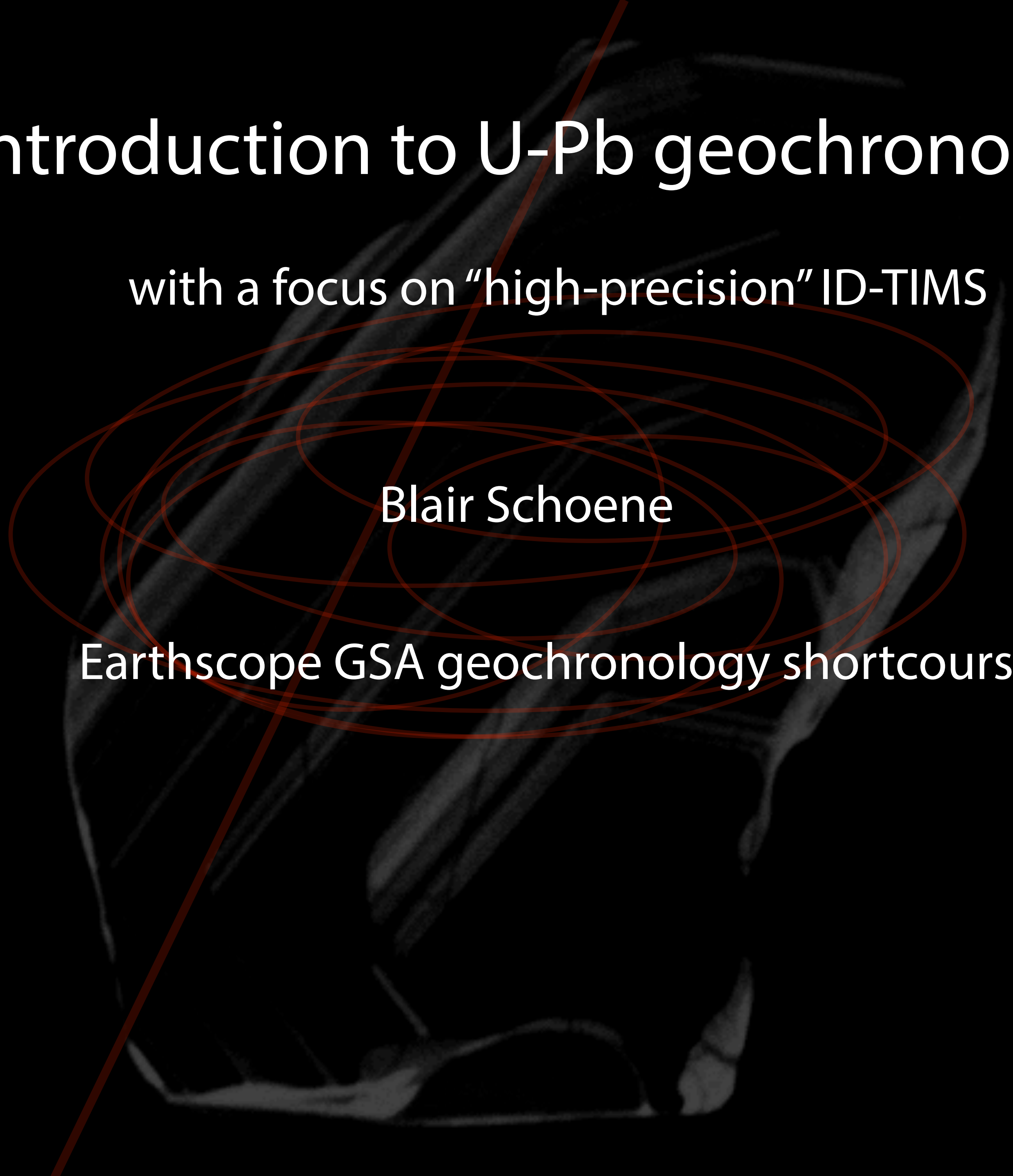
Introduction to U-Pb geochronology

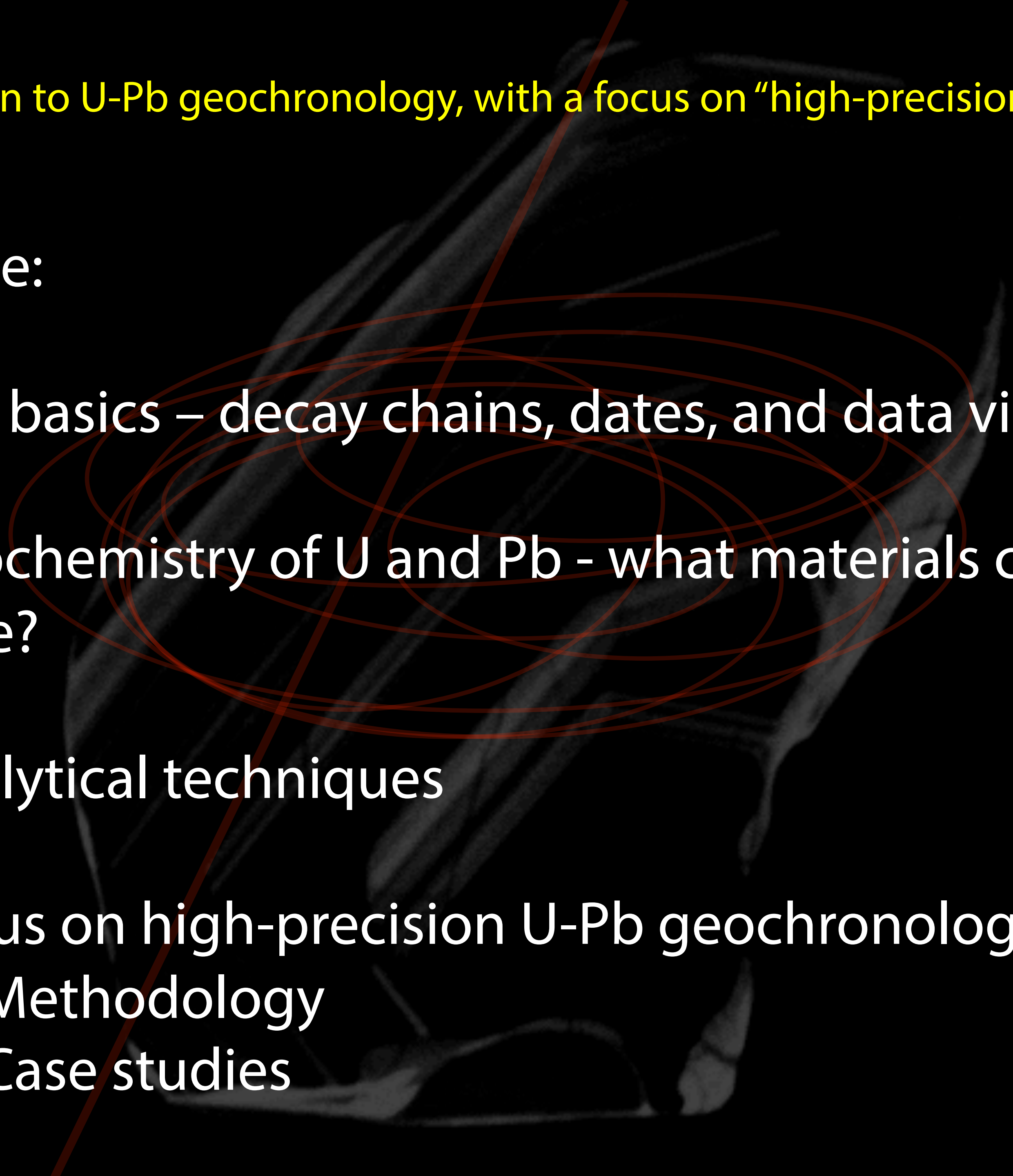
with a focus on “high-precision” ID-TIMS



Blair Schoene

Earthscope GSA geochronology shortcourse

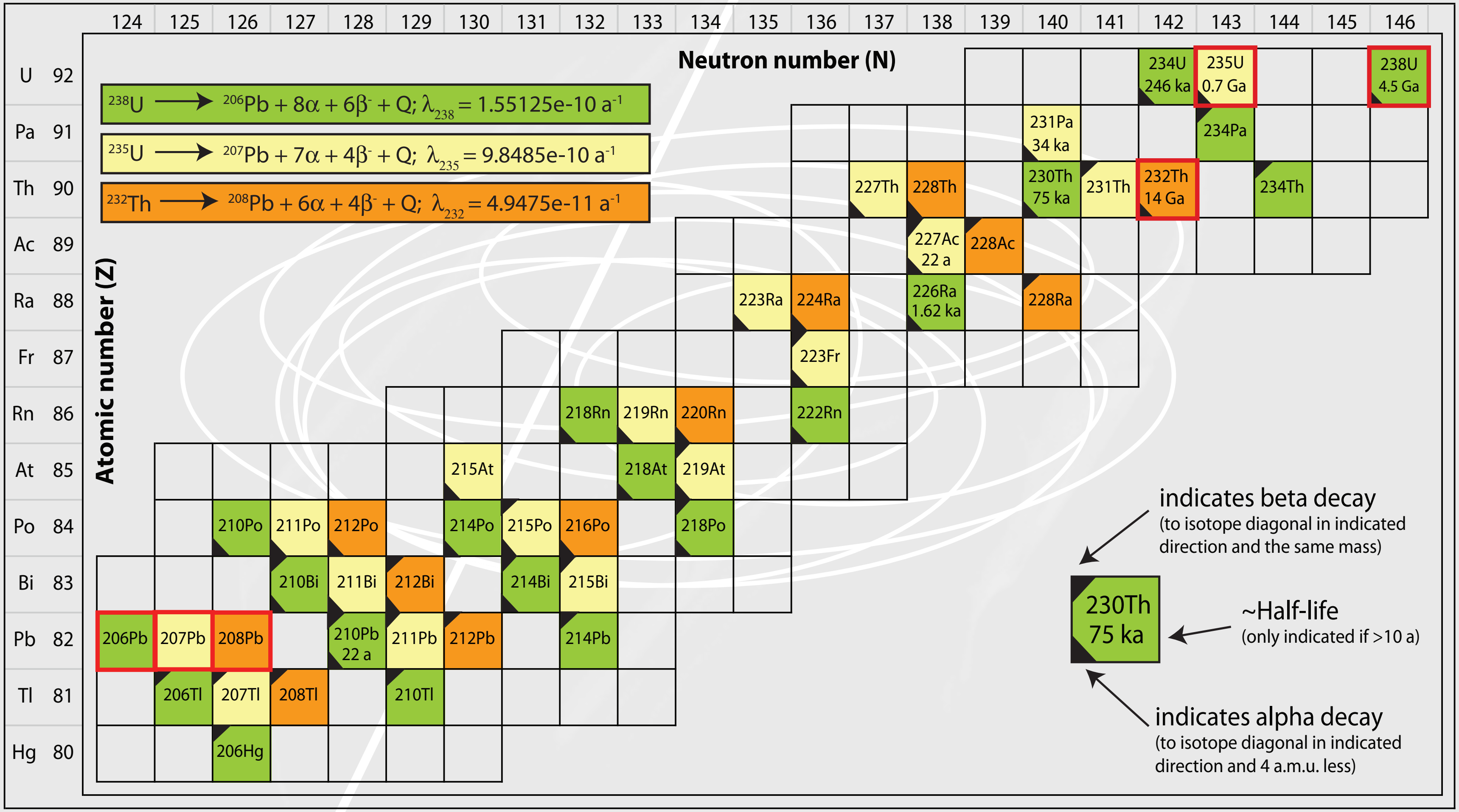
Introduction to U-Pb geochronology, with a focus on “high-precision” ID-TIMS



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



$^{238}U \longrightarrow {}^{206}Pb + 8\alpha + 6\beta^- + Q;\ \lambda_{238} = 1.55125e\text{-}10\ a^{-1}$

$^{235}U \longrightarrow {}^{207}Pb + 7\alpha + 4\beta^- + Q;\ \lambda_{235} = 9.8485e\text{-}10\ a^{-1}$

$^{232}Th \longrightarrow {}^{208}Pb + 6\alpha + 4\beta^- + Q;\ \lambda_{232} = 4.9475e\text{-}11\ a^{-1}$

Neutron number (N)

Atomic number (Z)

		124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146
U	92																			234U 246 ka	235U 0.7 Ga			238U 4.5 Ga
Pa	91																	231Pa 34 ka			234Pa			
Th	90														227Th	228Th		230Th 75 ka	231Th	232Th 14 Ga		234Th		
Ac	89															227Ac 22 a	228Ac							
Ra	88												223Ra	224Ra		226Ra 1.62 ka		228Ra						
Fr	87													223Fr										
Rn	86									218Rn	219Rn	220Rn		222Rn										
At	85							215At			218At	219At												
Po	84			210Po	211Po	212Po		214Po	215Po	216Po		218Po												
Bi	83				210Bi	211Bi	212Bi		214Bi	215Bi														
Pb	82	206Pb	207Pb	208Pb		210Pb 22 a	211Pb	212Pb		214Pb														
Tl	81		206Tl	207Tl	208Tl		210Tl																	
Hg	80			206Hg																				

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

230Th
75 ka

~Half-life
(only indicated if >10 a)

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

Three isochron equations for the three systems

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

$$\left(\frac{{}^{207}Pb}{{}^{204}Pb}\right)_{total} = \left(\frac{{}^{207}Pb}{{}^{204}Pb}\right)_{init.} + \left(\frac{{}^{235}U}{{}^{204}Pb}\right)_{now} \cdot \left(e^{\lambda 235 \cdot t} - 1\right) \qquad (2)$$

$$\left(\frac{{}^{208}Pb}{{}^{204}Pb}\right)_{total} = \left(\frac{{}^{208}Pb}{{}^{204}Pb}\right)_{init.} + \left(\frac{{}^{232}Th}{{}^{204}Pb}\right)_{now} \cdot \left(e^{\lambda 232 \cdot t} - 1\right) \qquad (3)$$

plus one extra:

$$\frac{\left(\frac{{}^{207}Pb}{{}^{204}Pb}\right)_{total} - \left(\frac{{}^{207}Pb}{{}^{204}Pb}\right)_{init.}}{\left(\frac{{}^{206}Pb}{{}^{204}Pb}\right)_{total} - \left(\frac{{}^{206}Pb}{{}^{204}Pb}\right)_{init.}} = \frac{1}{137.82} \cdot \frac{\left(e^{\lambda 235 \cdot t} - 1\right)}{\left(e^{\lambda 238 \cdot t} - 1\right)} \qquad (4)$$

slope of the isochron: $\frac{1}{137.82} \cdot \frac{\left(e^{\lambda 235 \cdot t} - 1\right)}{\left(e^{\lambda 238 \cdot t} - 1\right)}$

Correcting for initial daughter product (common Pb)

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

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

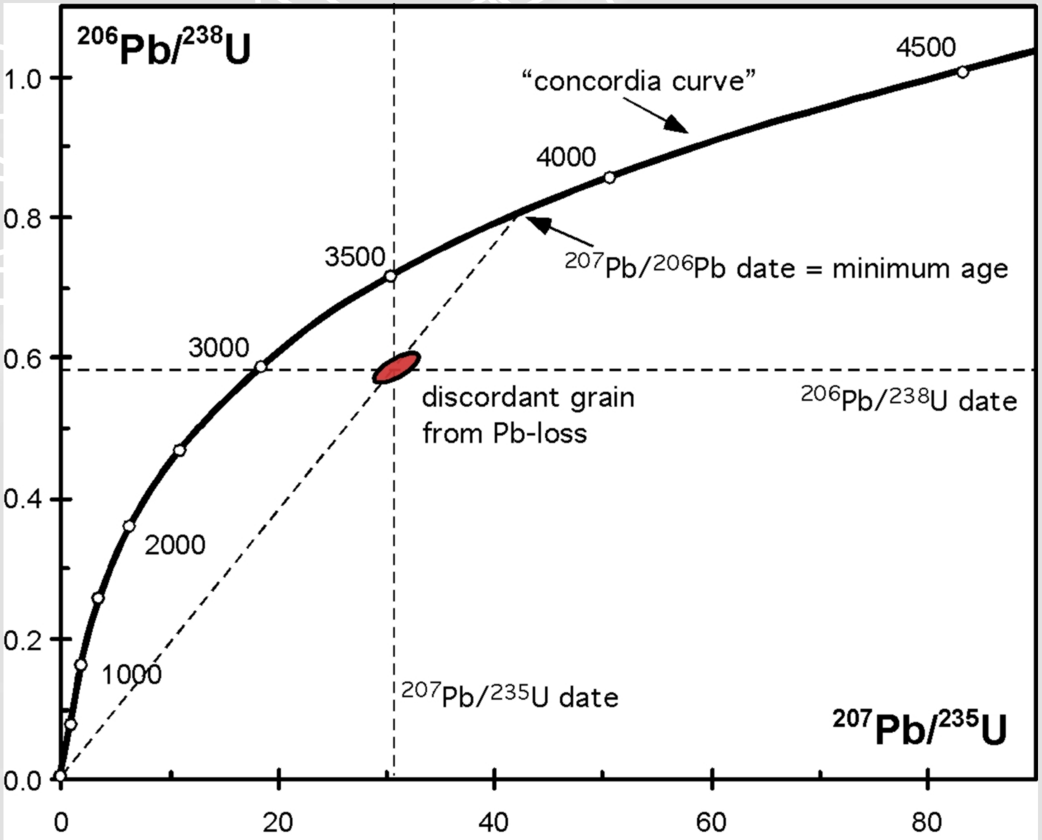
$$^{238}U \rightarrow {}^{206}Pb \qquad t_{1/2} \approx 4.5 Gyr$$

$$^{235}U \rightarrow {}^{207}Pb \qquad t_{1/2} \approx 0.7 Gyr$$

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

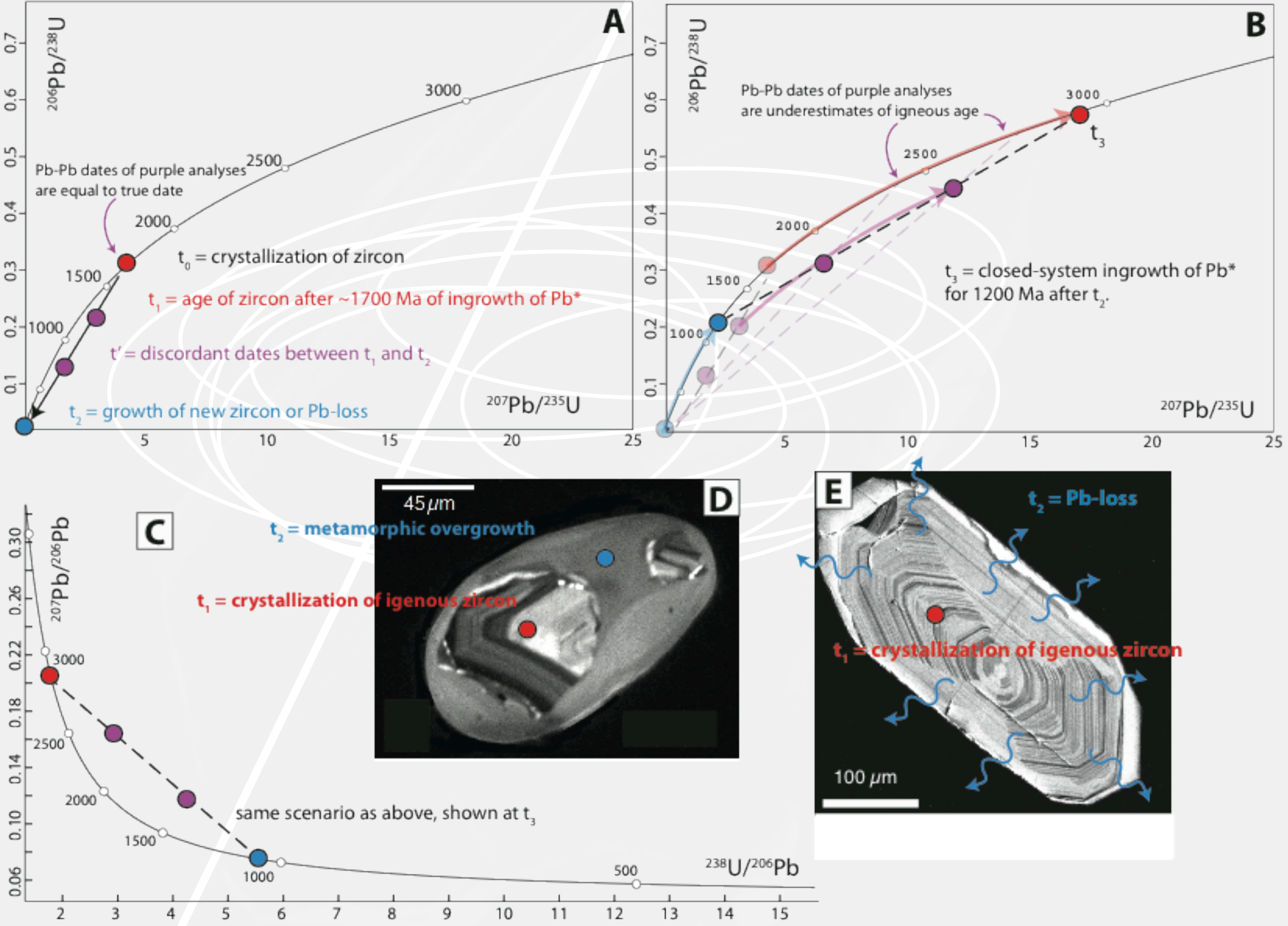
$$\frac{^{207}Pb}{^{235}U} = \exp(\lambda_{235} t) - 1$$

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

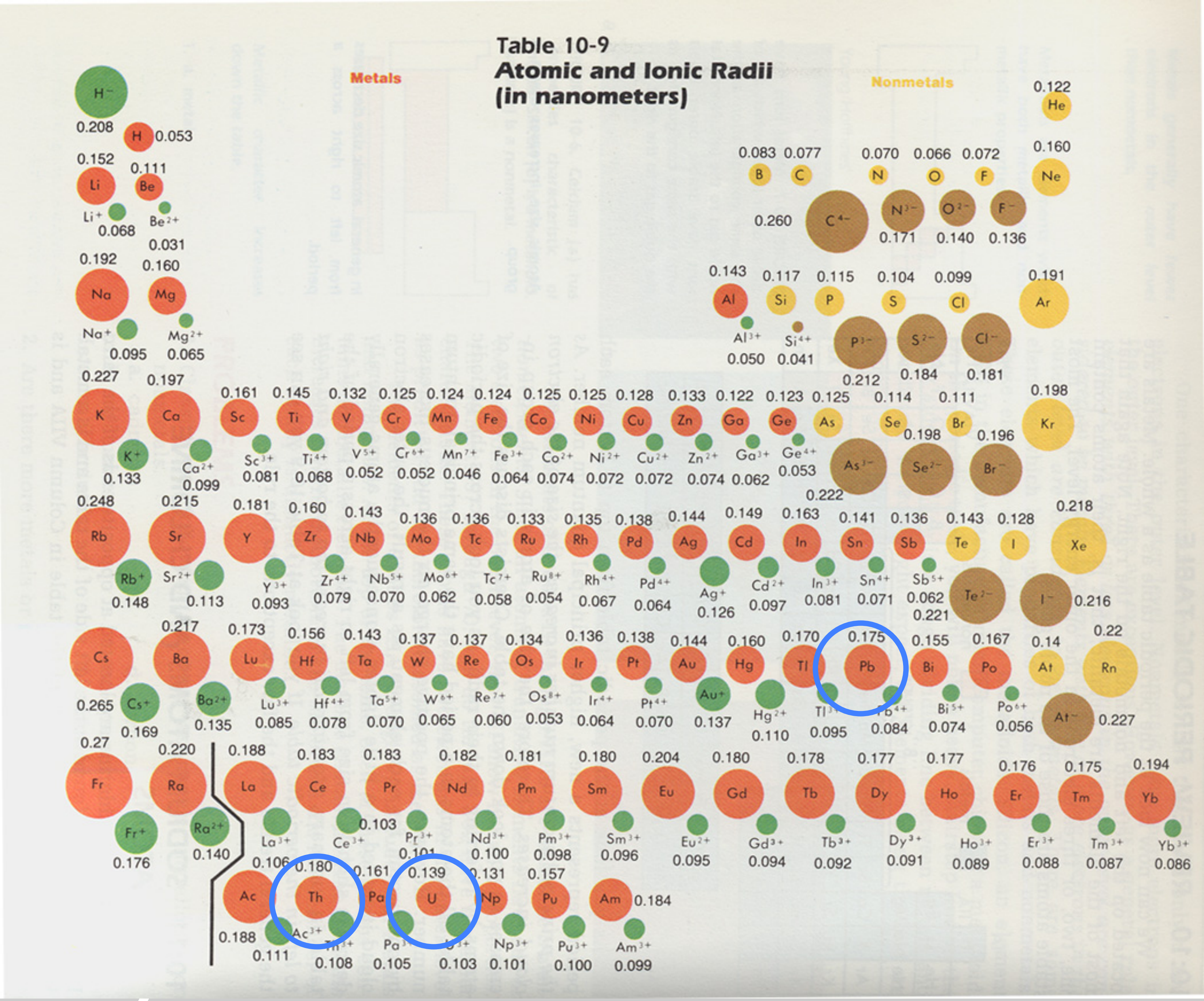


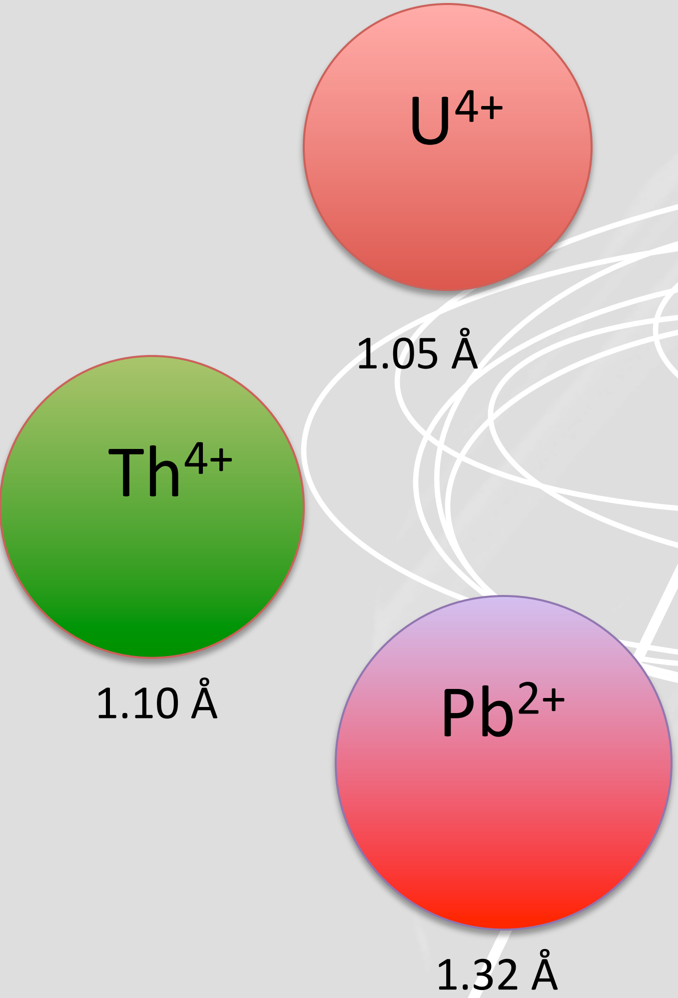
Table 10-9
Atomic and Ionic Radii
(in nanometers)

Metals

Nonmetals

H	0.053	H^-	0.208
He	0.122		
Li	0.152	Li^+	0.068
Be	0.111	Be^{2+}	0.031
B	0.083		
C	0.077	C^{4-}	0.260
N	0.070	N^{3-}	0.171
O	0.066	O^{2-}	0.140
F	0.072	F^-	0.136
Ne	0.160		
Na	0.192	Na^+	0.095
Mg	0.160	Mg^{2+}	0.065
Al	0.143	Al^{3+}	0.050
Si	0.117	Si^{4+}	0.041
P	0.115	P^{3-}	0.212
S	0.104	S^{2-}	0.184
Cl	0.099	Cl^-	0.181
Ar	0.191		
K	0.227	K^+	0.133
Ca	0.197	Ca^{2+}	0.099
Sc	0.161	Sc^{3+}	0.081
Ti	0.145	Ti^{4+}	0.068
V	0.132	V^{5+}	0.052
Cr	0.125	Cr^{6+}	0.052
Mn	0.124	Mn^{7+}	0.046
Fe	0.124	Fe^{3+}	0.064
Co	0.125	Co^{2+}	0.074
Ni	0.125	Ni^{2+}	0.072
Cu	0.128	Cu^{2+}	0.072
Zn	0.133	Zn^{2+}	0.074
Ga	0.122	Ga^{3+}	0.062
Ge	0.123	Ge^{4+}	0.053
As	0.125	As^{3-}	0.222
Se	0.114	Se^{2-}	0.198
Br	0.111	Br^-	0.196
Kr	0.198		
Rb	0.248	Rb^+	0.148
Sr	0.215	Sr^{2+}	0.113
Y	0.181	Y^{3+}	0.093
Zr	0.160	Zr^{4+}	0.079
Nb	0.143	Nb^{5+}	0.070
Mo	0.136	Mo^{6+}	0.062
Tc	0.136	Tc^{7+}	0.058
Ru	0.133	Ru^{8+}	0.054
Rh	0.135	Rh^{4+}	0.067
Pd	0.138	Pd^{4+}	0.064
Ag	0.144	Ag^+	0.126
Cd	0.149	Cd^{2+}	0.097
In	0.163	In^{3+}	0.081
Sn	0.141	Sn^{4+}	0.071
Sb	0.136	Sb^{5+}	0.062
Te	0.143	Te^{2-}	0.221
I	0.128	I^-	0.216
Xe	0.218		
Cs	0.265	Cs^+	0.169
Ba	0.217	Ba^{2+}	0.135
Lu	0.173	Lu^{3+}	0.085
Hf	0.156	Hf^{4+}	0.078
Ta	0.143	Ta^{5+}	0.070
W	0.137	W^{6+}	0.065
Re	0.137	Re^{7+}	0.060
Os	0.134	Os^{8+}	0.053
Ir	0.136	Ir^{4+}	0.064
Pt	0.138	Pt^{4+}	0.070
Au	0.144	Au^+	0.137
Hg	0.160	Hg^{2+}	0.110
Tl	0.170	Tl^{3+}	0.095
Pb	0.175	Pb^{4+}	0.084
Bi	0.155	Bi^{5+}	0.074
Po	0.167	Po^{6+}	0.056
At	0.14	At^-	0.227
Rn	0.22		
Fr	0.27	Fr^+	0.176
Ra	0.220	Ra^{2+}	0.140
La	0.188	La^{3+}	0.106
Ce	0.183	Ce^{3+}	0.103
Pr	0.183	Pr^{3+}	0.101
Nd	0.182	Nd^{3+}	0.100
Pm	0.181	Pm^{3+}	0.098
Sm	0.180	Sm^{3+}	0.096
Eu	0.204	Eu^{2+}	0.095
Gd	0.180	Gd^{3+}	0.094
Tb	0.178	Tb^{3+}	0.092
Dy	0.177	Dy^{3+}	0.091
Ho	0.177	Ho^{3+}	0.089
Er	0.176	Er^{3+}	0.088
Tm	0.175	Tm^{3+}	0.087
Yb	0.194	Yb^{3+}	0.086
Ac	0.188	Ac^{3+}	0.111
Th	0.180	Th^{4+}	0.108
Pa	0.161	Pa	0.105
U	0.139	U^{4+}	0.103
Np	0.131	Np^{3+}	0.101
Pu	0.157	Pu^{3+}	0.100
Am	0.184	Am^{3+}	0.099

Geochemistry of U, Th and Pb



U^{4+}

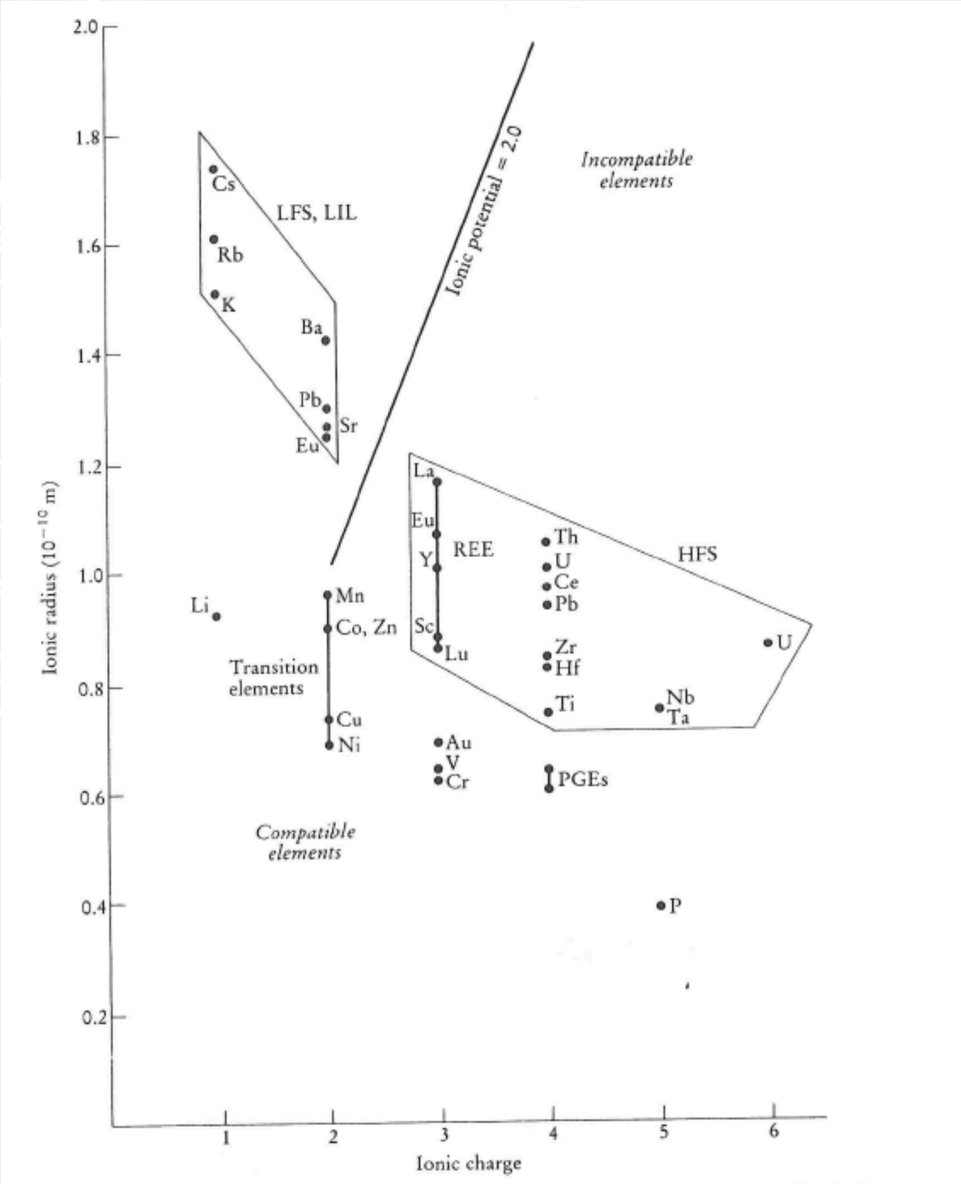
1.05 Å

Th^{4+}

1.10 Å

Pb^{2+}

1.32 Å

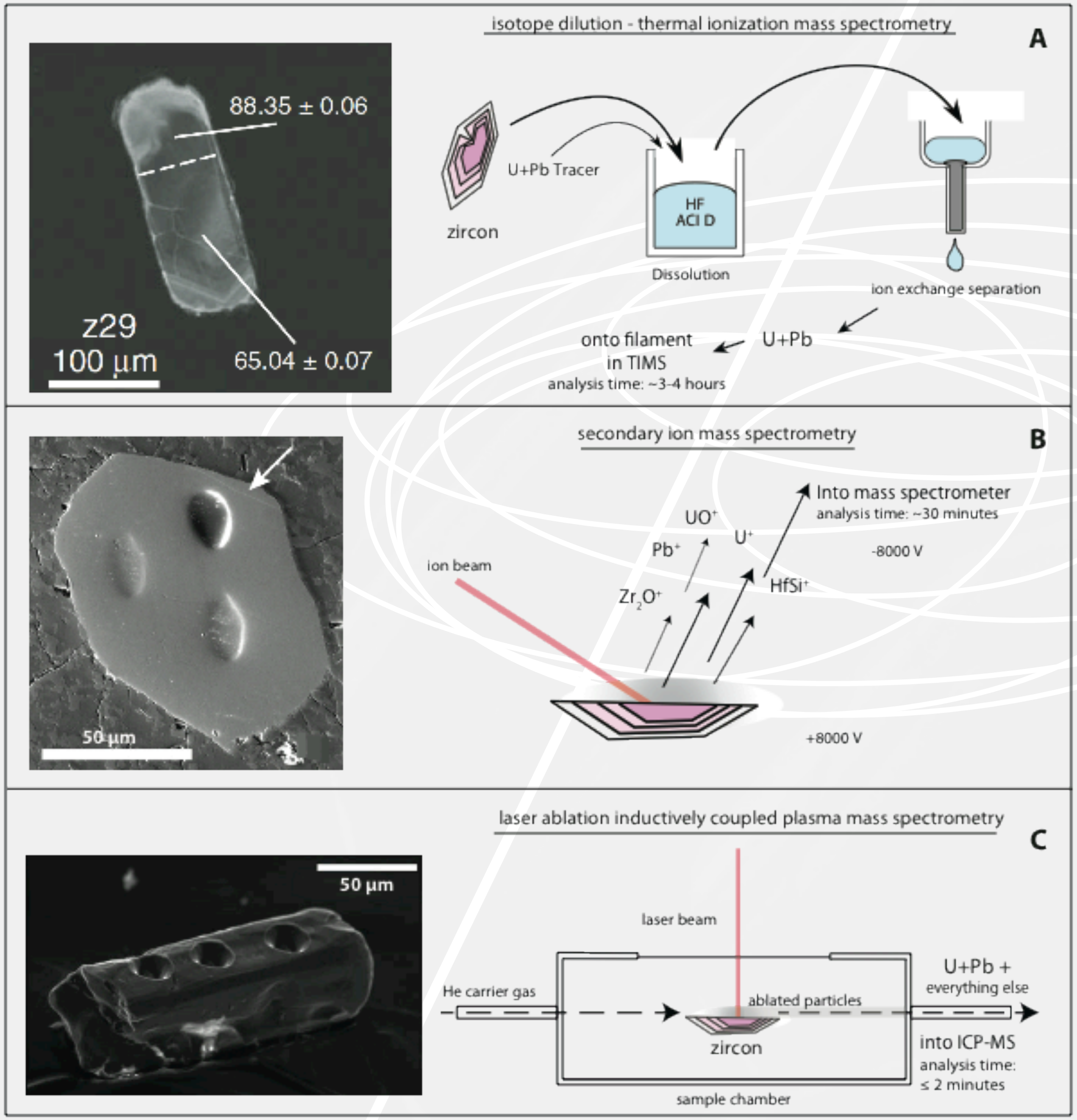


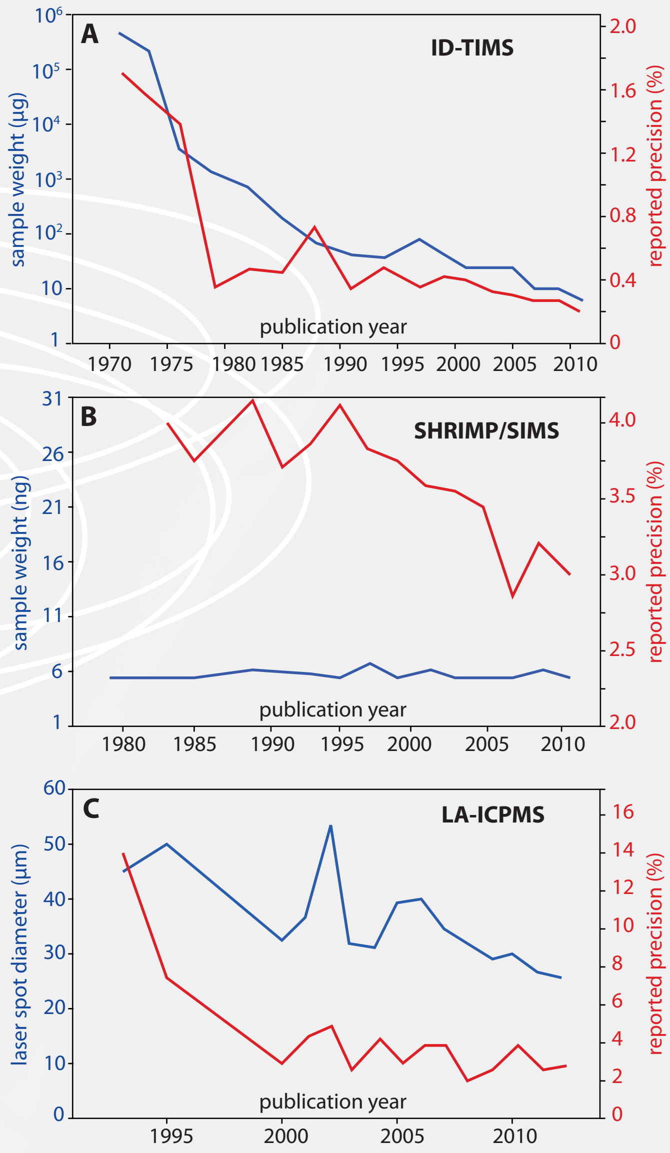
Minerals used in U-Th-Pb dating

Mineral	Formula	U content (ppm)	Th/U	Common Pb (ppm)	Rock Type
Zircon	$ZrSiO_4$	1 - >10,000	0.1-2	< 1	most
Titanite (sphene)	$CaTiOSiO_4$	4 -500	0.5-20	5 -40	k,c,a,m,ig, mp, gp,hv, gn,sk
Monazite	$(Ce,La,Th)PO_4$	282 - >50,000	5-1000	< 10	mp,sg, hv,gp
Xenotime	YPO_4	5,000 - 30,000	0.1-2	< 5	gp,sg
Thorite	$ThSiO_4$	> 50,000	huge	< 2	gp,sg
Allanite	$(Ca,Ce)_2(Fe^{+2},Fe^{+3})Al_2O{\bullet}OH[Si_2O_7][SiO_4]$	130- 600	2-200	5 -30	ig,gp,sk
Perovskite	$(Ca,Na,Fe^{+2},Ce)(Ti,Nb)O_3$	21 -348		< 2- 90	k,c
Baddeleyite	ZrO_2	58 - 3410	<0.2	< 5	k,c,um, m,a
Rutile	TiO_2	< 1 - 390	0.1-5	< 2-10	gp,gn, hv
Apatite	$Ca_5(PO_4)_3(OH,F,Cl)$	8 -114	2-20	< 5-30	most

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

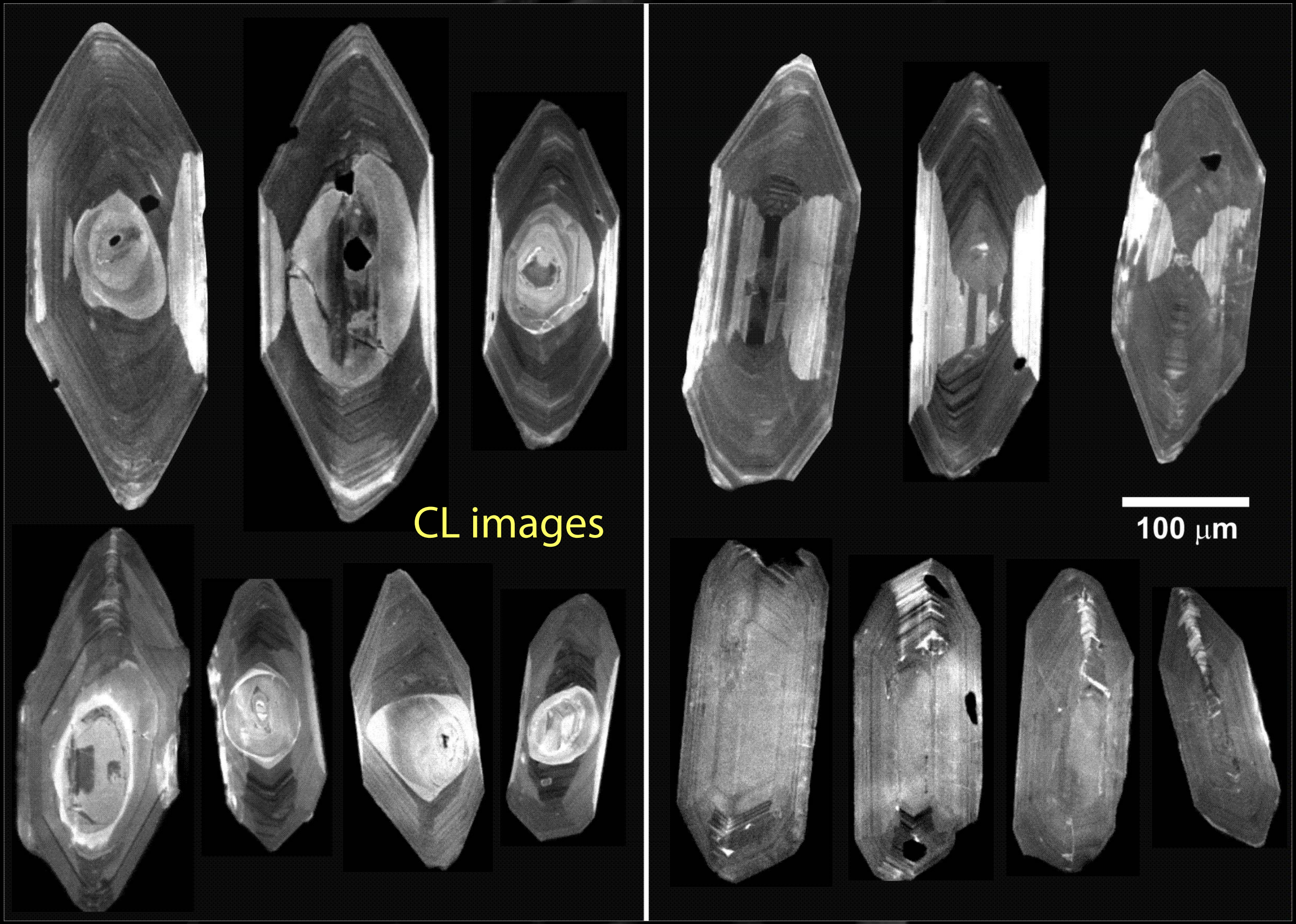




Imaging of chemical zoning – important for guiding ID-TIMS geochronology

Zircon with inherited cores (to be avoided or microsampled)

Zircon without cores (to be dated or microsampled)

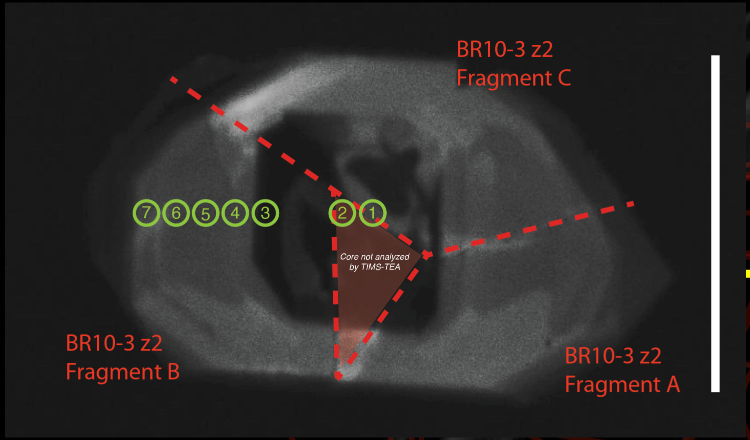


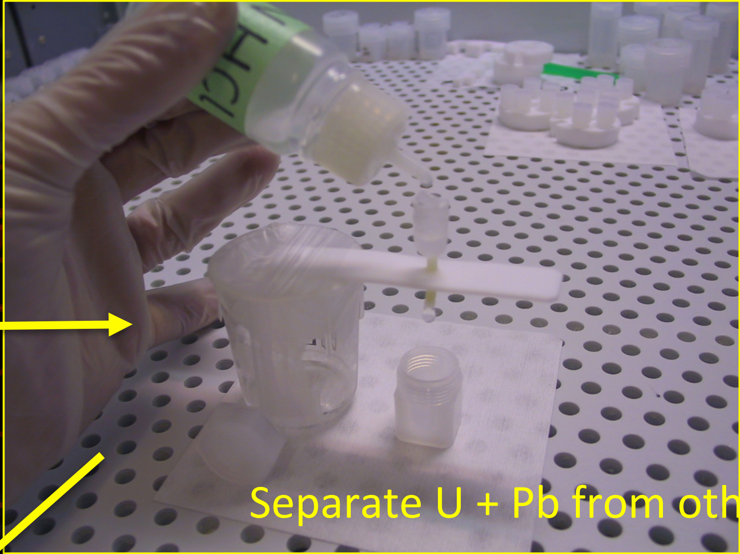
- Detection of age domains in complex zircon

Slide courtesy of J. Crowley

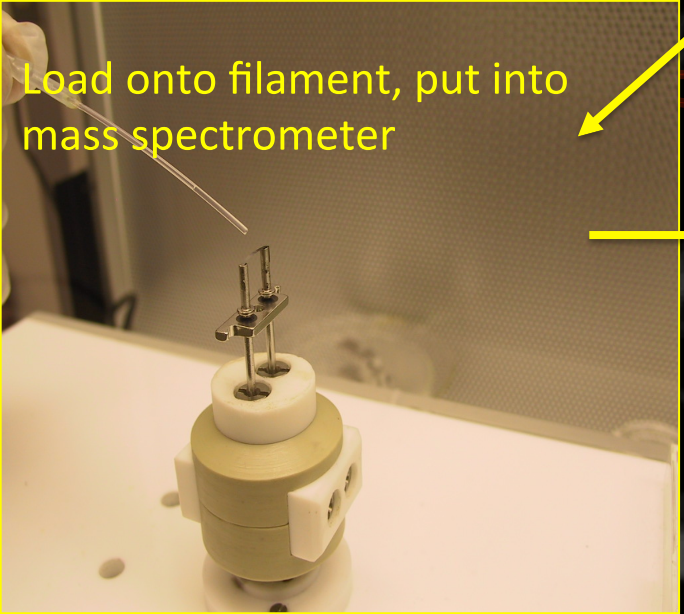
CA-ID-TIMS U-Pb on zircon

Zircon in grain mount

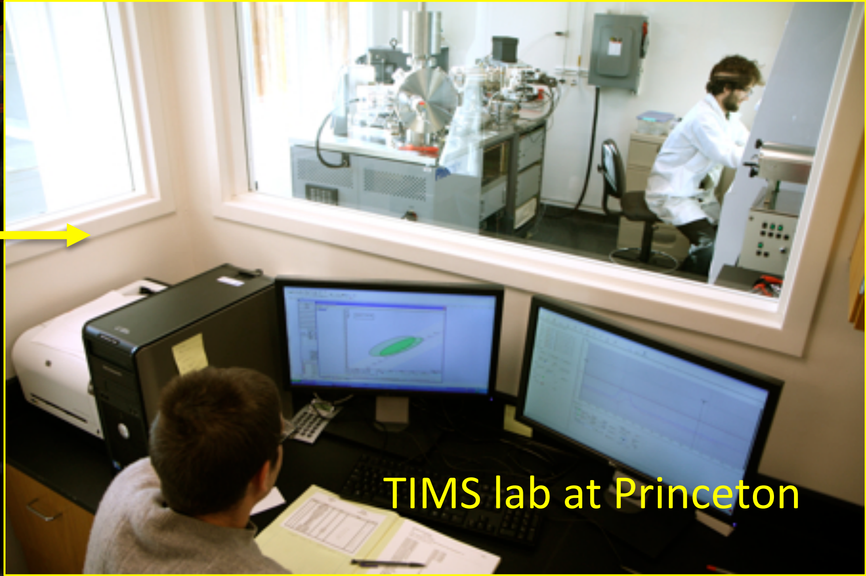




Separate U + Pb from other elements



Load onto filament, put into mass spectrometer

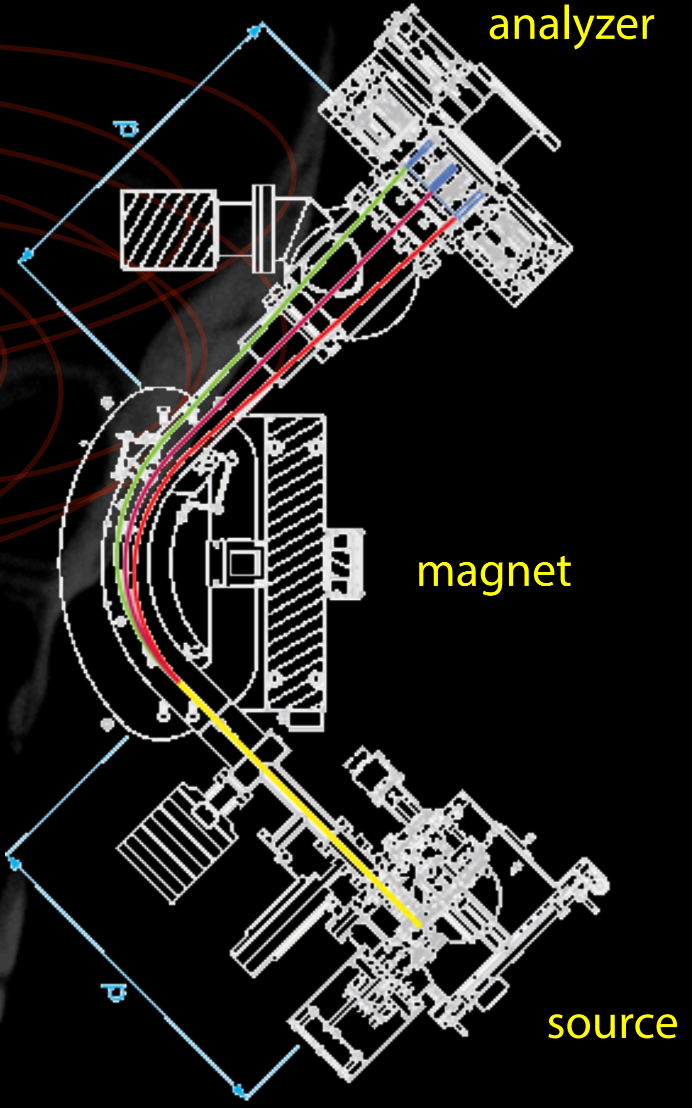


TIMS lab at Princeton

A thermal ionization mass spectrometer (TIMS)

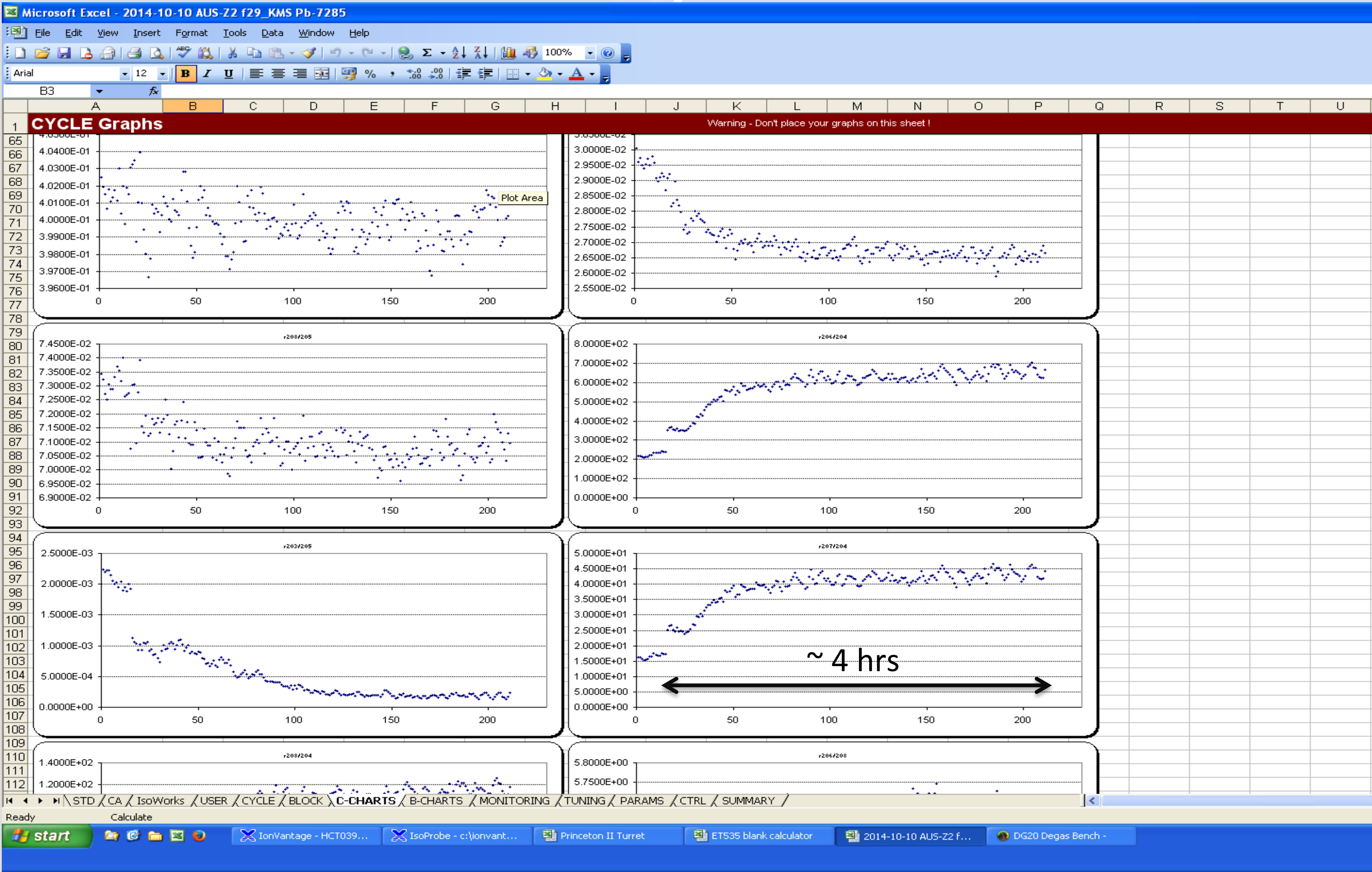
An IsotopX Phoenix62 at Princeton University

Footprint is ~2 x 1 m



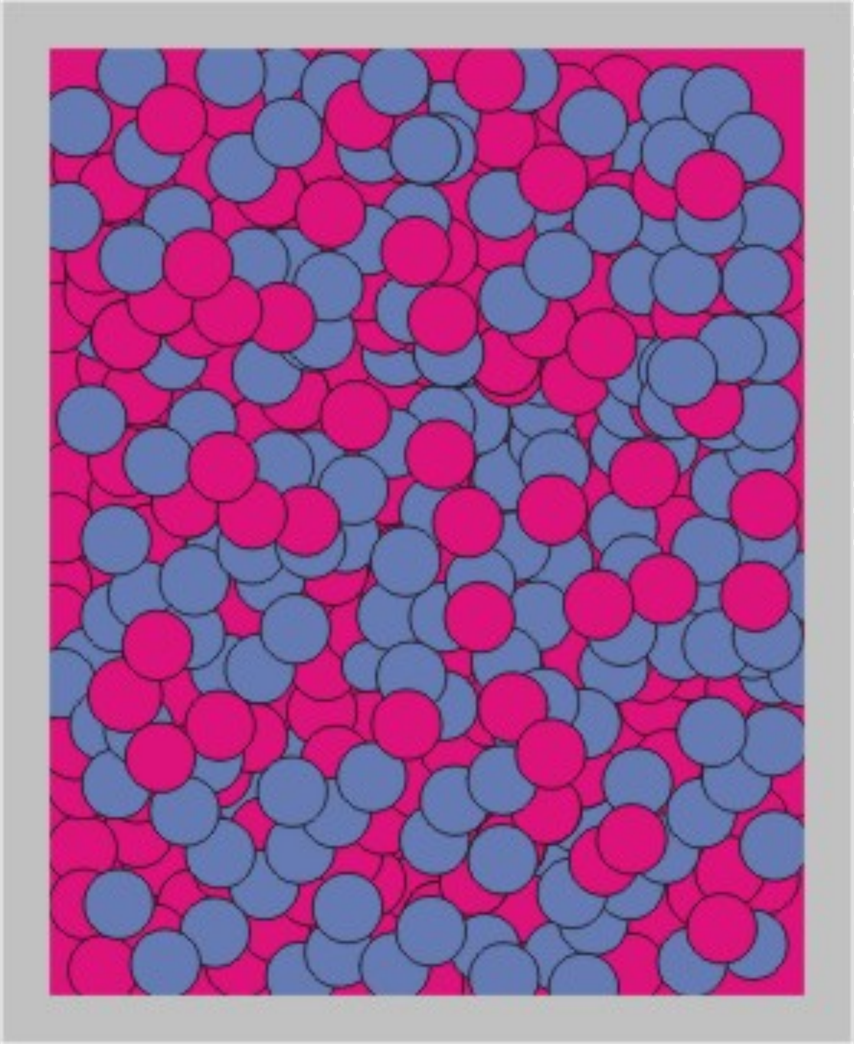
Why is precision so good with TIMS?

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



Why is precision so good with TIMS?

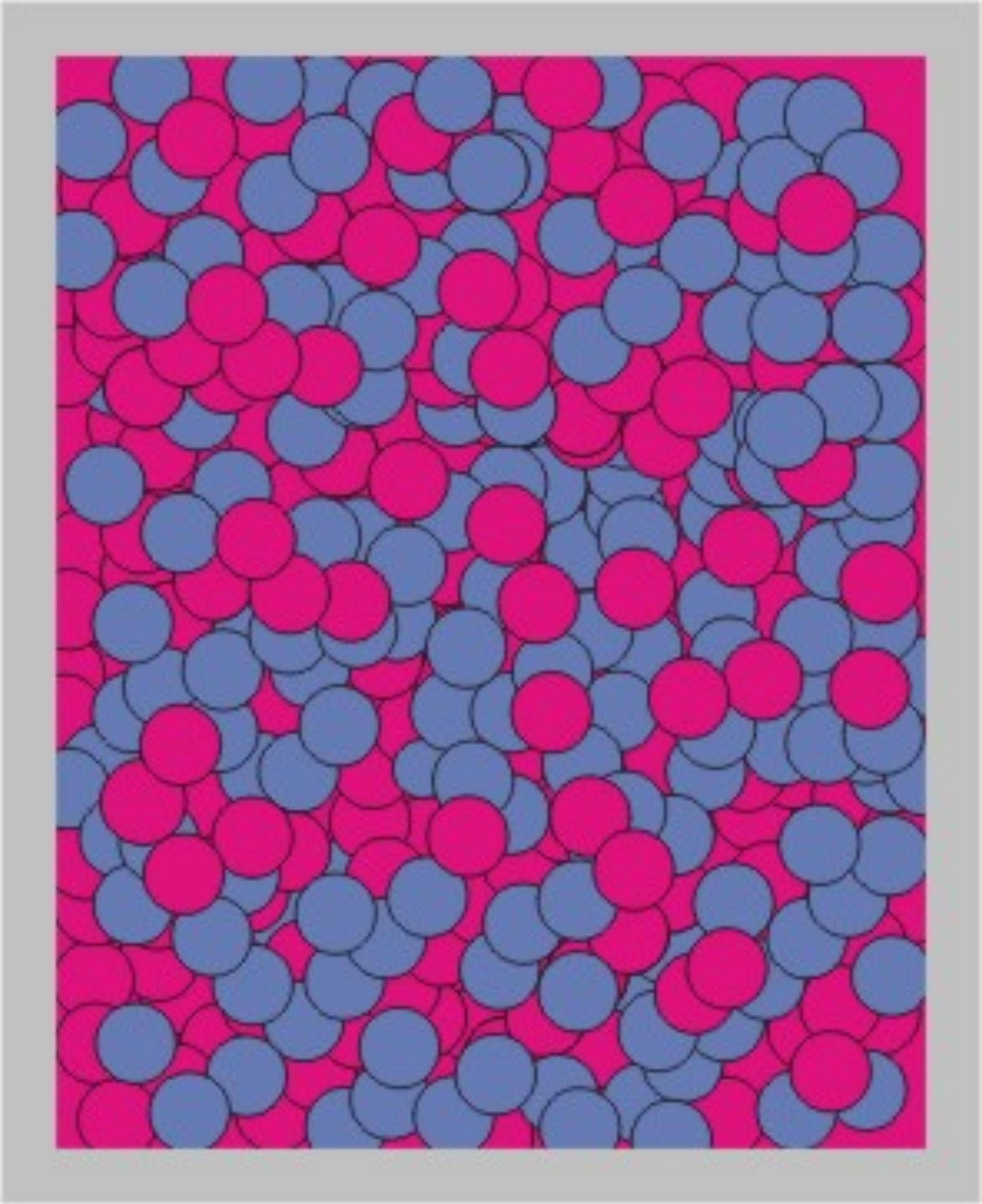
2. Isotope dilution allows us to measured Pb and U separately, and thus not worry about interelemental fractionation during measurements (which is a limiting factor in precision of other techniques).



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

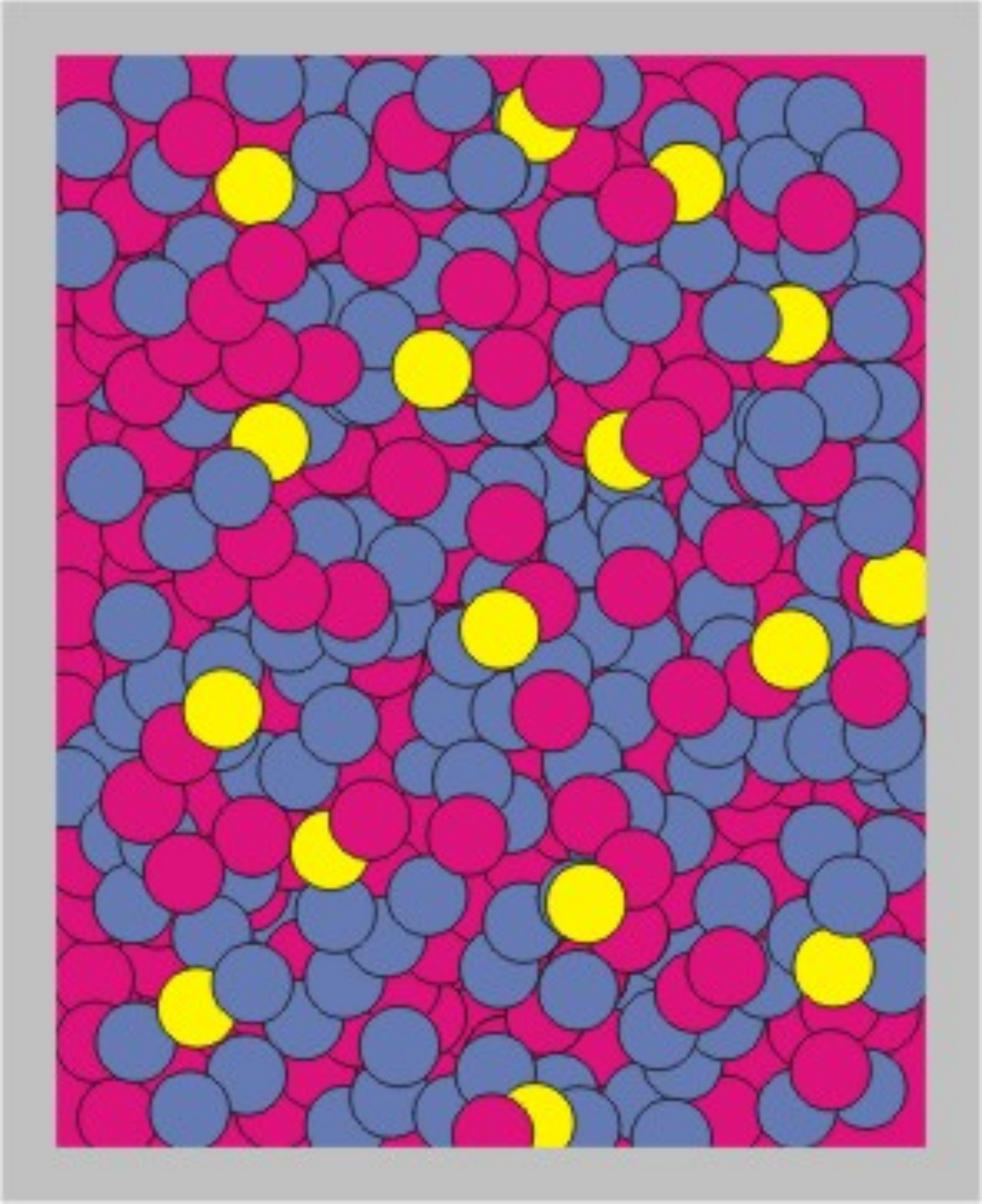
Answer:

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

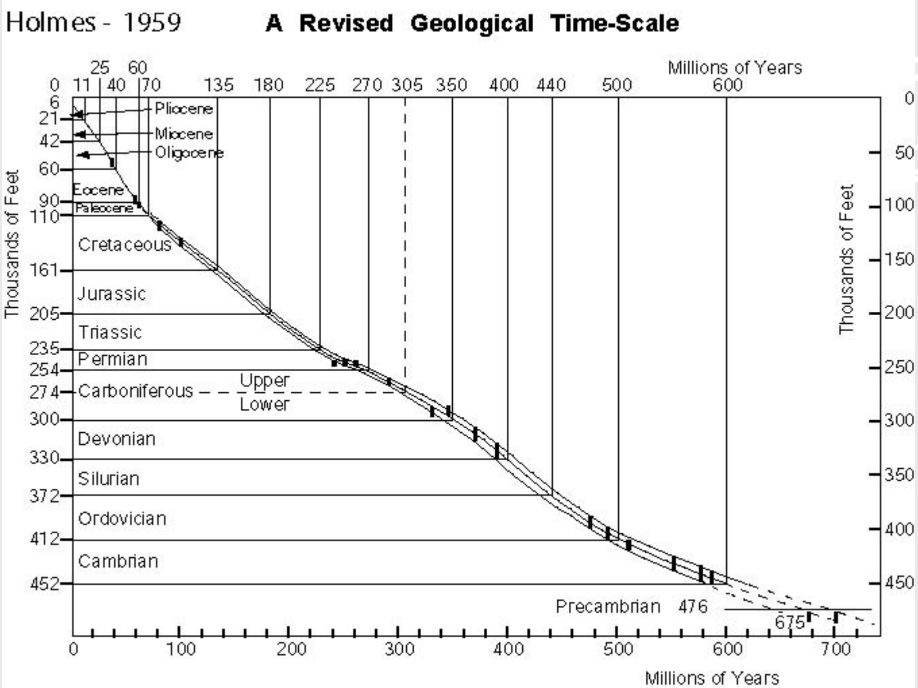
measure:

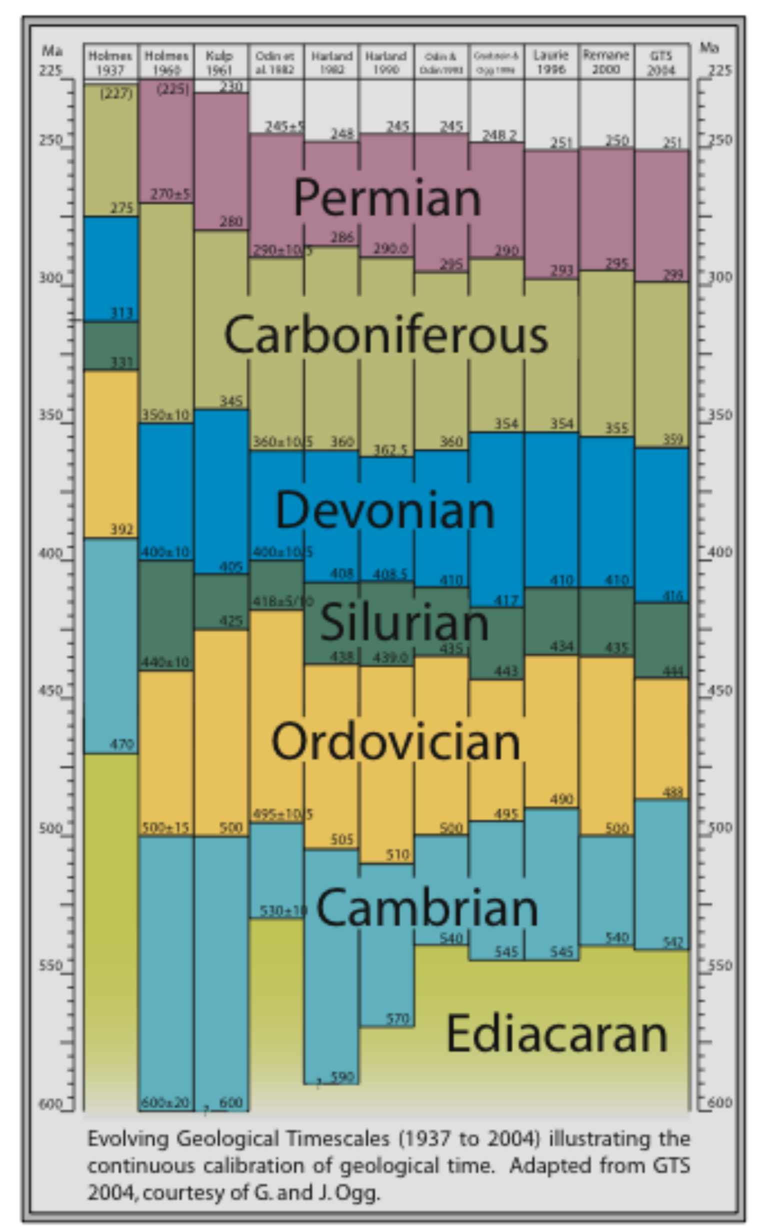
Yellow/red = 0.05

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

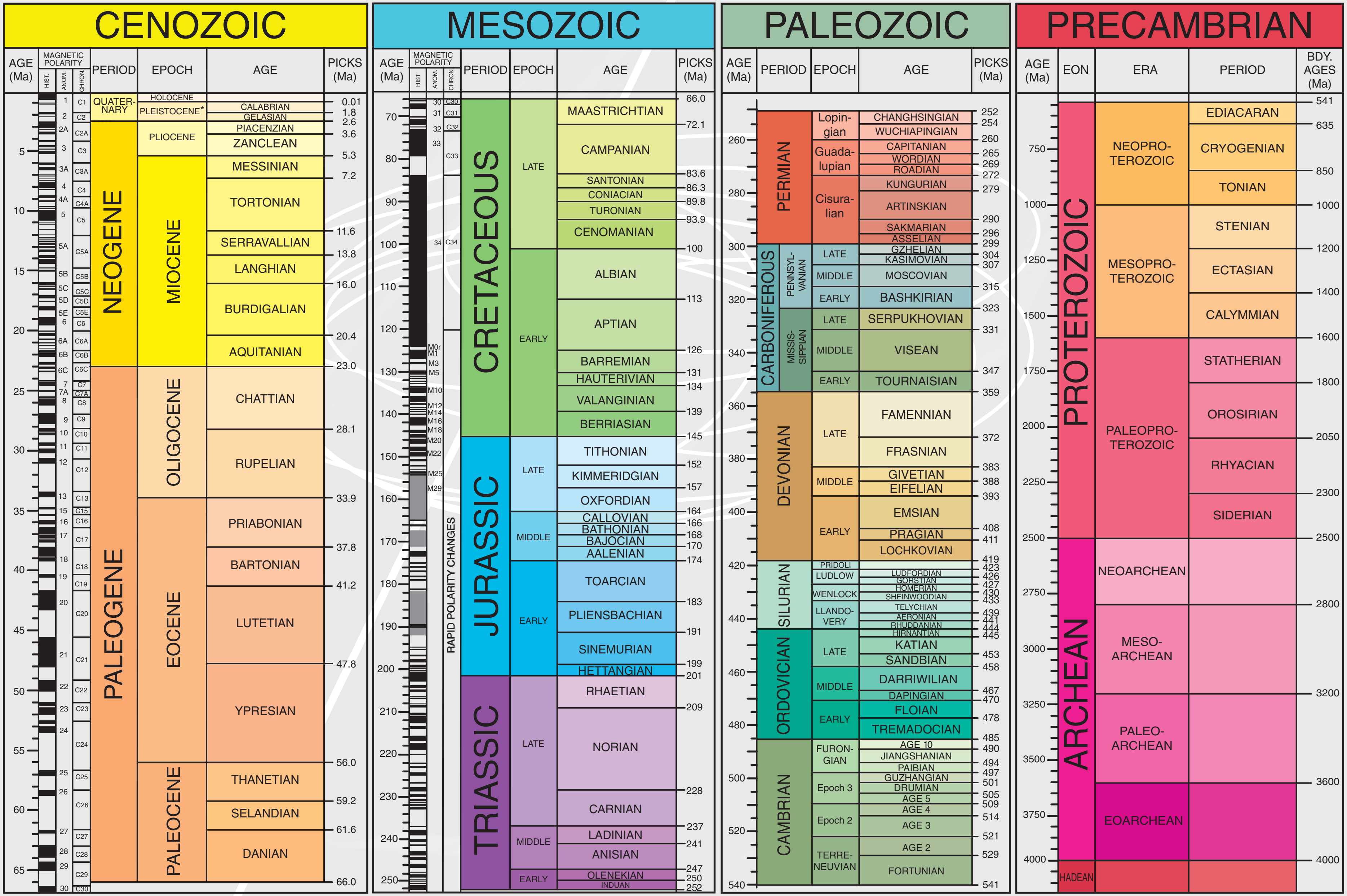
Application 1: calibration of the geologic timescale and earth history


Holmes - 1959 **A Revised Geological Time-Scale**



Evolving Geological Timescales (1937 to 2004) illustrating the continuous calibration of geological time. Adapted from GTS 2004, courtesy of G. and J. Ogg.

GSA GEOLOGIC TIME SCALE v. 4.0



CENOZOIC

PERIOD	EPOCH	AGE	PICKS (Ma)
QUATERNARY	HOLOCENE		0.01
	PLEISTOCENE*	CALABRIAN	1.8
		GELASIAN	2.6
NEOGENE	PLIOCENE	PIACENZIAN	3.6
		ZANCLEAN	5.3
	MIOCENE	MESSINIAN	7.2
		TORTONIAN	11.6
		SERRAVALLIAN	13.8
		LANGHIAN	16.0
		BURDIGALIAN	20.4
		AQUITANIAN	23.0
PALEOGENE	OLIGOCENE	CHATTIAN	28.1
		RUPELIAN	33.9
	EOCENE	PRIABONIAN	37.8
		BARTONIAN	41.2
		LUTETIAN	47.8
		YPRESIAN	56.0
	PALEOCENE	THANETIAN	59.2
		SELANDIAN	61.6
		DANIAN	66.0

MESOZOIC

PERIOD	EPOCH	AGE	PICKS (Ma)
			66.0
CRETACEOUS	LATE	MAASTRICHTIAN	72.1
		CAMPANIAN	83.6
		SANTONIAN	86.3
		CONIACIAN	89.8
		TURONIAN	93.9
		CENOMANIAN	100
	EARLY	ALBIAN	113
		APTIAN	126
		BARREMIAN	131
		HAUTERIVIAN	134
		VALANGINIAN	139
		BERRIASIAN	145
JURASSIC	LATE	TITHONIAN	152
		KIMMERIDGIAN	157
		OXFORDIAN	164
	MIDDLE	CALLOVIAN	166
		BATHONIAN	168
		BAJOCIAN	170
		AALENIAN	174
	EARLY	TOARCIAN	183
		PLIENSBACHIAN	191
		SINEMURIAN	199
		HETTANGIAN	201
TRIASSIC	LATE	RHAETIAN	209
		NORIAN	228
		CARNIAN	237
	MIDDLE	LADINIAN	241
		ANISIAN	247
	EARLY	OLENEKIAN	250
		INDUAN	252

PALEOZOIC

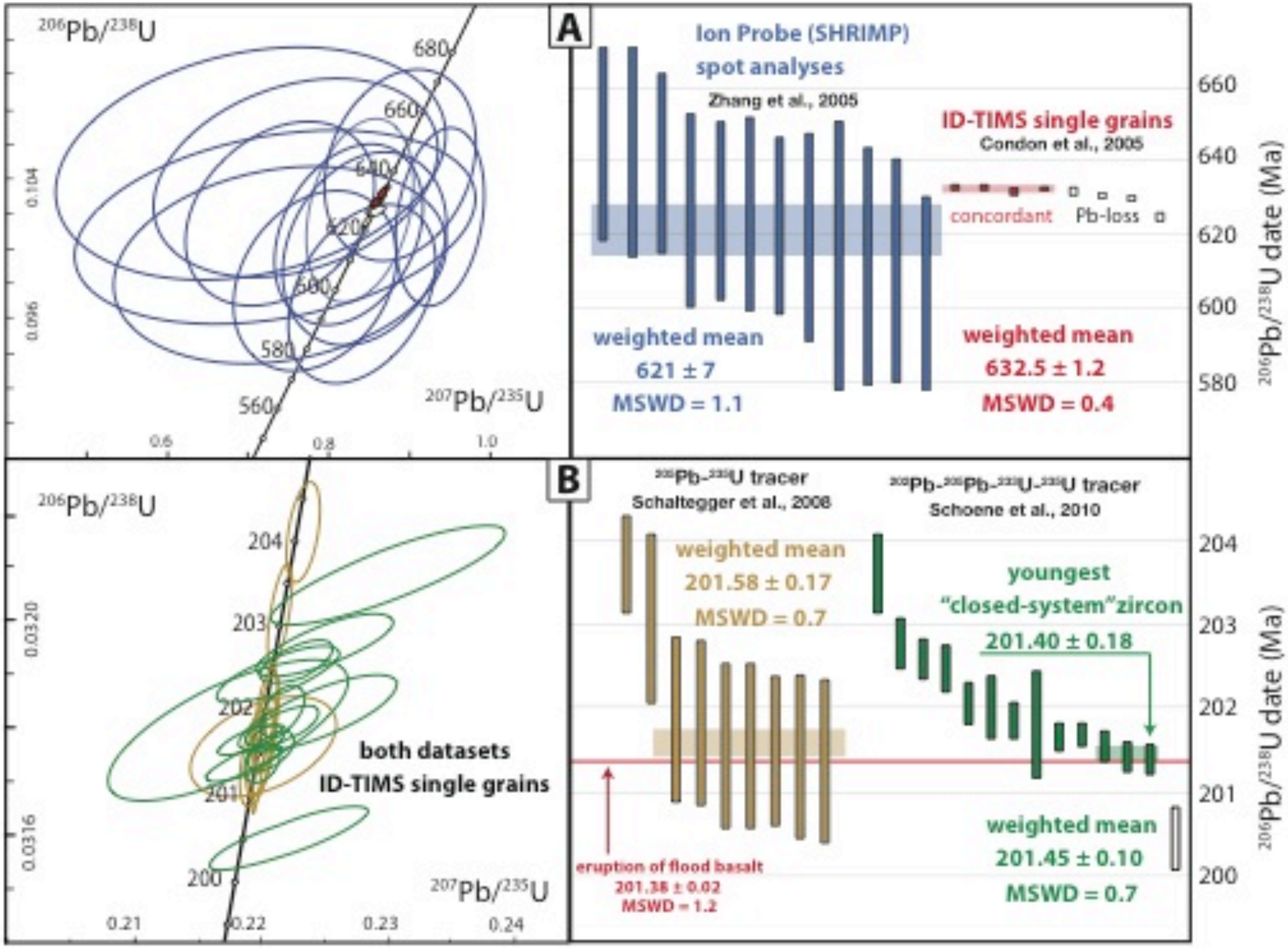
PERIOD		EPOCH	AGE	PICKS (Ma)
				252
PERMIAN		Lopingian	CHANGHSINGIAN	254
			WUCHIAPINGIAN	260
		Guadalupian	CAPITANIAN	265
			WORDIAN	269
			ROADIAN	272
		Cisuralian	KUNGURIAN	279
			ARTINSKIAN	290
			SAKMARIAN	296
			ASSELIAN	299
CARBONIFEROUS	PENNSYLVANIAN	LATE	GZHELIAN	304
			KASIMOVIAN	307
		MIDDLE	MOSCOVIAN	315
		EARLY	BASHKIRIAN	323
	MISSISSIPPIAN	LATE	SERPUKHOVIAN	331
		MIDDLE	VISEAN	347
		EARLY	TOURNAISIAN	359
DEVONIAN		LATE	FAMENNIAN	372
			FRASNIAN	383
		MIDDLE	GIVETIAN	388
			EIFELIAN	393
		EARLY	EMSIAN	408
			PRAGIAN	411
			LOCHKOVIAN	419
SILURIAN		PRIDOLI		423
		LUDLOW	LUDFORDIAN	426
			GORSTIAN	427
		WENLOCK	HOMERIAN	430
			SHEINWOODIAN	433
		LLANDOVERY	TELYCHIAN	439
			AERONIAN	441
			RHUDDANIAN	444
ORDOVICIAN		LATE	HIRNANTIAN	445
			KATIAN	453
			SANDBIAN	458
		MIDDLE	DARRIWILIAN	467
			DAPINGIAN	470
		EARLY	FLOIAN	478
			TREMADOCIAN	485
CAMBRIAN		FURONGIAN	AGE 10	490
			JIANGSHANIAN	494
			PAIBIAN	497
		Epoch 3	GUZHANGIAN	501
			DRUMIAN	505
			AGE 5	509
		Epoch 2	AGE 4	514
			AGE 3	521
		TERRENEUVIAN	AGE 2	529
			FORTUNIAN	541

PRECAMBRIAN

EON	ERA	PERIOD	BDY. AGES (Ma)
			541
PROTEROZOIC	NEOPROTEROZOIC	EDIACARAN	635
		CRYOGENIAN	850
		TONIAN	1000
	MESOPROTEROZOIC	STENIAN	1200
		ECTASIAN	1400
		CALYMMIAN	1600
	PALEOPROTEROZOIC	STATHERIAN	1800
		OROSIRIAN	2050
		RHYACIAN	2300
		SIDERIAN	2500
ARCHEAN	NEOARCHEAN		2800
	MESOARCHEAN		3200
	PALEOARCHEAN		3600
	EOARCHEAN		4000
HADEAN			

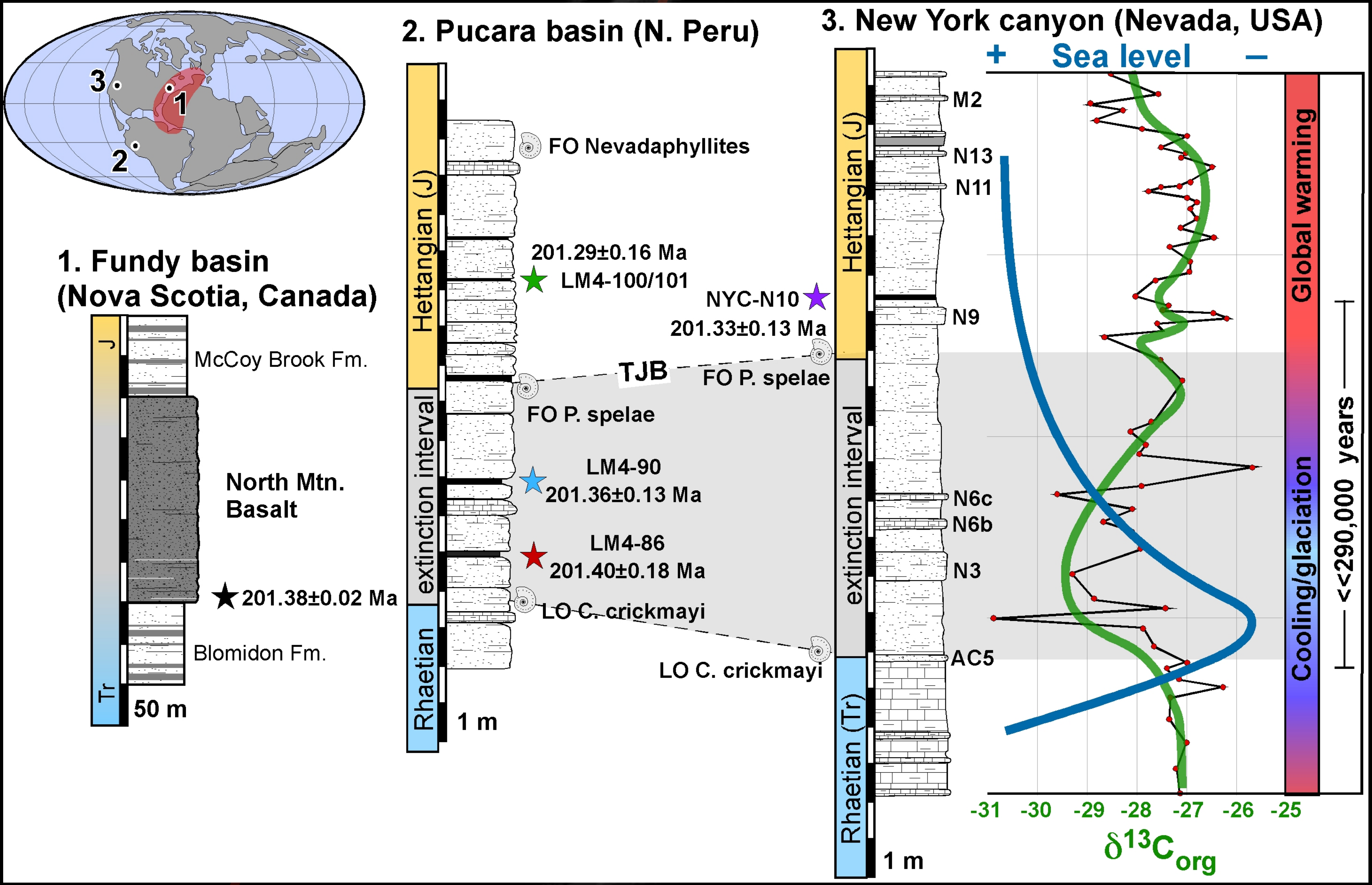
When precision and accuracy really matter….

Examples of ashbed geochronology from the stratigraphic record.



Why the need for higher precision?

Volcanism extinction environment



Application 2: evolution of magmatic systems

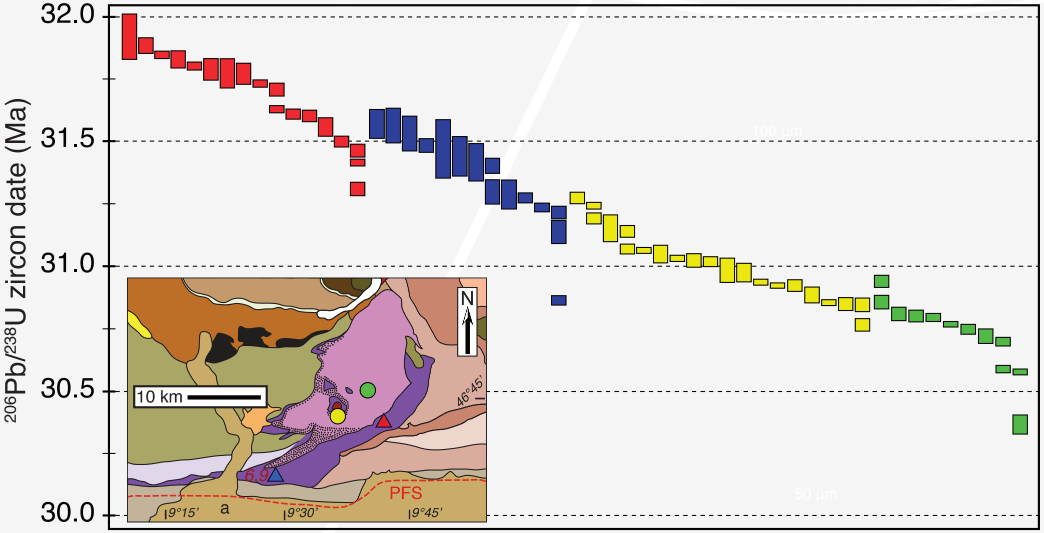
What are the rates of mass and heat transport in the crust?

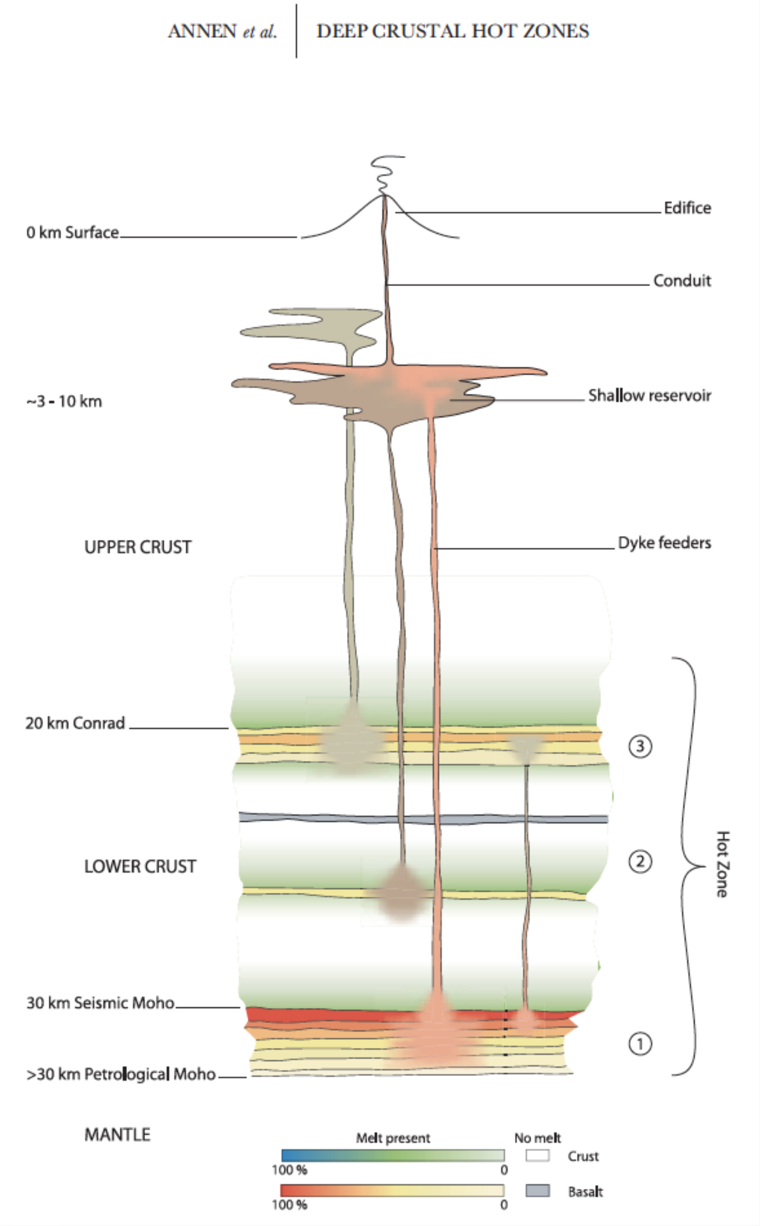
What are the rheological properties of the crust during orogenesis?

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

How are batholiths made?

Why do super volcano eruptions occur?

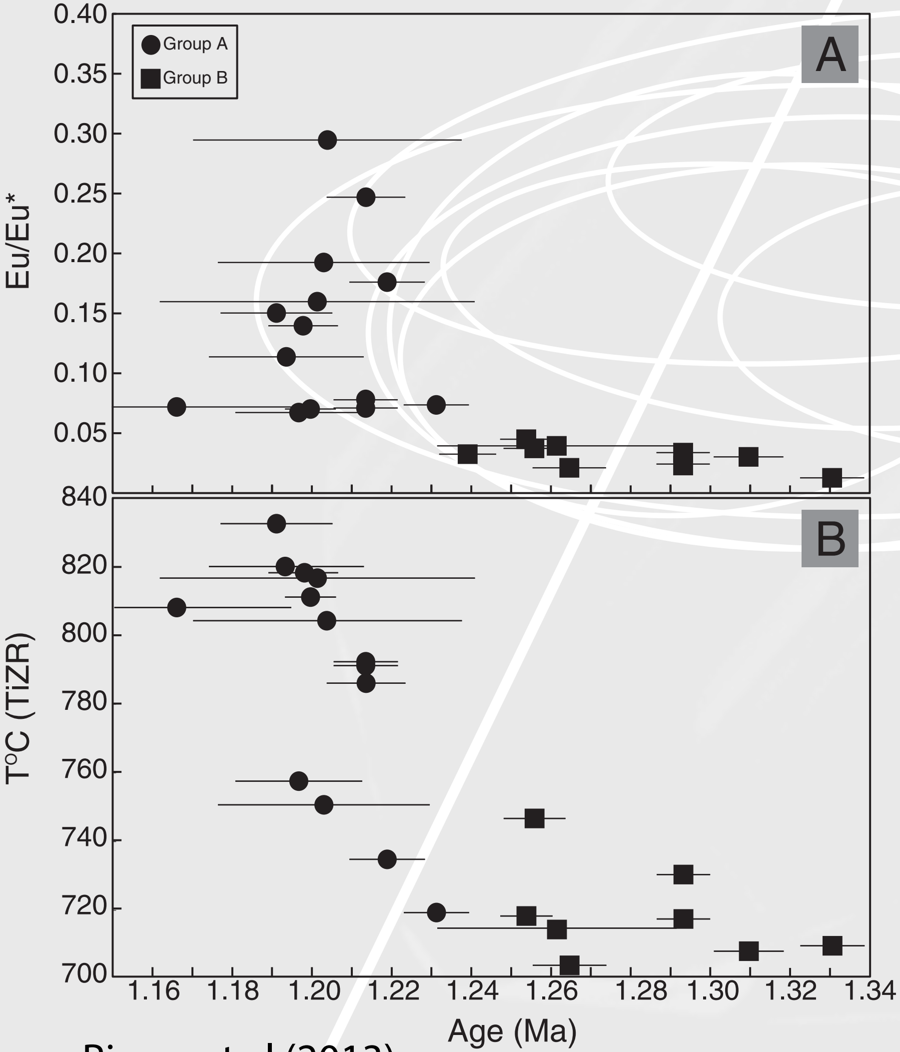




Integration of ID-TIMS with mineral chemistry helps generate petrologic models

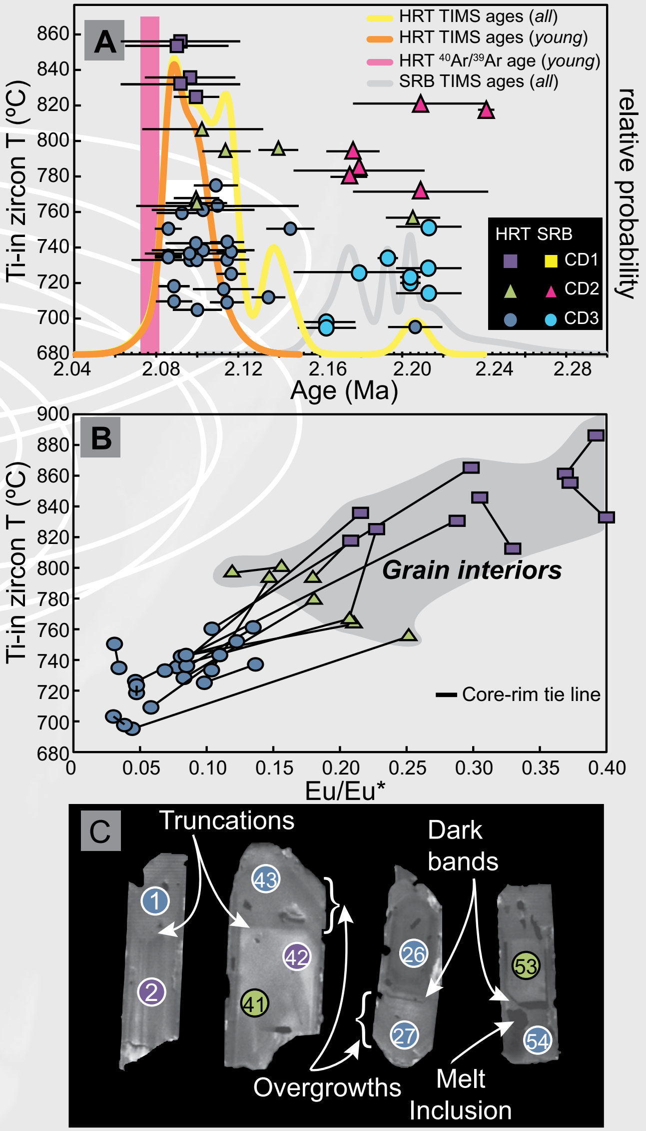
First do laser ablation for zircon geochemistry, then do ID-TIMS U-Pb geochron

Alder Creek Rhyolite



Rivera et al (2013)

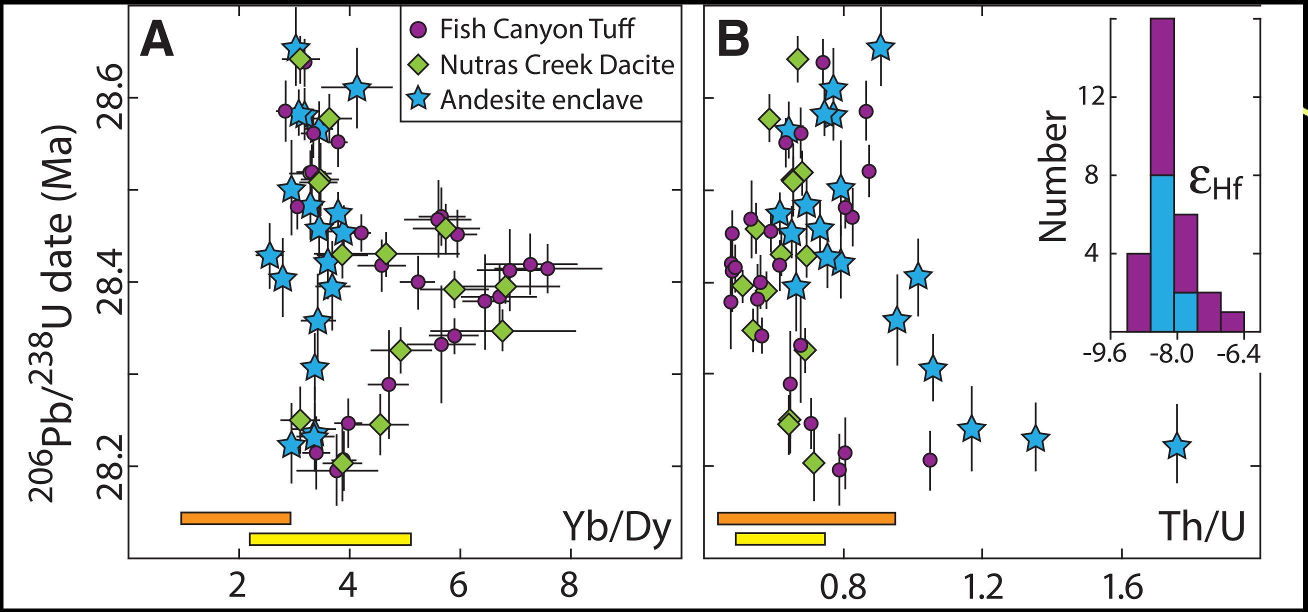
Huckleberry Ridge Tuff



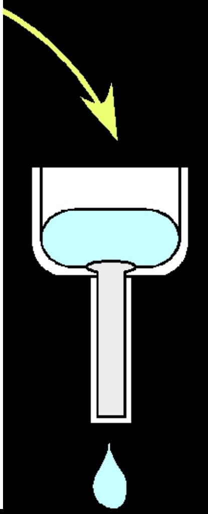
Rivera et al (2014)

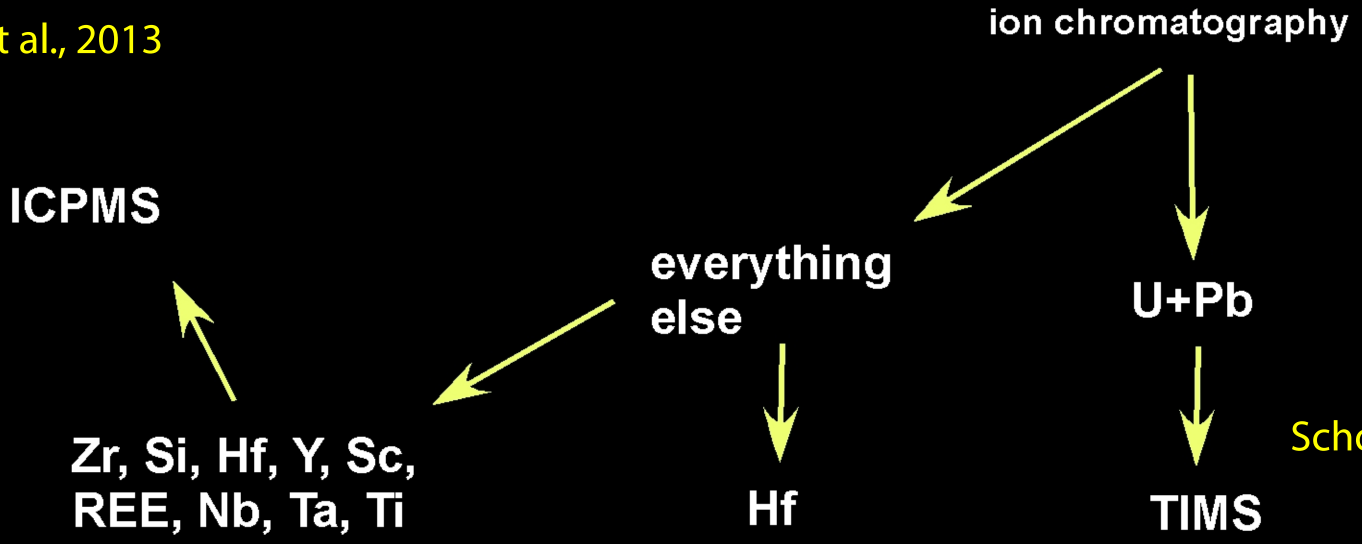
Integration of ID-TIMS with mineral chemistry helps generate petrologic models

U-Pb TIMS-TEA (trace element analysis)



Wotzlaw et al., 2013





ion chromatography

everything else

U+Pb

ICPMS

Zr, Si, Hf, Y, Sc, REE, Nb, Ta, Ti

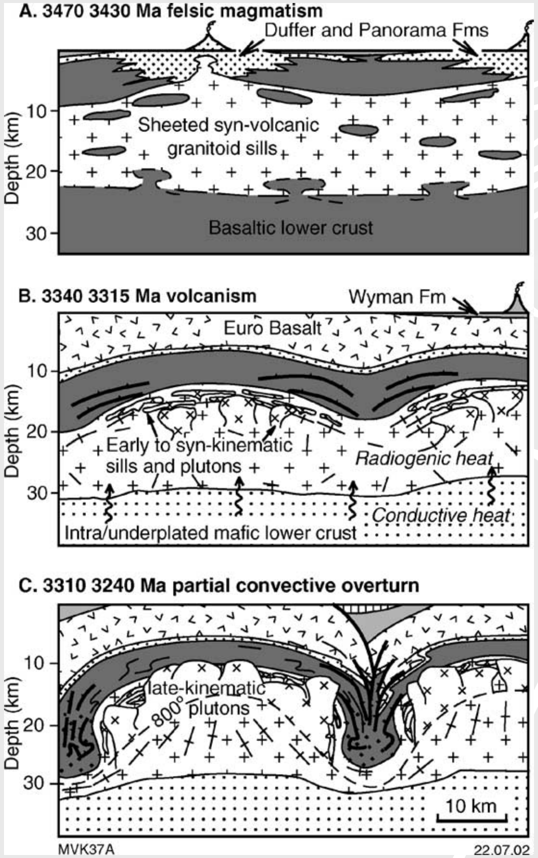
Hf

TIMS

Schoene et al., 2010

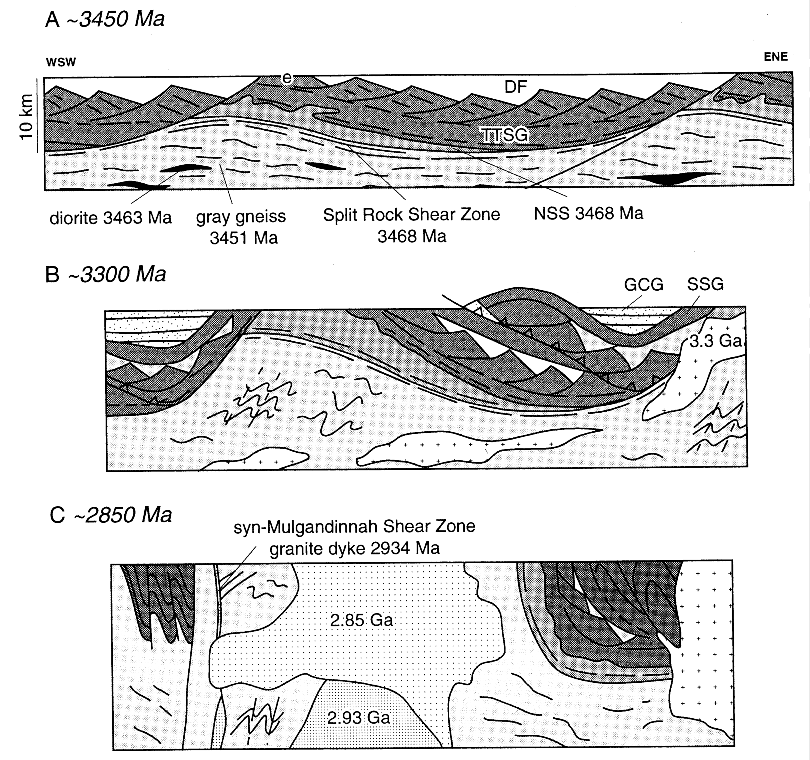
Application 3: calibrating the Archean

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



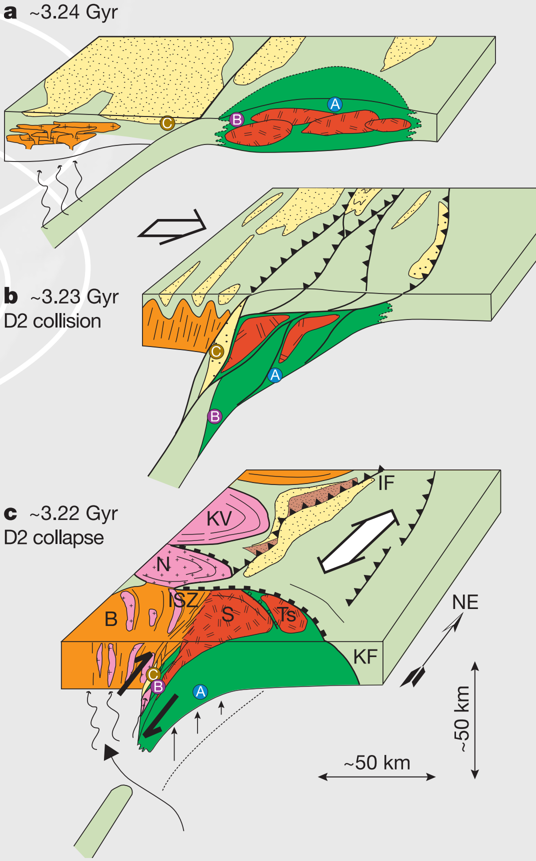
"vertical" tectonics in the Pilbara craton

Van Kranendonk et al., 2004



Core-complex/extensional Tectonics in the Pilbara craton

Zegers et al., 1999

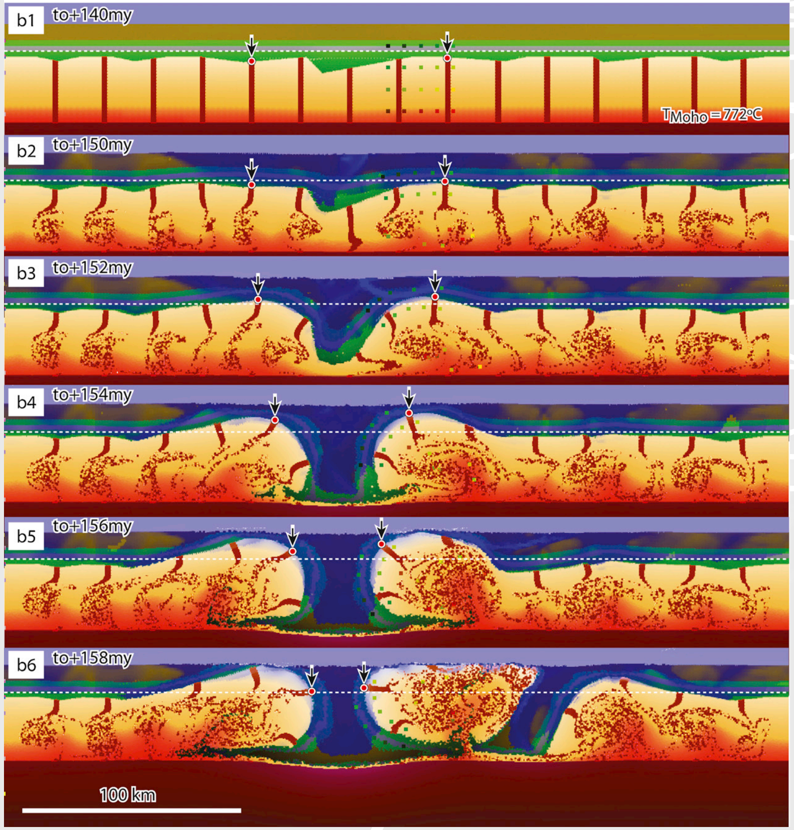


Subduction/accretion in the Kaapvaal craton

Moyen et al., 2006

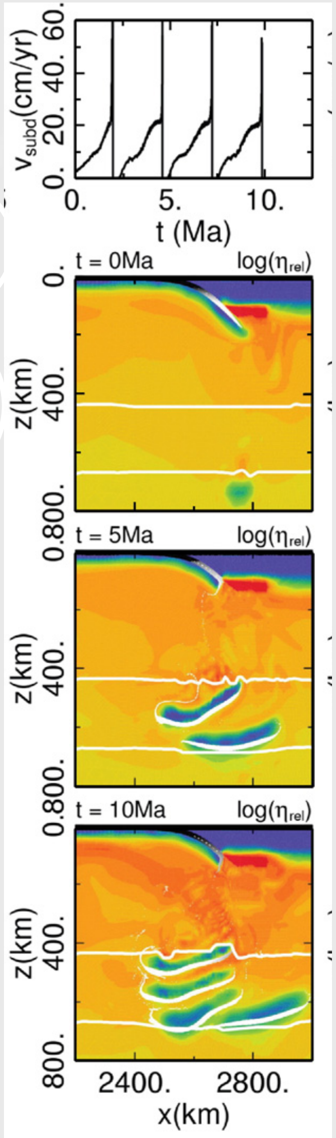
Numerical modeling can make predictions for tectonics if one makes it hotter…

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

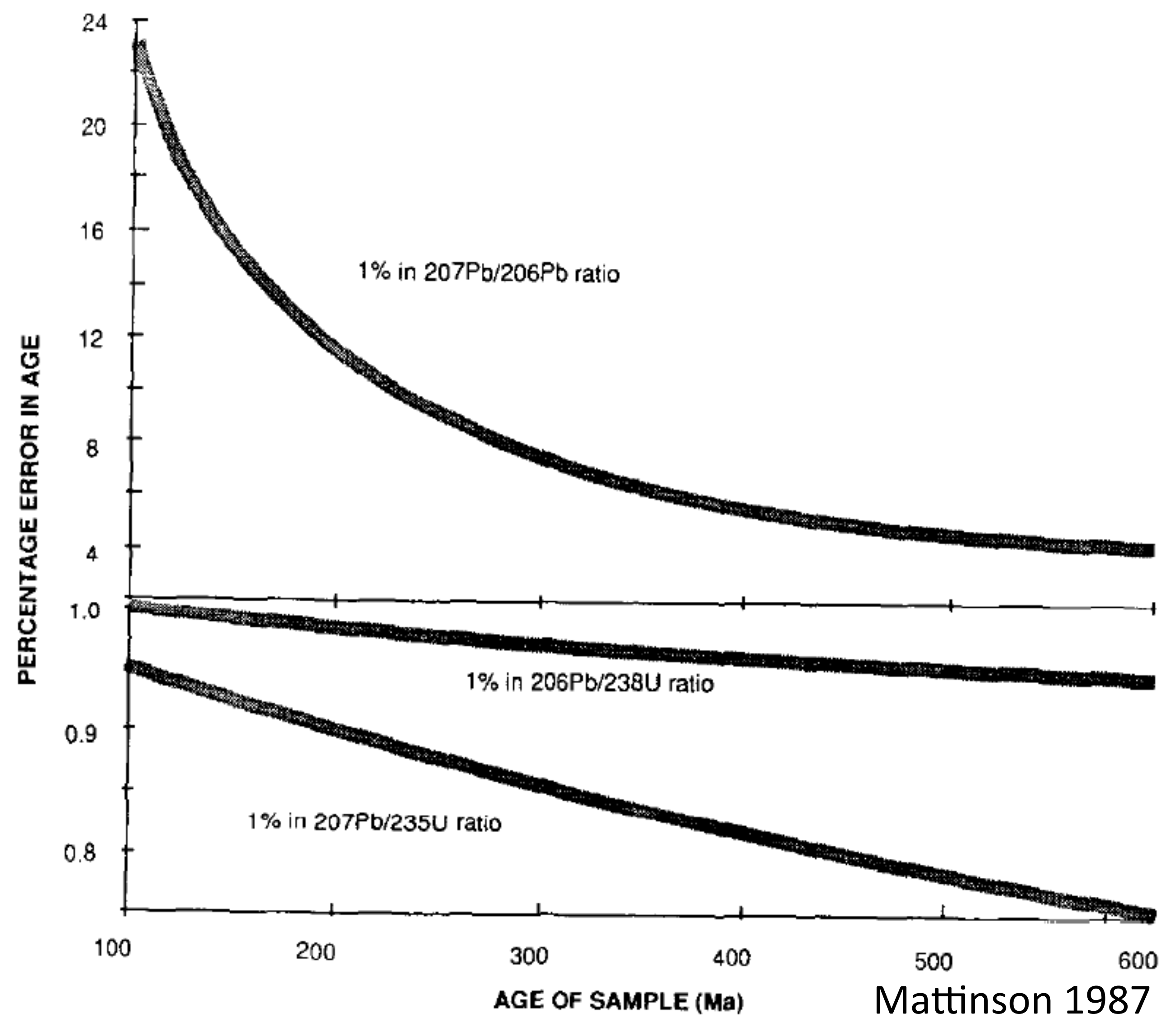
Thebaud and Rey, 2013



Subduction/accretion

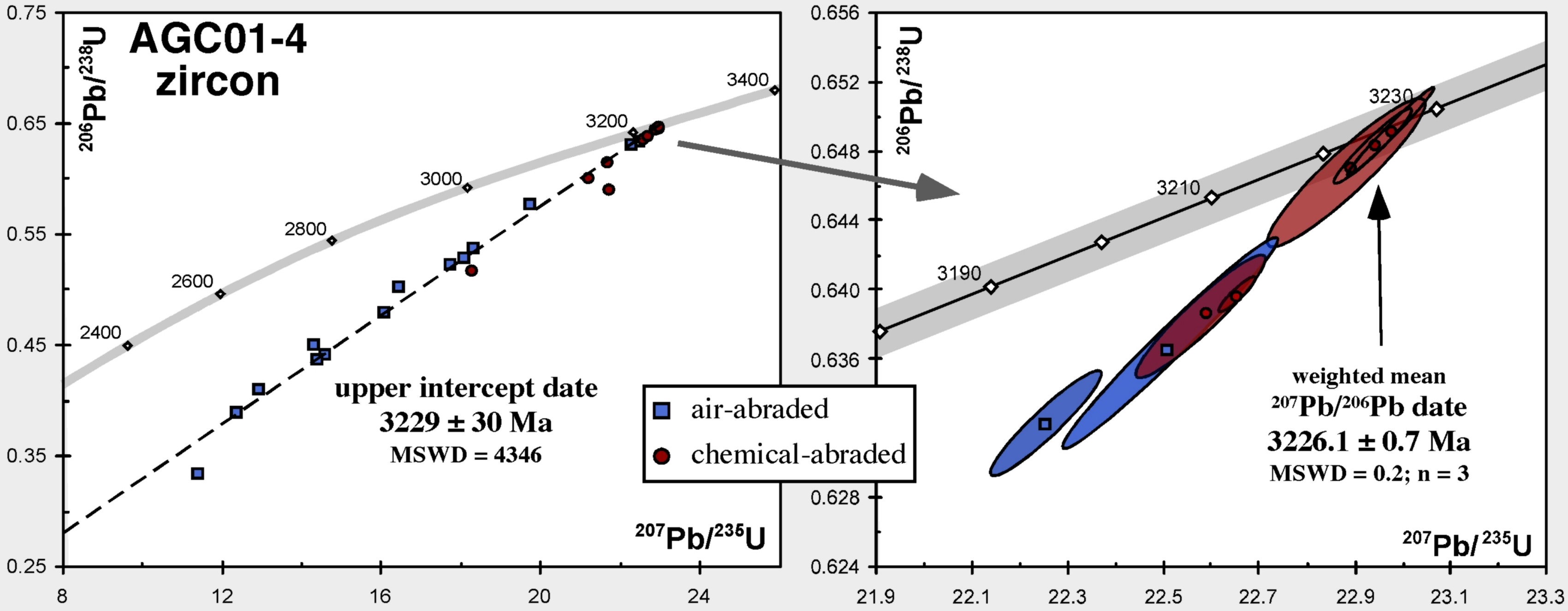
Van Hunen and Van der Berg., 2008

Reducing age uncertainties – using the $^{207}Pb/^{206}Pb$ chronometer



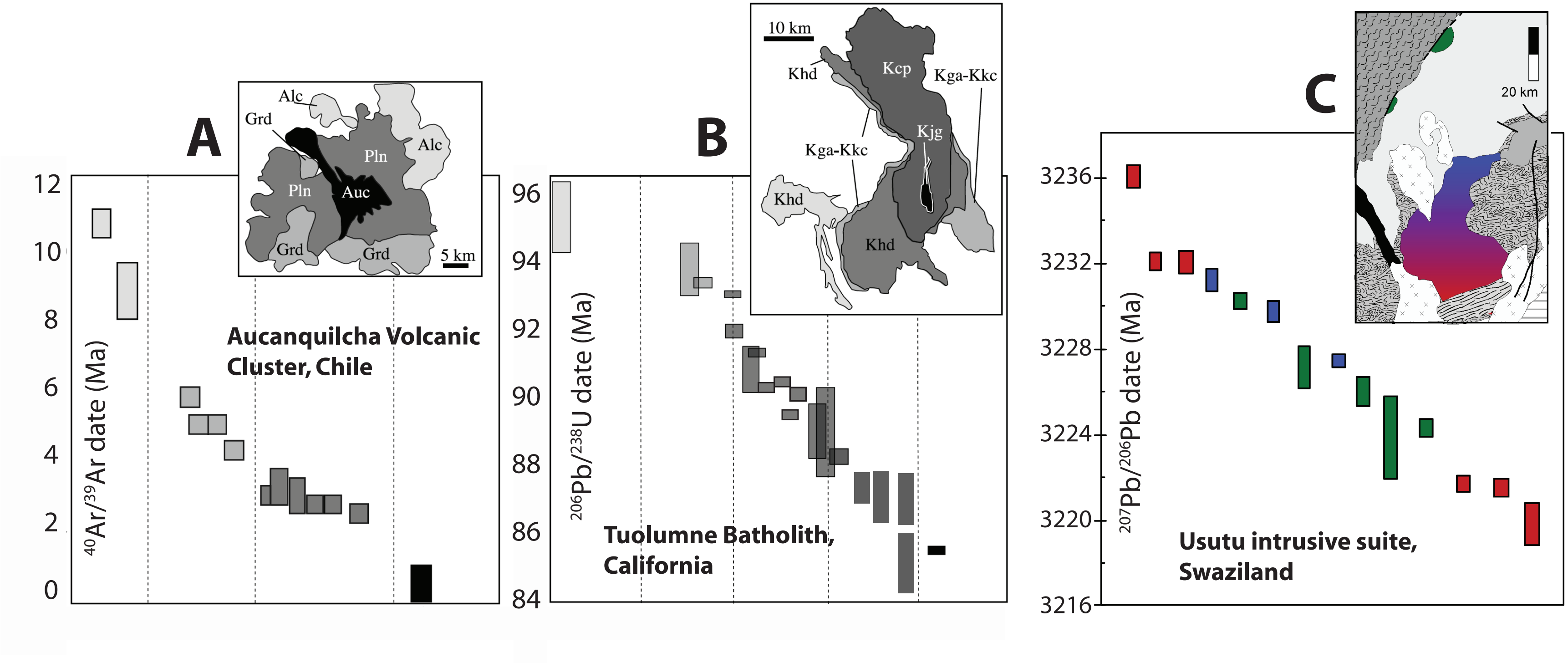
Mattinson 1987

Reducing age uncertainties – using the $^{207}Pb/^{206}Pb$ chronometer



Using the $^{207}Pb/^{206}Pb$ 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:

Bowring, S. A., and Schmitz, M. D., 2003, High-precision U-Pb zircon geochronology and the stratigraphic record, *in* Hanchar, J. M., and Hoskin, P. W. O., eds., Zircon, Volume 53: Washington, D.C., Mineralogical Society of America, p. 305-326.

Bowring, S. A., Schoene, B., Crowley, J. L., Ramezani, J., and Condon, D. C., 2006, High- precision U-Pb zircon geochronology and the stratigraphic record: progress and promise, *in* Olszewski, T., ed., Geochronology: Emerging Opportunities, Paleontological Society Short Course, Volume 12: Philidelphia, PA, The Paleontological Society p. 25-45.

Parrish, R. R., and Noble, S. R., 2003, Zircon U-Th-Pb geochronology by isotope dilution – thermal ionization mass spectrometry (ID-TIMS), *in* Hanchar, J. M., and Hoskin, P. W. O., eds., Zircon, Volume 53: Washington, D.C., Mineralogical Society of America, p. 183-213.

Schoene, B., 2014, U-Th-Pb geochronology, *in* Rudnick, R., ed., Treatise on Geochemistry, Volume 4.10: Oxford, U.K., Elsevier, p. 341-378.

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