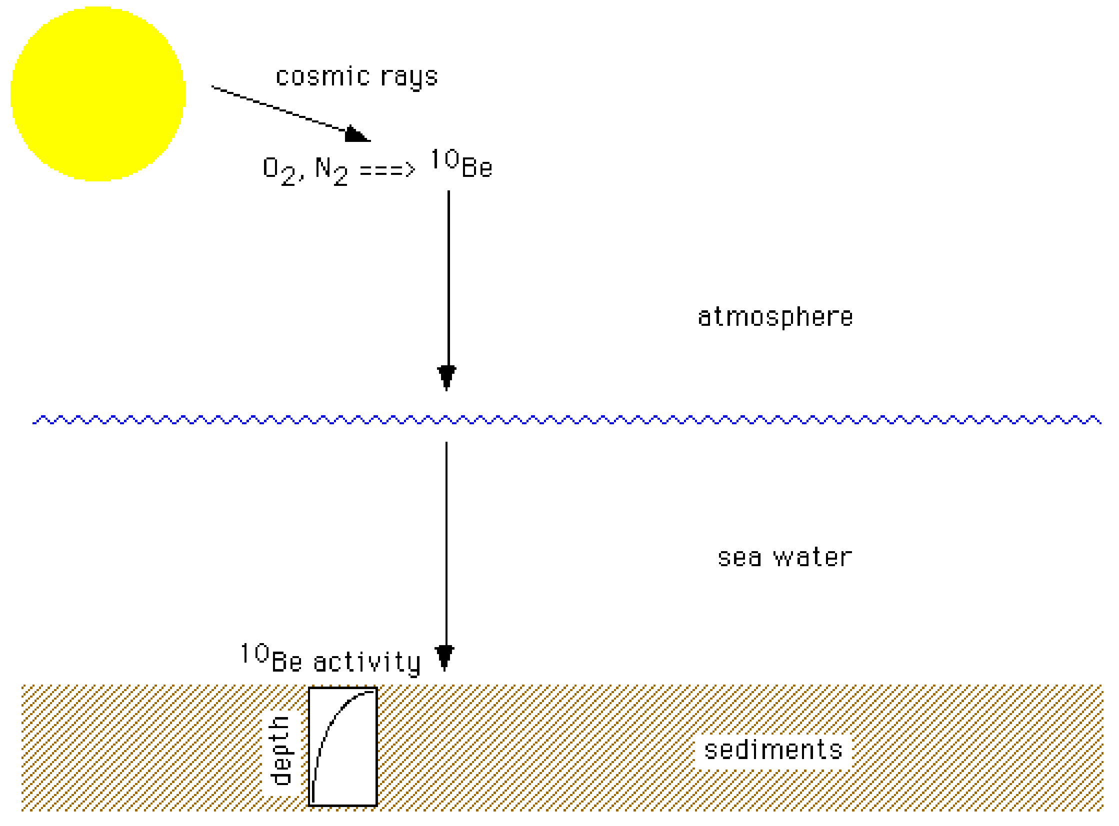
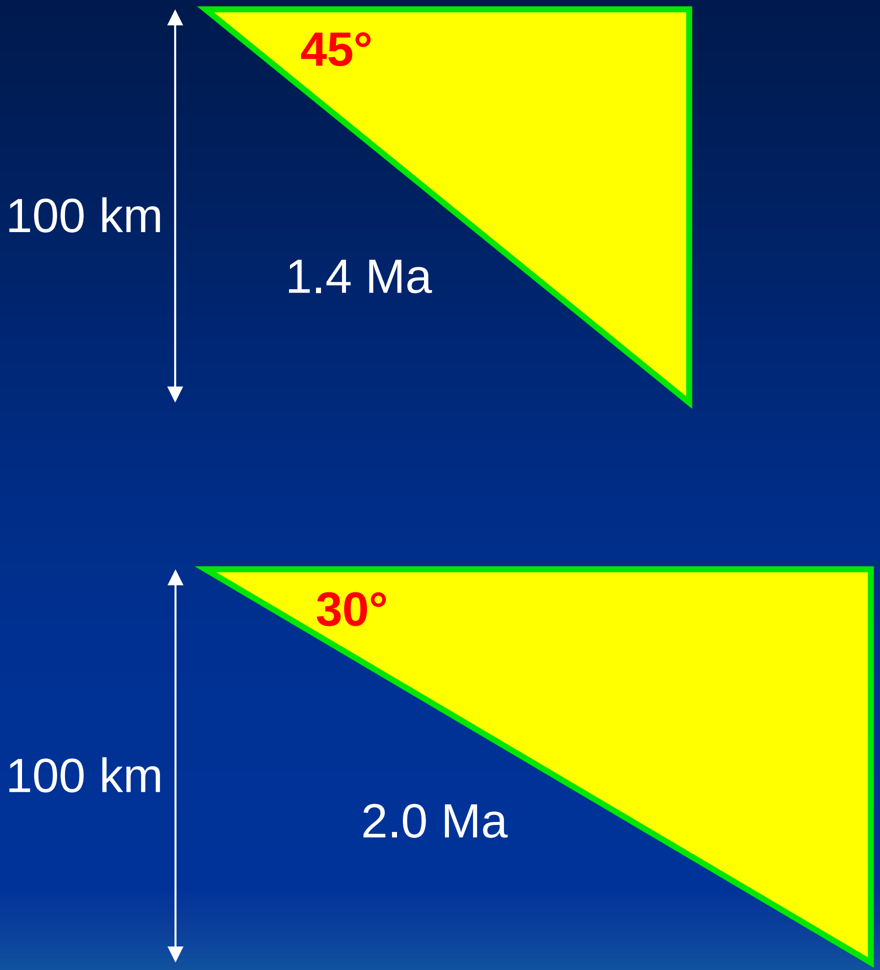
^{10}Be

^{10}Be is produced by reactions of cosmic ray protons with N_2 and O_2 in the upper atmosphere

Be is a particle reactive element → becomes concentrated in clay-rich oceanic sediments

^{10}Be then undergoes decay to ^{10}B with a half-life of about 1.5 Ma (long enough to be subducted, but quickly lost to mantle systems).

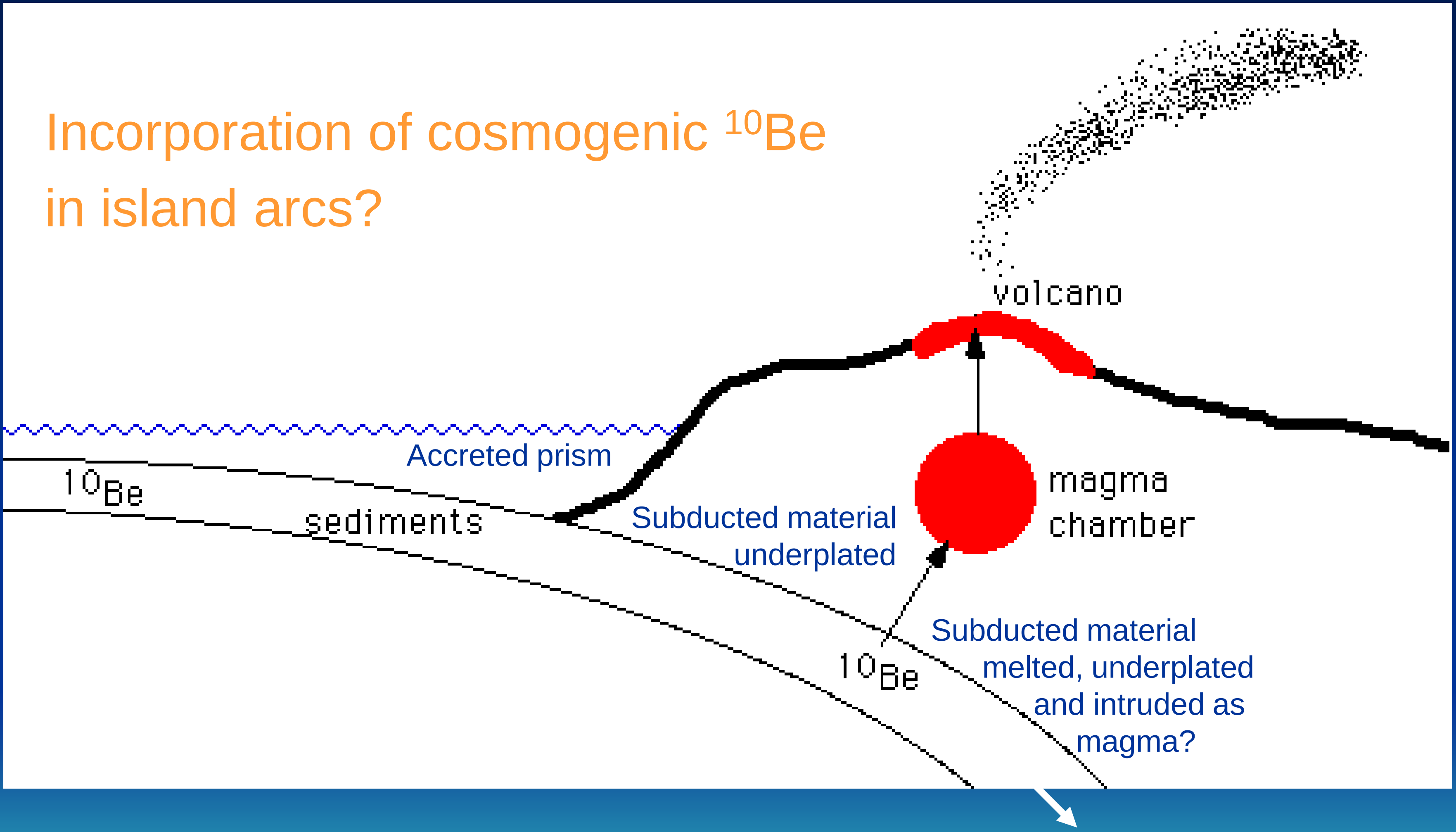




Time to burial to 100 km

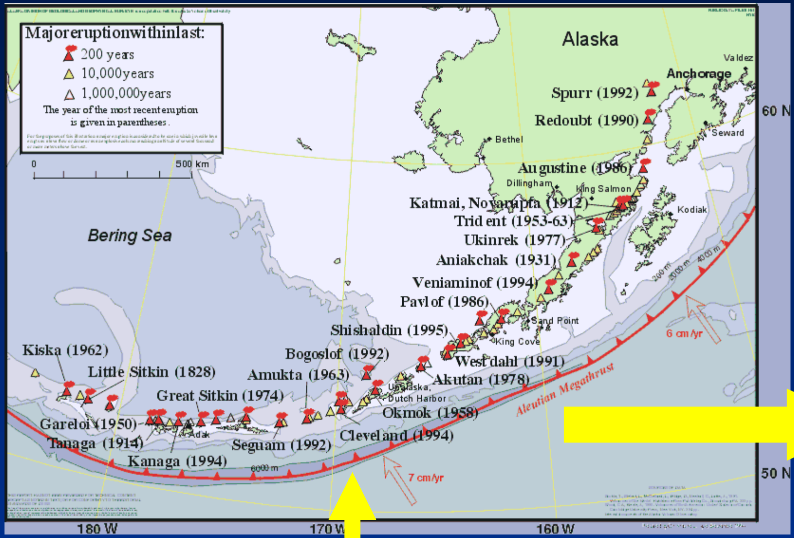
Subduction Velocity:
10 cm/a

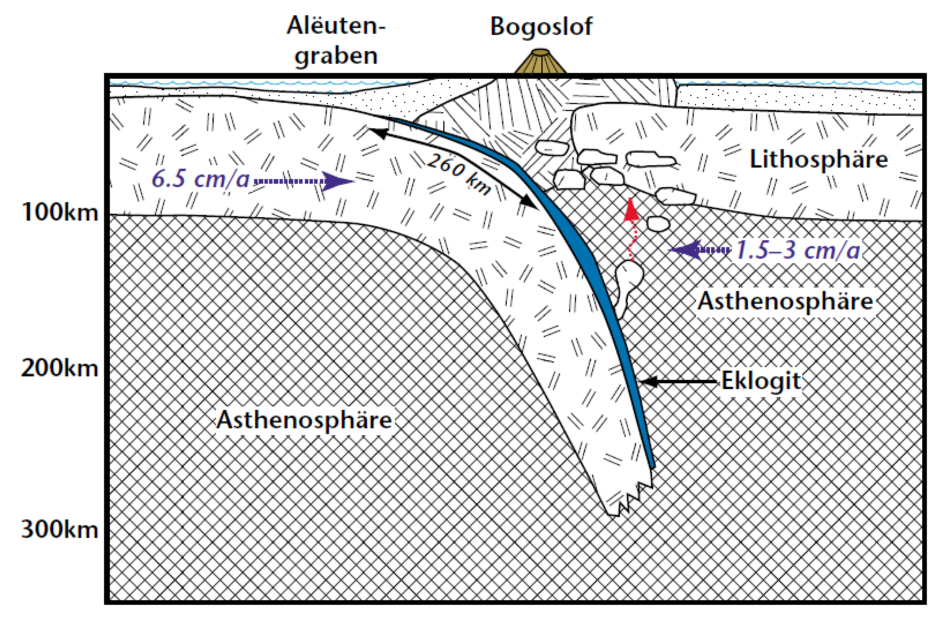
^{10}Be


Incorporation of cosmogenic ^{10}Be in island arcs?

Material returned to mantle

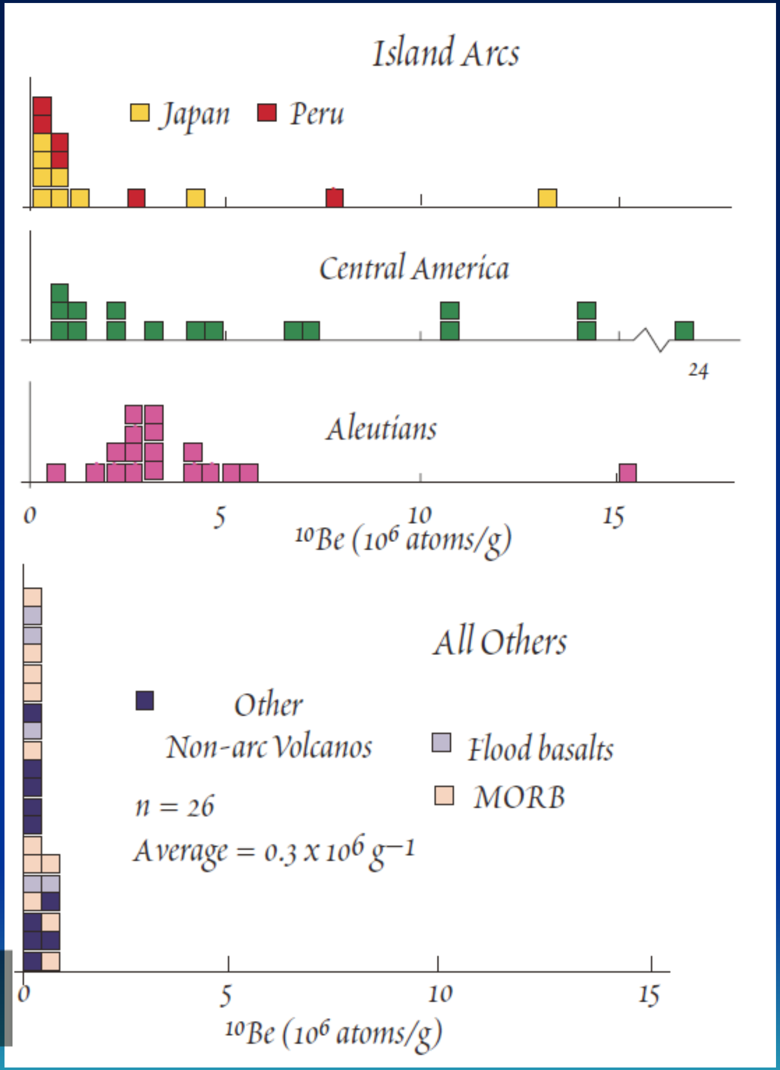
^{10}Be in arc lavas





^{10}Be in arc lavas

Smoking gun evidence for sediment subduction



… but no ^{10}Be in lavas from the Lesser Antilles

Brown et al. (1982) Nature 299
Tera et al. (1986) GCA 50

Direct evidence for subduction

- ^{10}Be has been found in lava flows from island arcs e.g. Aleutians and central America!
- They mark sediment that was subducted, melted and returned at island arcs all within some 5 Ma.
- Many other subduction zone magmas do not have ^{10}Be (e.g., Lesser Antilles).

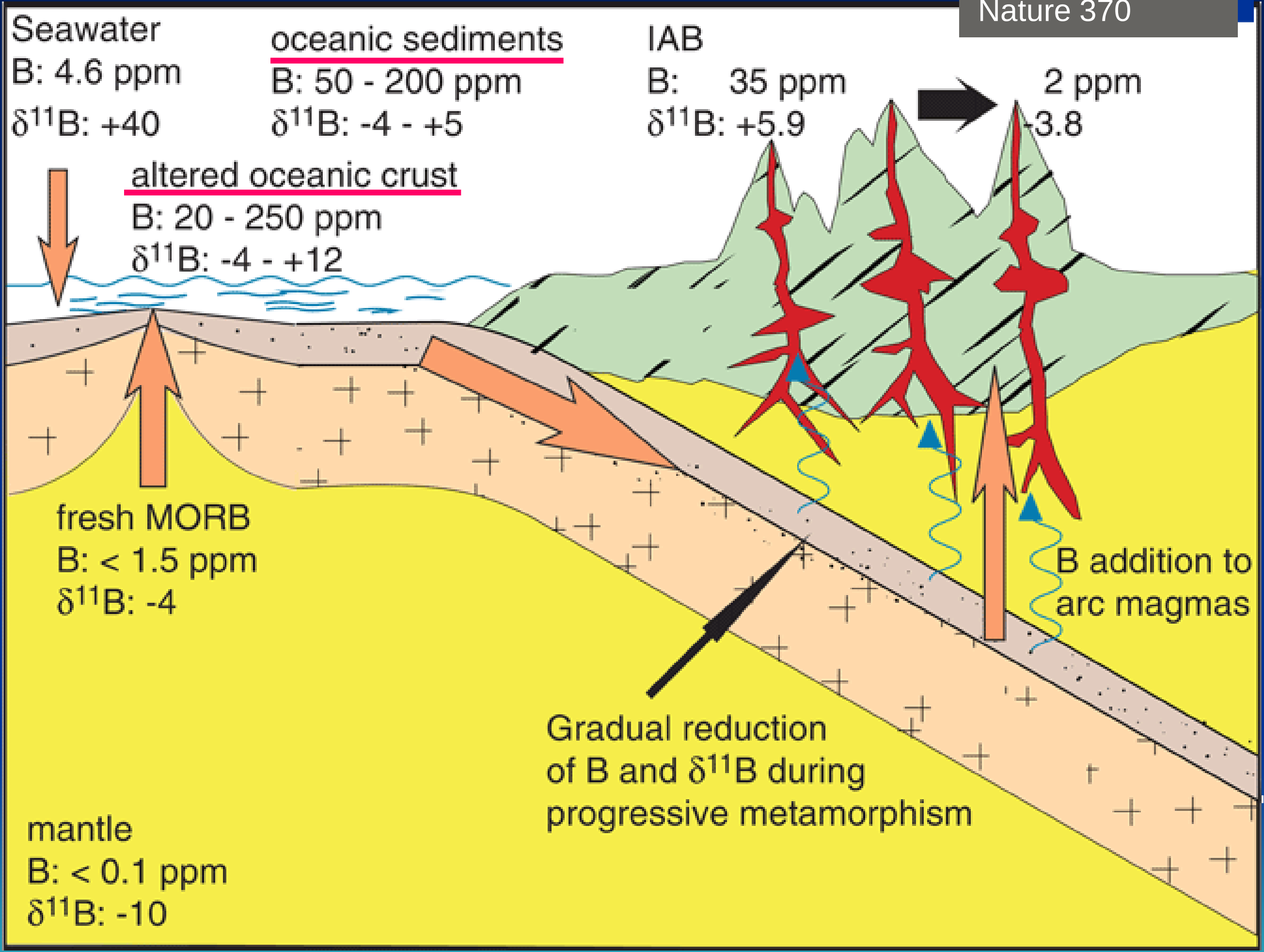
Boron signals

$\delta^{11}B = \{[(^{11}B/^{10}B)_{sample}/(^{11}B/^{10}B)_{standard}] - 1\} \times 1000$

e.g. Izu arc:
Ishikawa &
Nakamura (1993)
Nature 370

Boron isotopes help to define mechanism of mass transfer between slab and overlying mantle wedge

^{11}B partitions into liquid or vapour phase relative to minerals and silica melt.



Boron isotopes

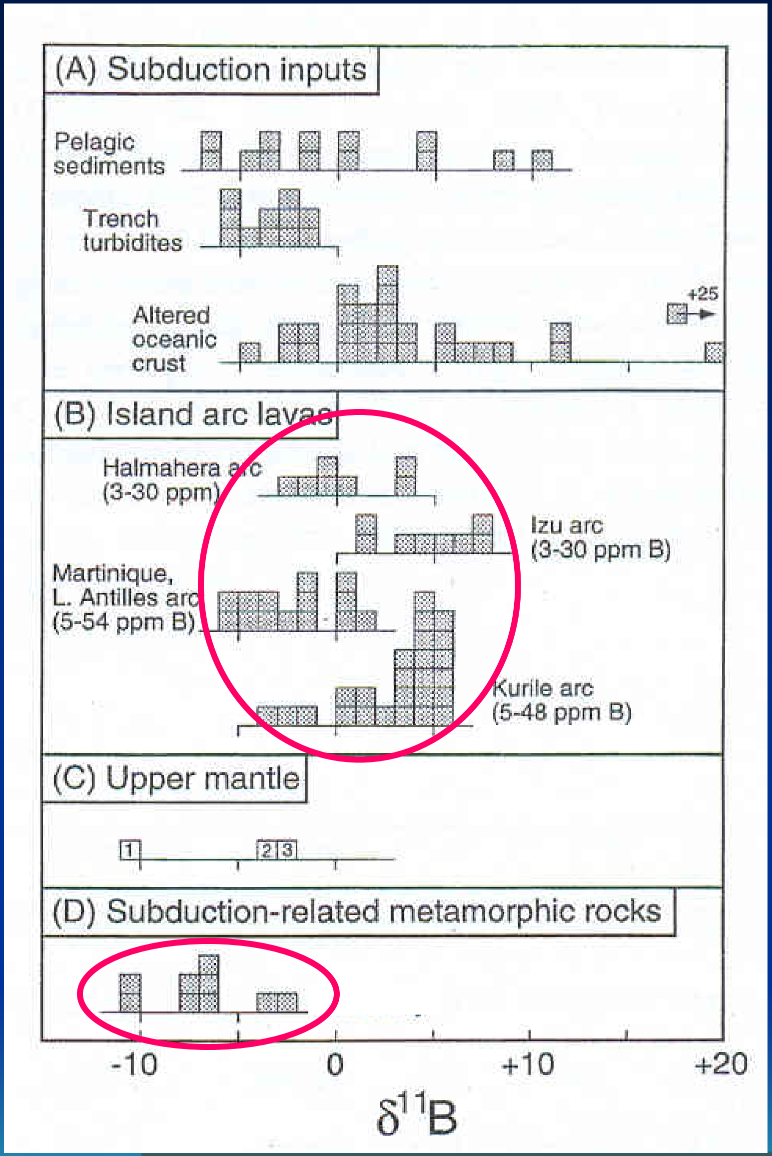
^{10}B – tetrahedrally, ^{11}B – trigonal

in aqueous fluids (>50°C) B is trigonal coordinated

Boron is transferred from the slab to the arc magma by **aqueous fluids** and not by silicate melts.

Agent of mass transfer is a fluid

Keppler (1996)
Nature 380



Peacock & Hervig (1999) Chem Geol 160

Fluxes

- How much goes down?
  - No clue
  - Estimates are between 0.1-0.8 km^3/yr
- How much comes up in arcs?

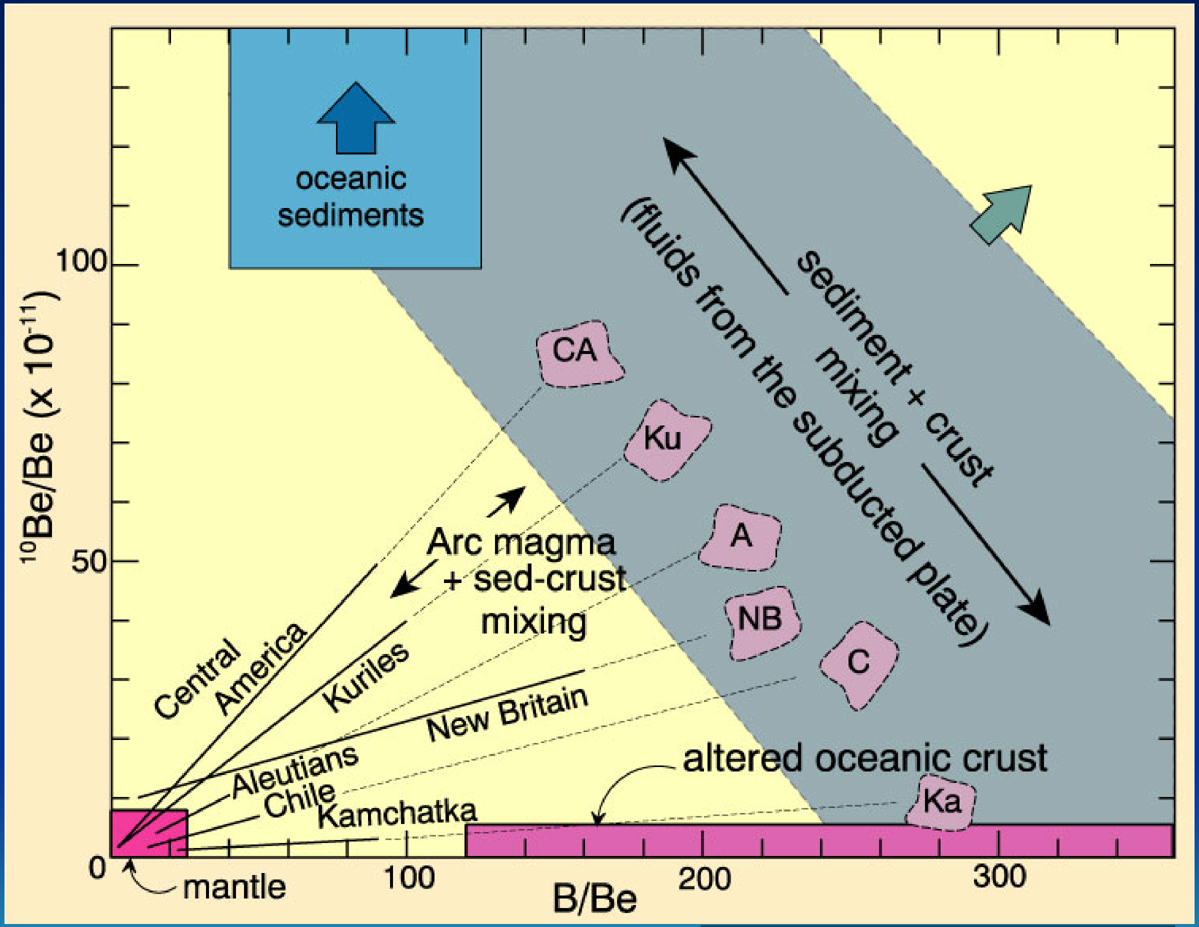
Boron & Beryllium

$^{10}\text{Be/Be}_{\text{total}}$ vs. B/Be for six arcs

Each arc forms a linear array, each has a unique slope

Homogenization process needed to explain the correlation for different arcs

→ Repeated precipitation and dehydration reactions in the hydrated mantle

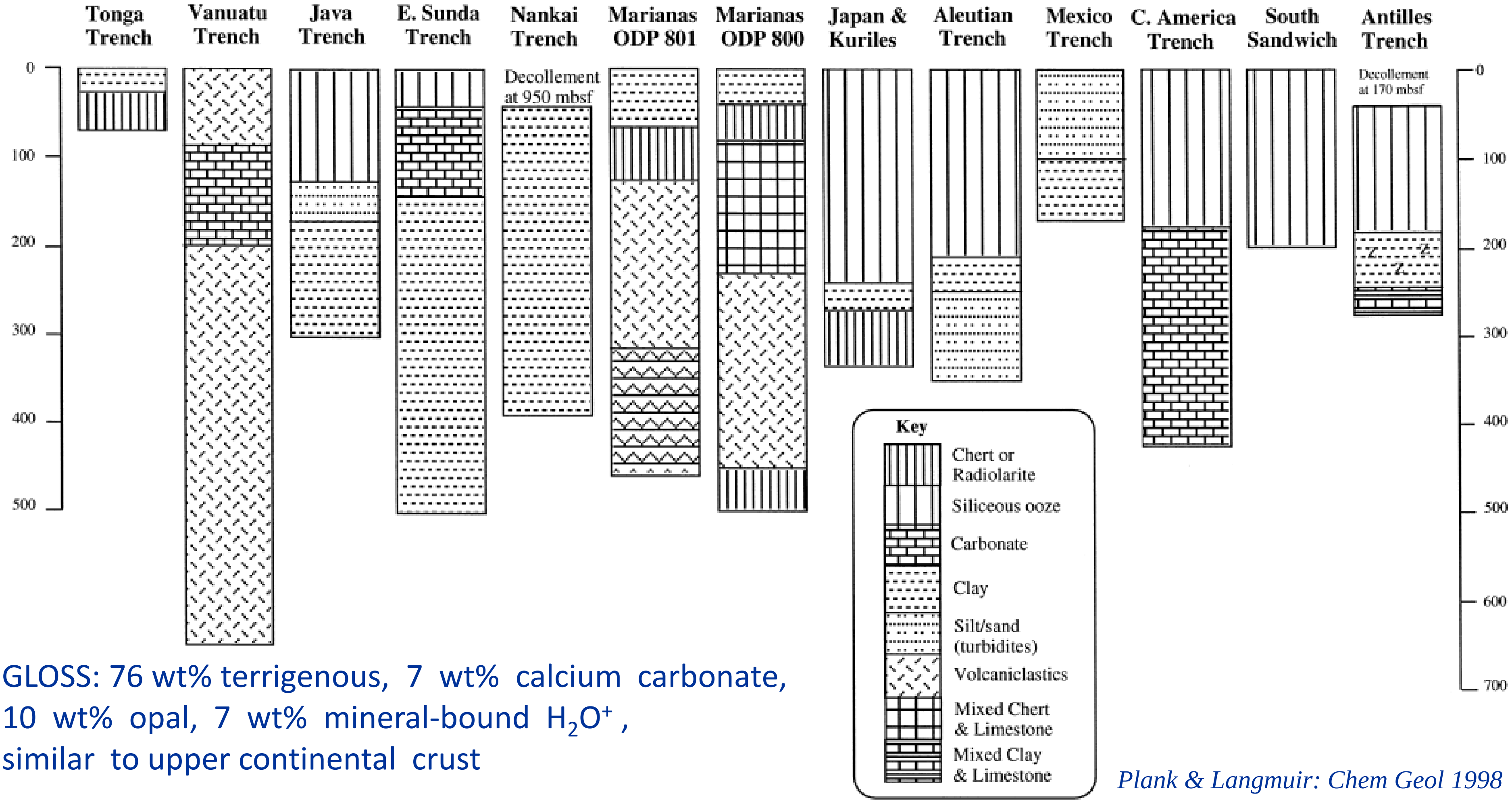


Morris et al. (1990) Nature 344

Who much sediment is recycled to the arc and how much goes down?

Mass balance calculations of inputs and outputs will provide an answer to this question

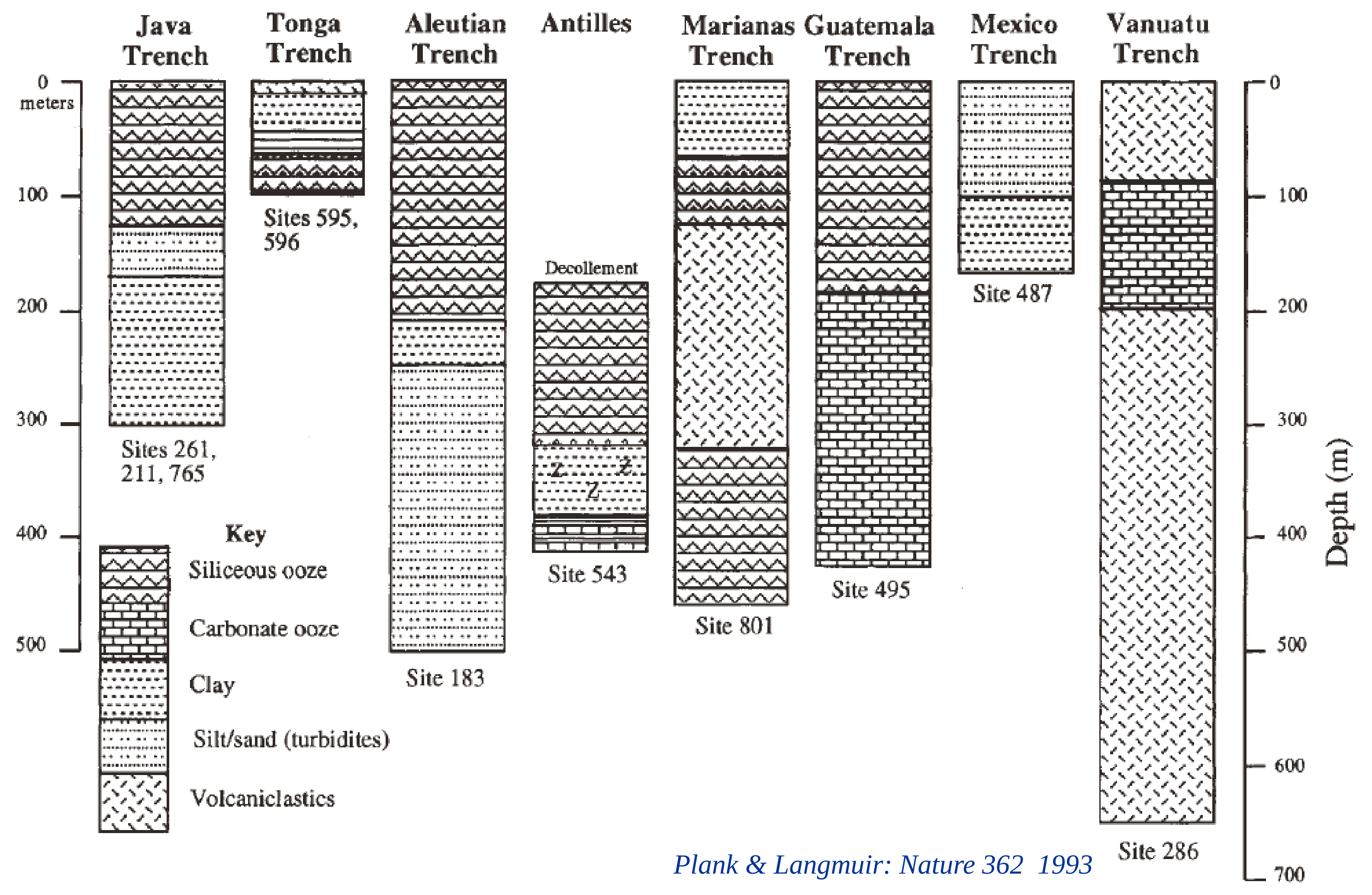
Global sediment subduction (GLOSS)



GLOSS: 76 wt% terrigenous, 7 wt% calcium carbonate, 10 wt% opal, 7 wt% mineral-bound H_2O^+, similar to upper continental crust

Plank & Langmuir: Chem Geol 1998

Global sediment subduction (GLOSS)



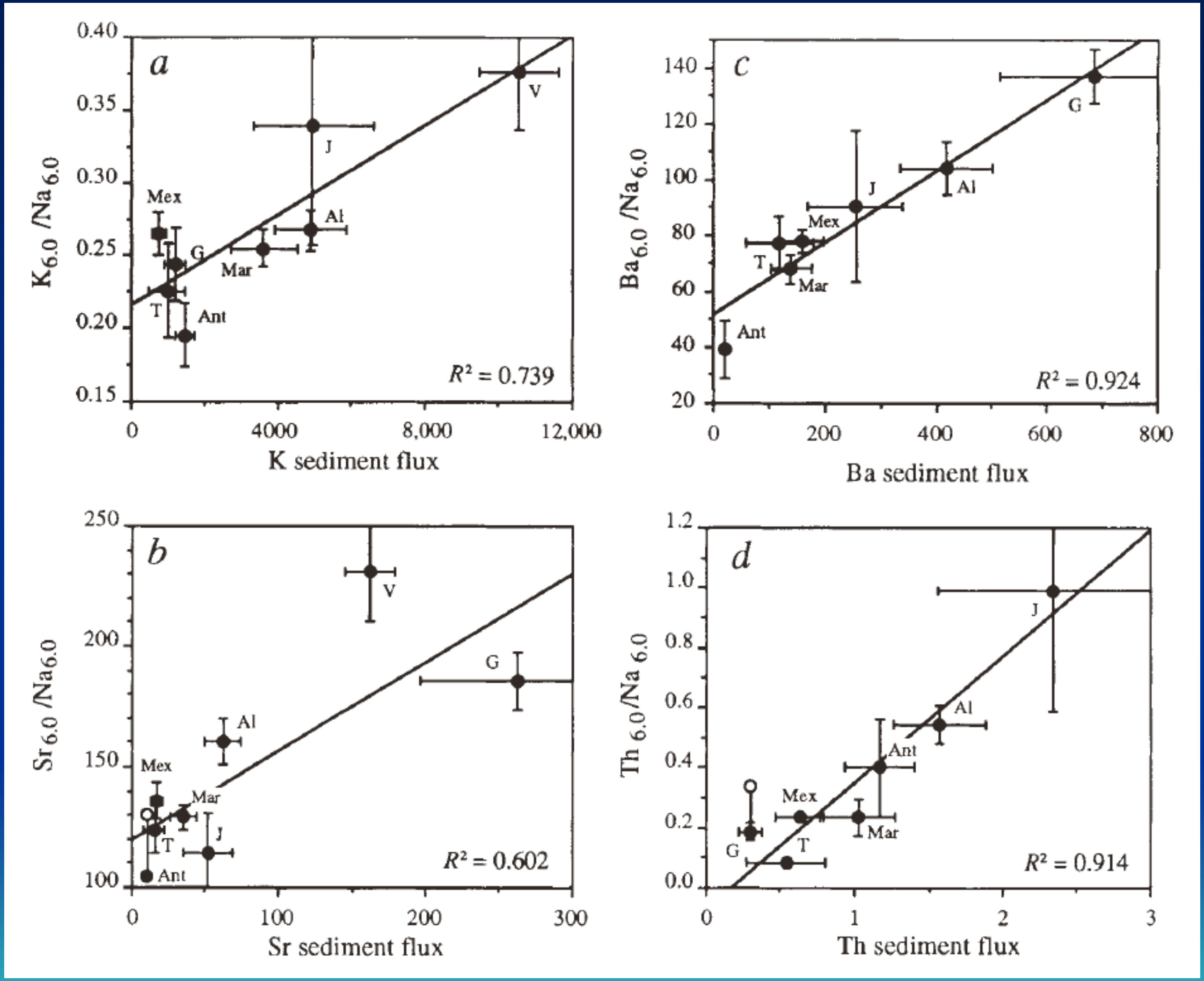
Plank & Langmuir: Nature 362 1993

Global sediment flux into trenches and enrichment in arc basalts

P & L considered only the most primitive arc basalts (> 5 wt.% MgO)

Avg. composition for each volcano was calculated at a reference value of 6 wt.% MgO

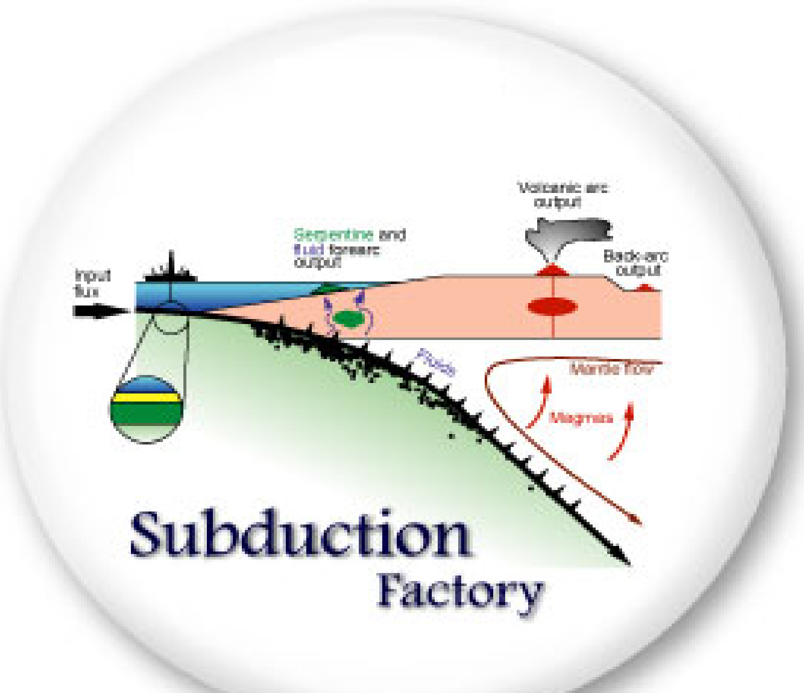
e.g., $Ba_{6.0}$ = avg. Ba concentration at 6% MgO

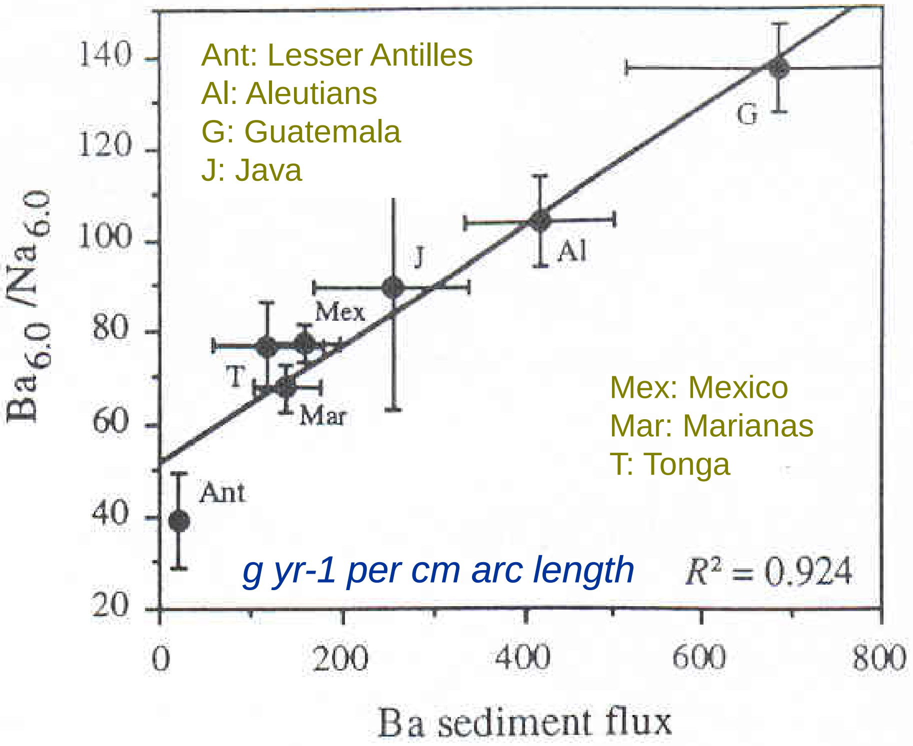


Plank & Langmuir: Nature 362 1993

Mass balancing the inputs and outputs

“What goes down must come up”





Ant: Lesser Antilles
Al: Aleutians
G: Guatemala
J: Java

Mex: Mexico
Mar: Marianas
T: Tonga

g yr-1 per cm arc length

Ba6.0 = avg. Ba concentration at 6% MgO, normalized to Na6.0 which varies inversely with the extend of melting

“…some keeps going down”

Plank & Langmuir (1993) Nature 362
Plank & Langmuir (1998) Chem Geol 145

Such mass balance calculations show that **~20%** of element budget in subducted sediments is recycled to the arc volcanics

Are trace elements signature of the continental crust

e.g. Ce/Pb, Nb/U , Th/La

created at arcs or inherited?

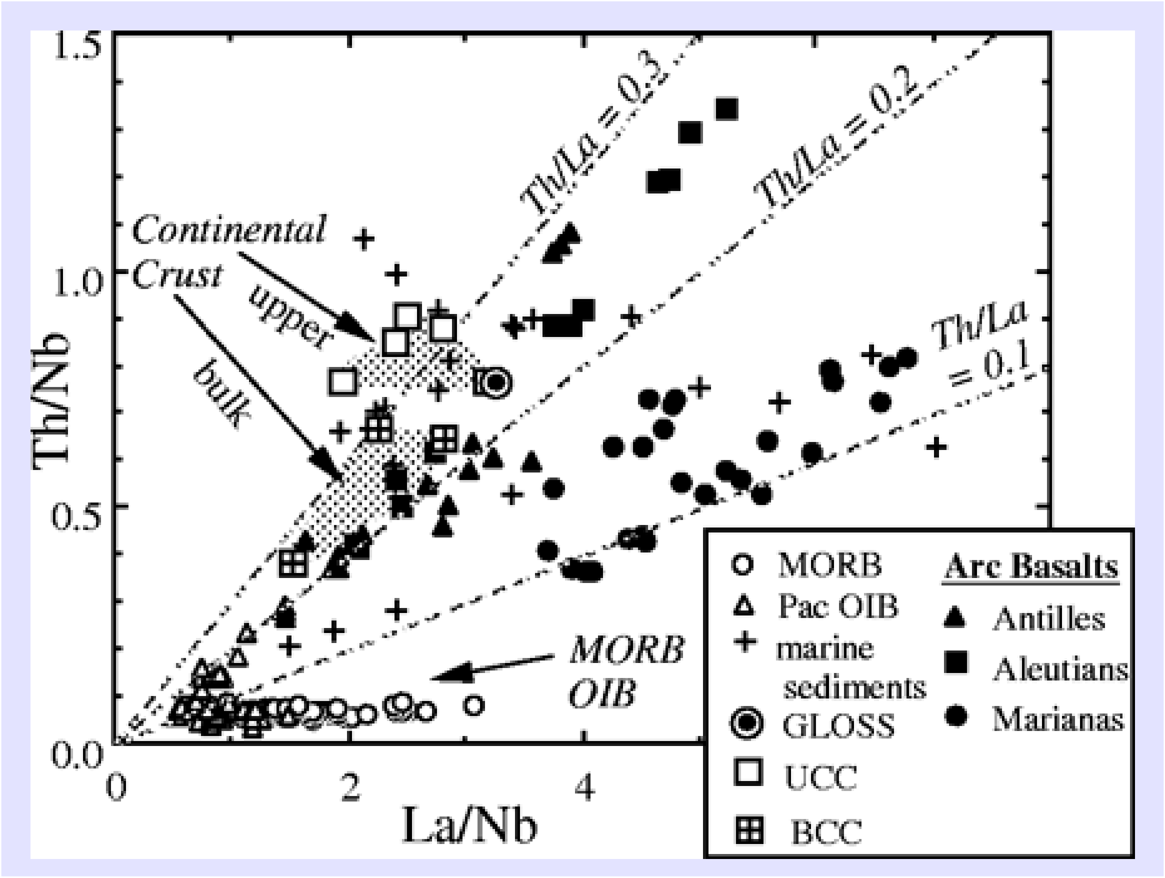
Geochemical signatutes of arc magmas:

Arc magmas and the continental crust share many chemical features

are these newly created by subduction or recycled from subducting sediment?

incompatibility during mantle melting:
Th > Nb > La

GLOSS = global subducting sediment
UCC = upper cont. crust
BCC = bulk cont. crust

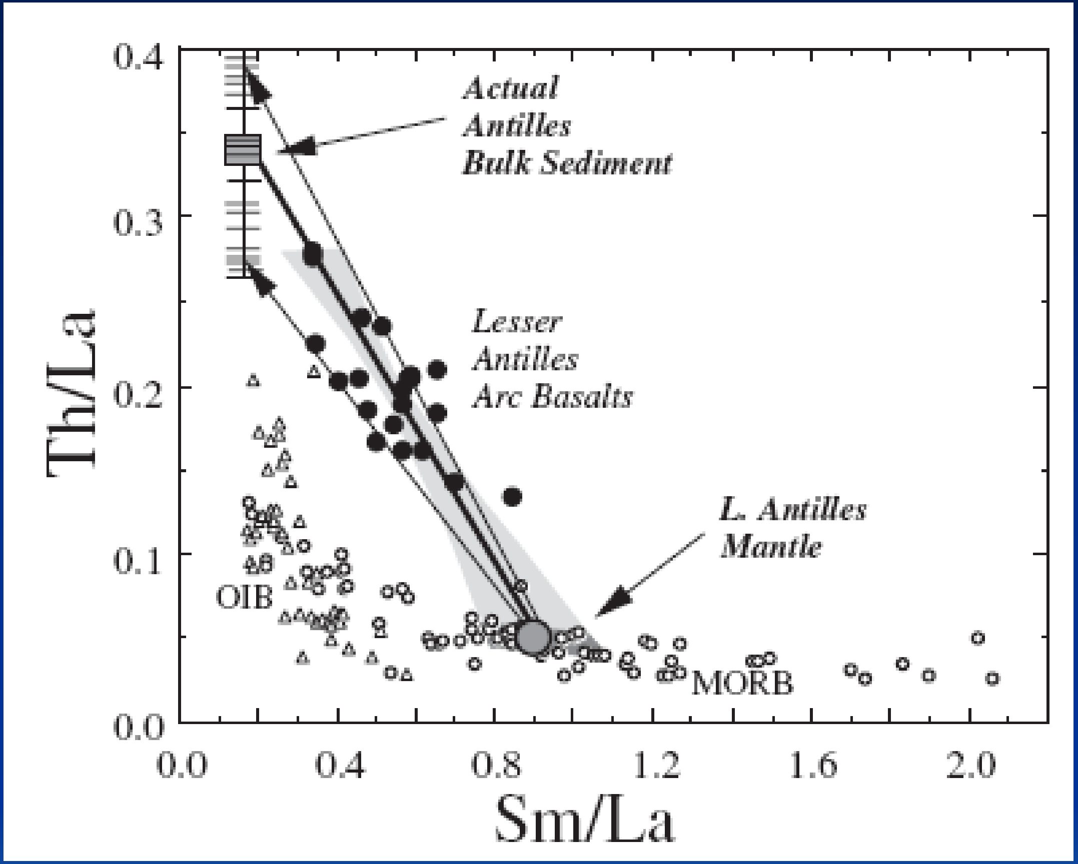


T.Plank (2005)
J Petrol 46: 921-44

Geochemical signatutes of arc magmas:

Sedimentary end-member corresponds to the same as local trench sediment

Mantle end-member varies for different arcs between depleted and enriched

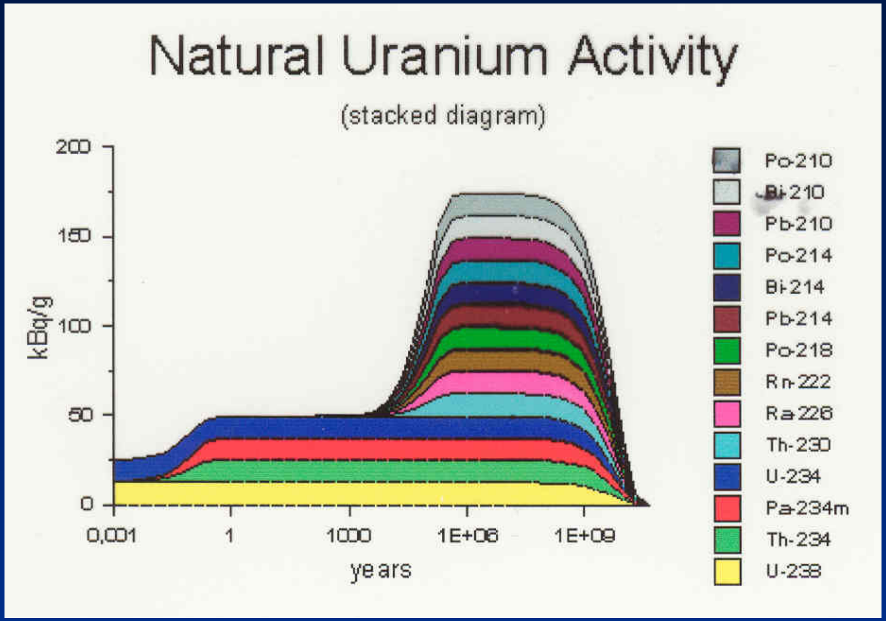


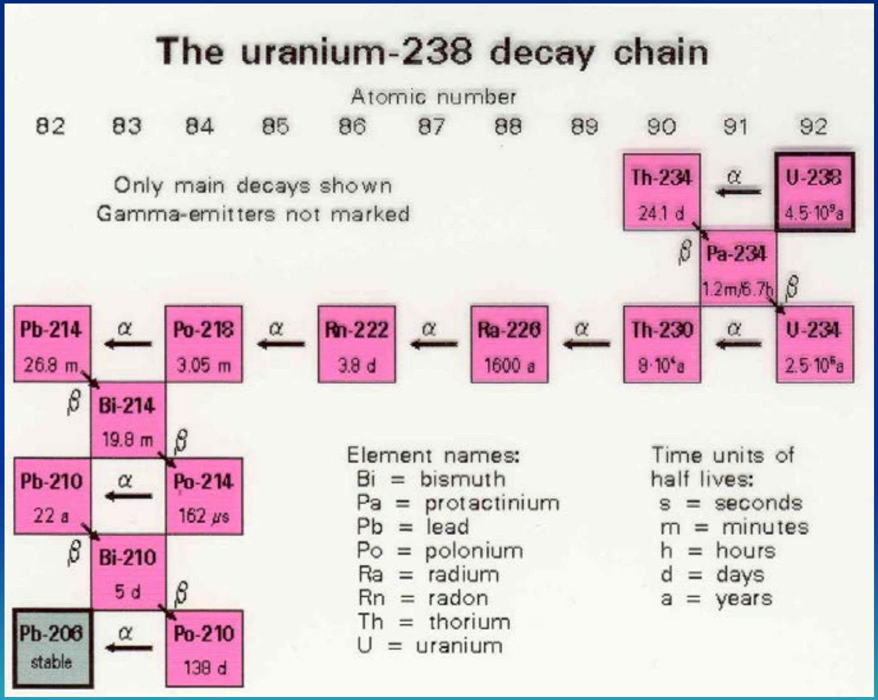
T.Plank (2005)
J Petrol 46: 921-44

Crust has lost 25-60% of its (low Th/La) mafic residues to founderinig

Intracrustal differentiation (partial melting, crystal fractionation, granulite facies metamorphism) is needed to create high Th/La upper crust and low-Th/La lower crust

^{238}U-^{230}Th-disequilibrium in volcanic rocks

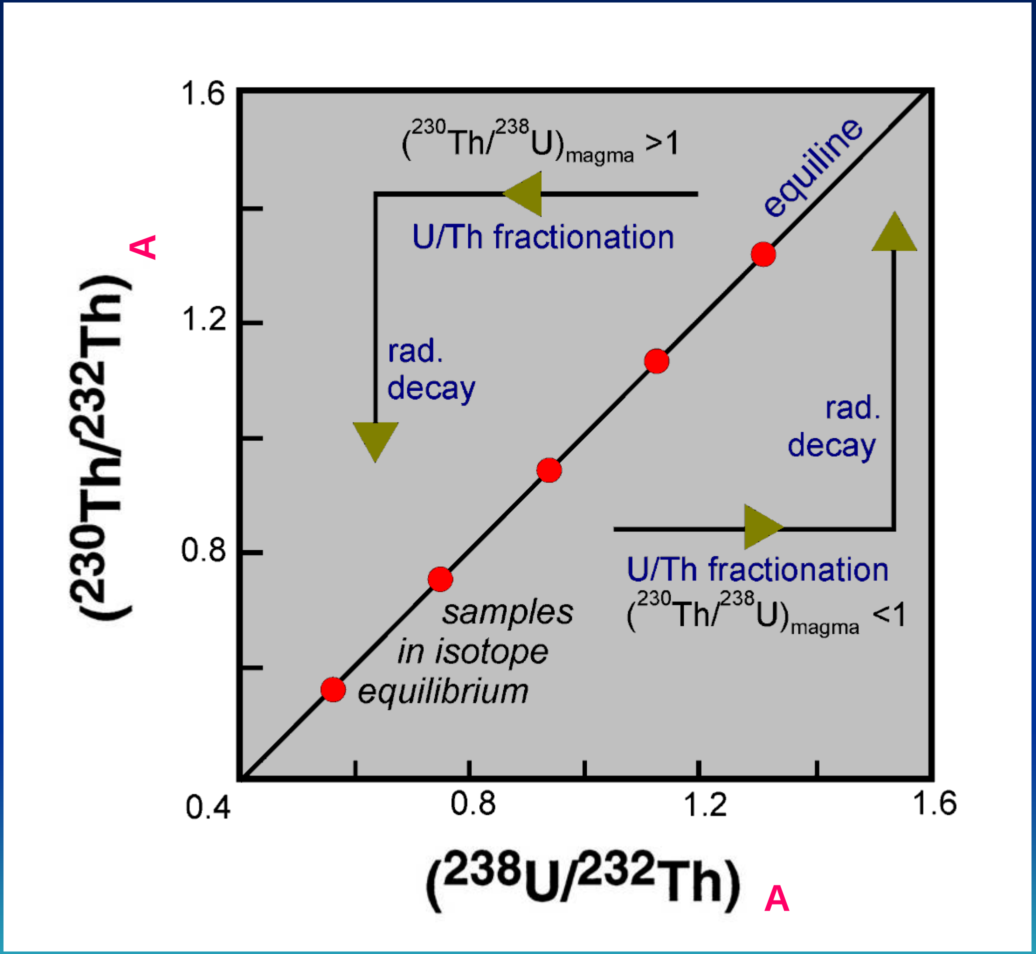




U-Th-Ra isotopes in arc magmas

$^{238}U \rightarrow {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{206}Pb$ (excluding some "shorties")

$T_{1/2}$ = 75 ka **$T_{1/2}$ = 1.6 ka**



Equilibrium:
$\lambda_1 N_1 = \lambda_2 N_2$
$A_1 = A_2$
$(^{230}Th/^{238}U) = 1$

Allègre & Condomines (1976) EPSL 28, (1982) Nature 299

Relation between activity ratio and isotope ratio

$$\text{für}\ \frac{A_{230}}{A_{238}} = 1\ gilt:$$

$$\boxed{\frac{A_{230}}{A_{238}} = \frac{\lambda_{230} \times N_1}{\lambda_{238} \times N_2}}$$

$$\lambda_1 N_1 = \lambda_2 N_2 \Rightarrow$$

$$\frac{{}^{230}Th}{{}^{238}U} = \frac{1.55125 \times 10^{-10}\, a^{-1}}{9.217 \times 10^{-6}\, a^{-1}} = 1.7 \times 10^{-5}$$

U-Th-Ra isotopes in arc magmas

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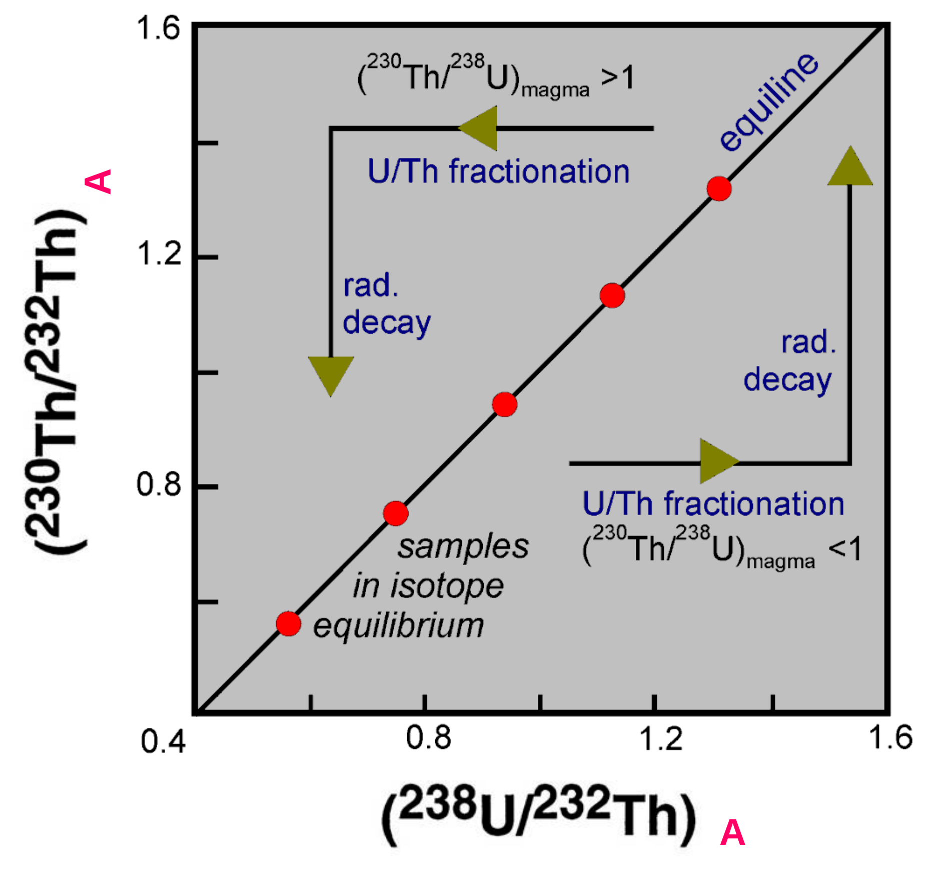

Equilibrium:

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Allègre & Condomines (1976) EPSL 28, (1982) Nature 299

U-Th isotopes in arc magmas

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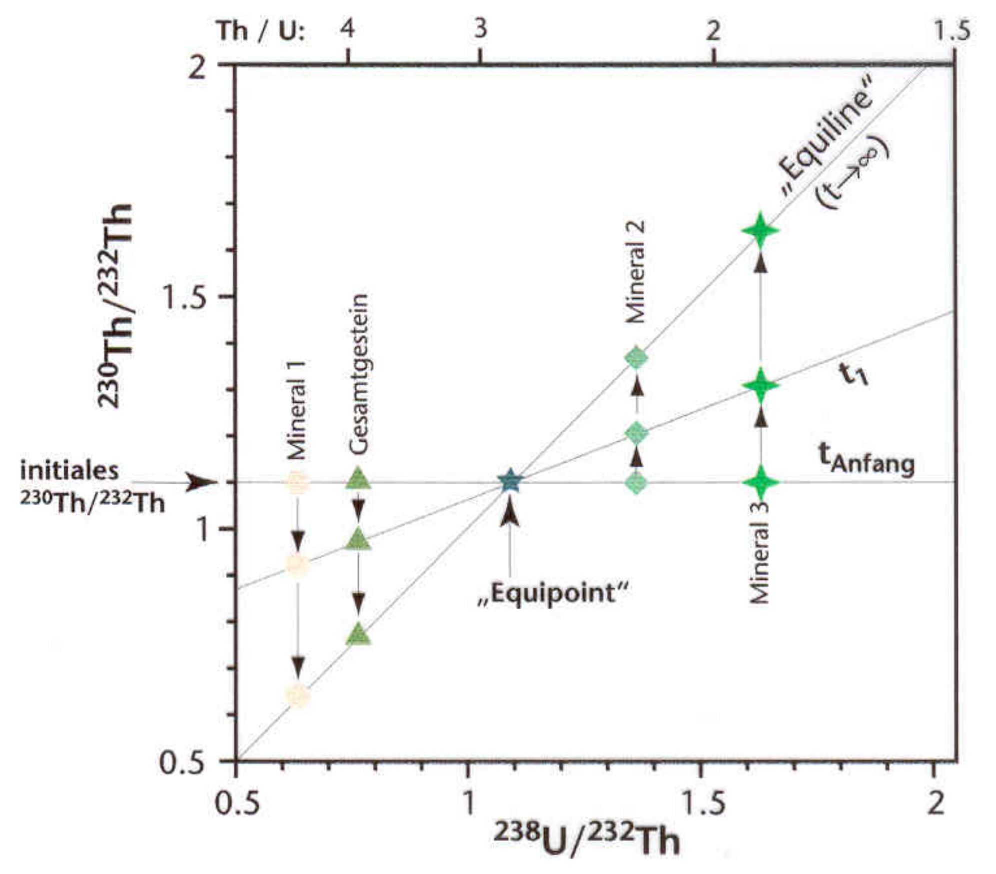
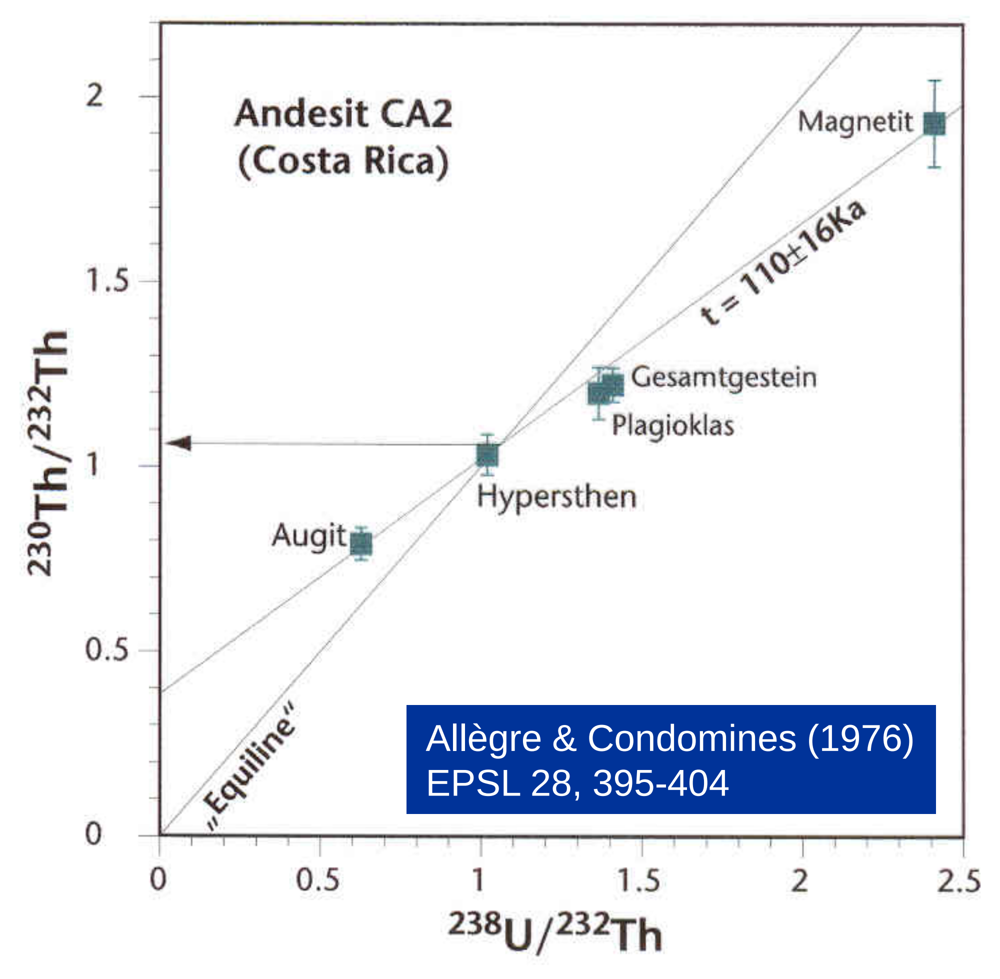


For equilibrium:
$\lambda_1 N_1 = \lambda_2 N_2$
$A_1 = A_2$
$(^{230}Th/^{238}U) = 1$

U-Th isotopes in arc magmas



Allègre & Condomines (1976)
EPSL 28, 395-404

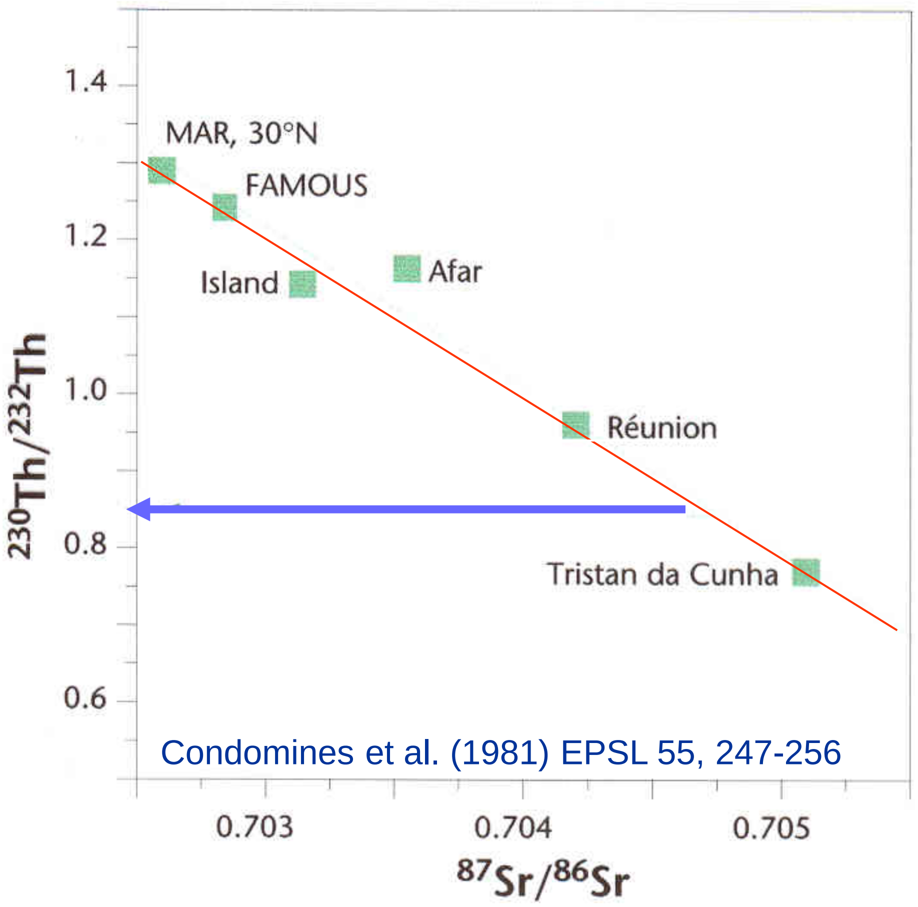
Bateman's equation:

$$\frac{A_{230}}{A_{232}} = \left(\frac{A_{230}}{A_{232}}\right) e^{-\lambda_{230} t} + \left(\frac{A_{238}}{A_{232}}\right)\left(1 - e^{-\lambda_{230} t}\right)$$

↑

unsupported

U-Th isotopes in arc magmas



Condomines et al. (1981) EPSL 55, 247-256

$$A_{230} = A_{238} \Rightarrow \frac{A_{230}}{A_{232}} = \frac{A_{238}}{A_{232}}$$

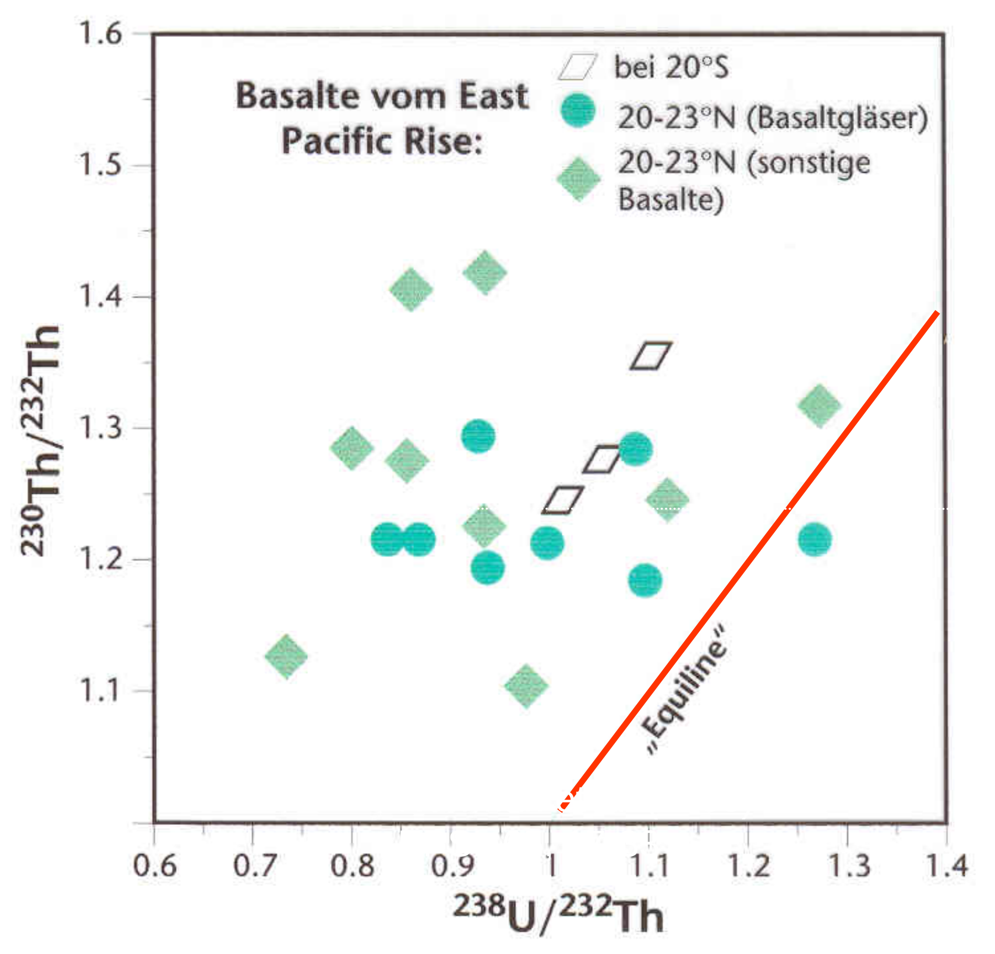
$$\frac{A_{230}}{A_{232}} = \frac{N_{238}}{N_{232}} \times \frac{\lambda_{238}}{\lambda_{232}}$$

$$\frac{N_{232}}{N_{238}} = \frac{A_{232}}{A_{230}} \times \frac{\lambda_{238}}{\lambda_{232}}$$

Thorium-Uran Verhältnis:

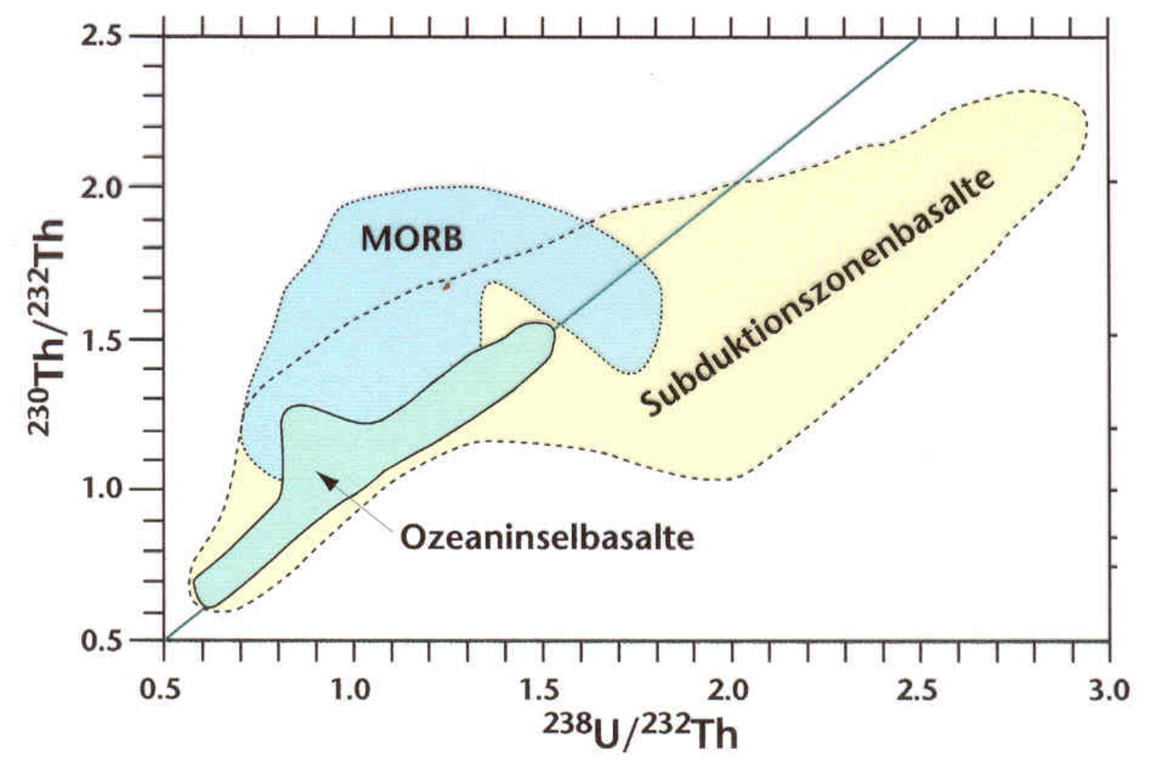
$$\frac{N_{232}}{N_{238}} = \frac{1}{0.86} \times \frac{1.55125 \times 10^{-10}}{4.9475 \times 10^{-11}} = 3.65$$

U-Th isotopes in arc magmas

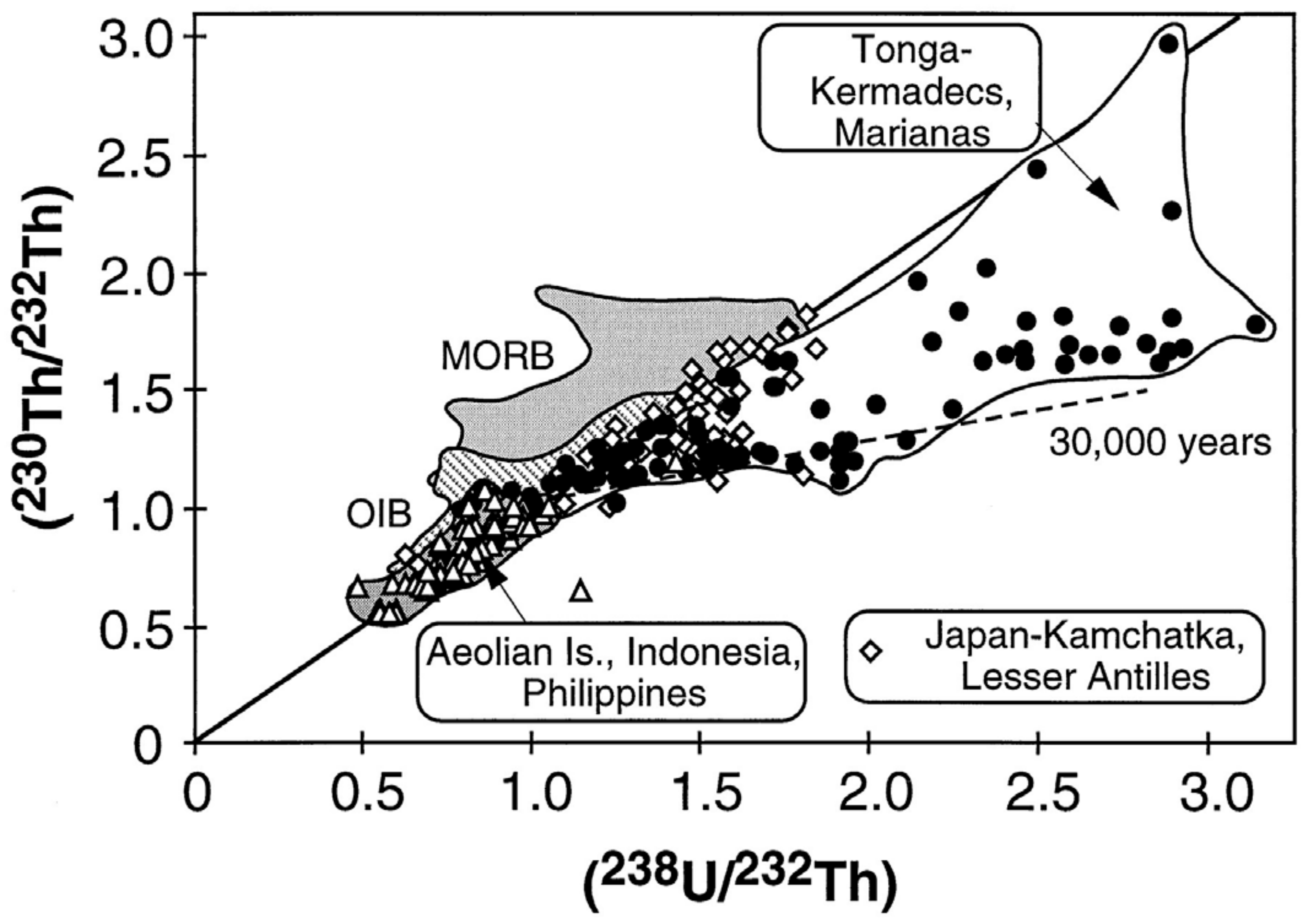


$$\frac{^{232}Th}{^{238}U} = \left(\frac{1}{1.22}\right) \times \left(\frac{\lambda^{238}U}{\lambda^{232}Th}\right) = 2.57$$

U–Th isotopes

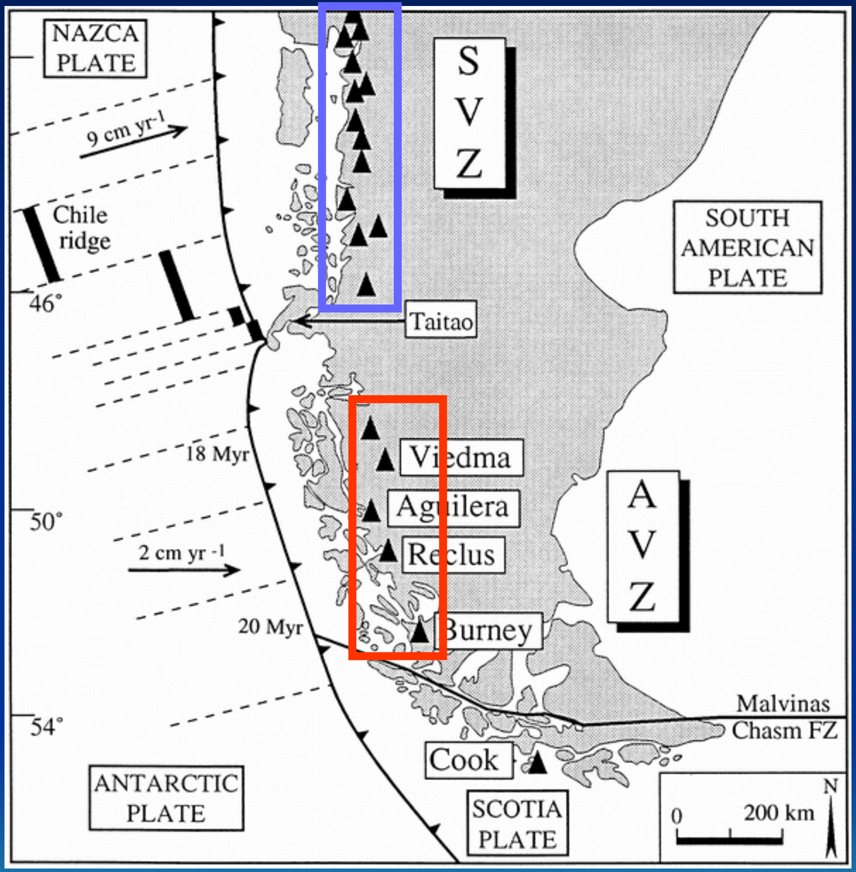


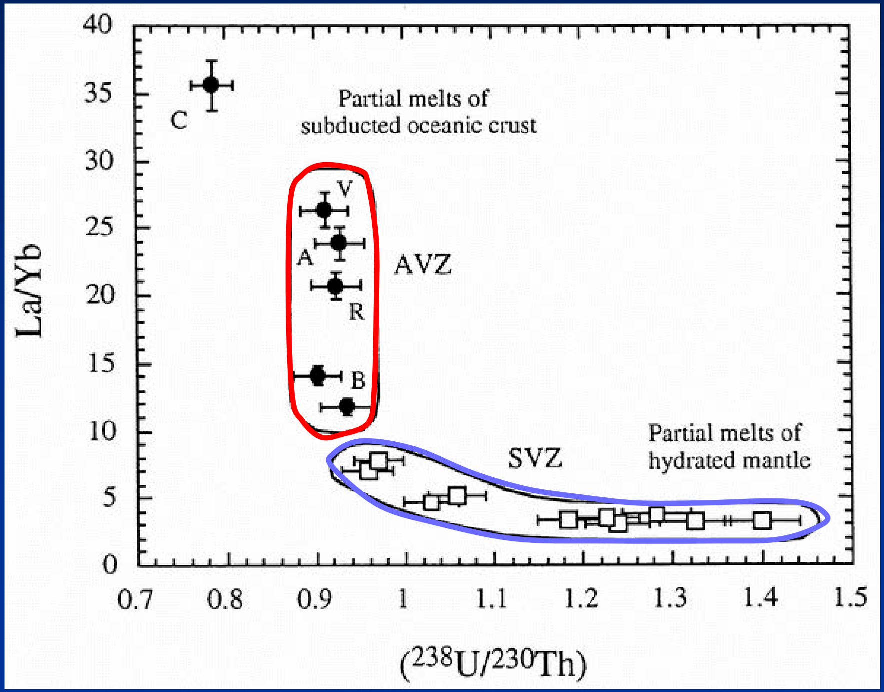
U–Th isotopes



Hawkesworth et al. (1997) Science 276

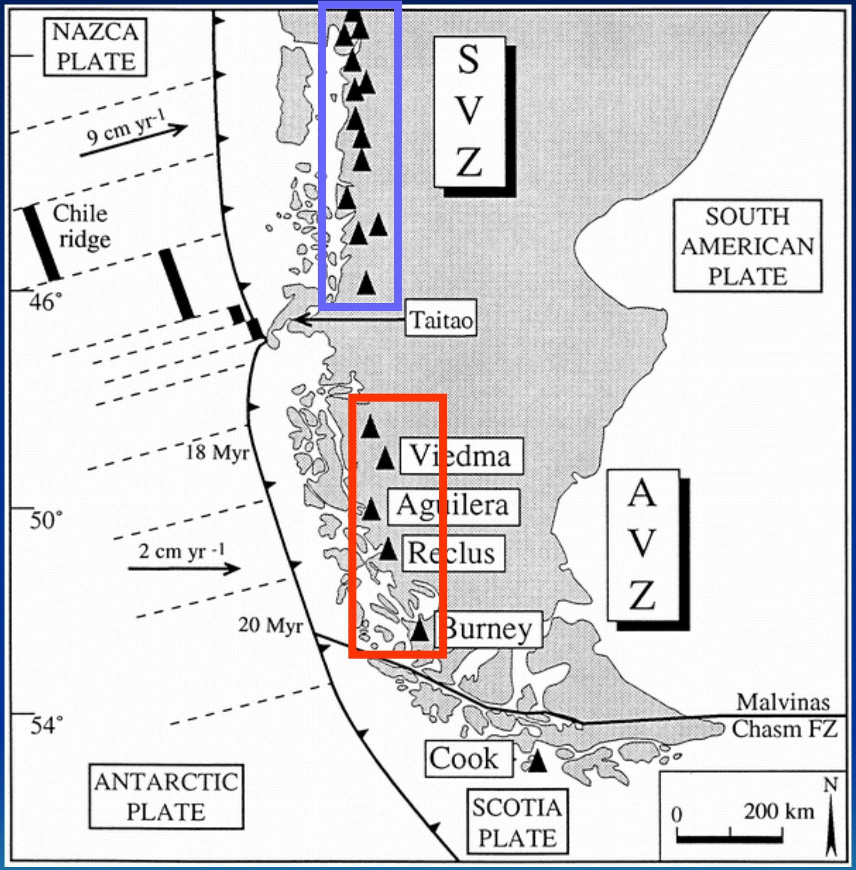
Melting of a subducting oceanic slab?

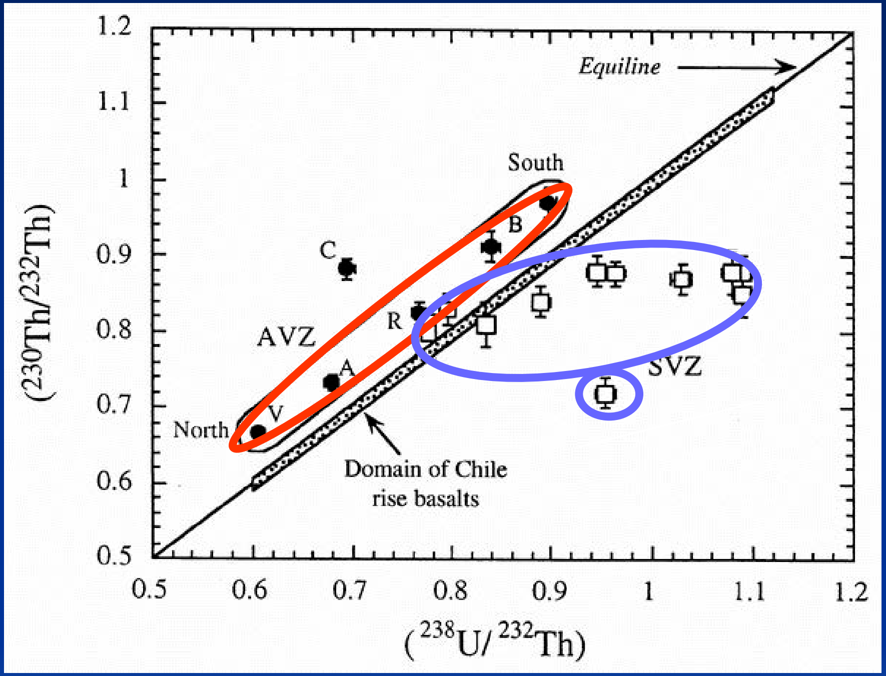




Sigmarsson et al. (1998) Nature 394

Melting of a subducting oceanic slab?



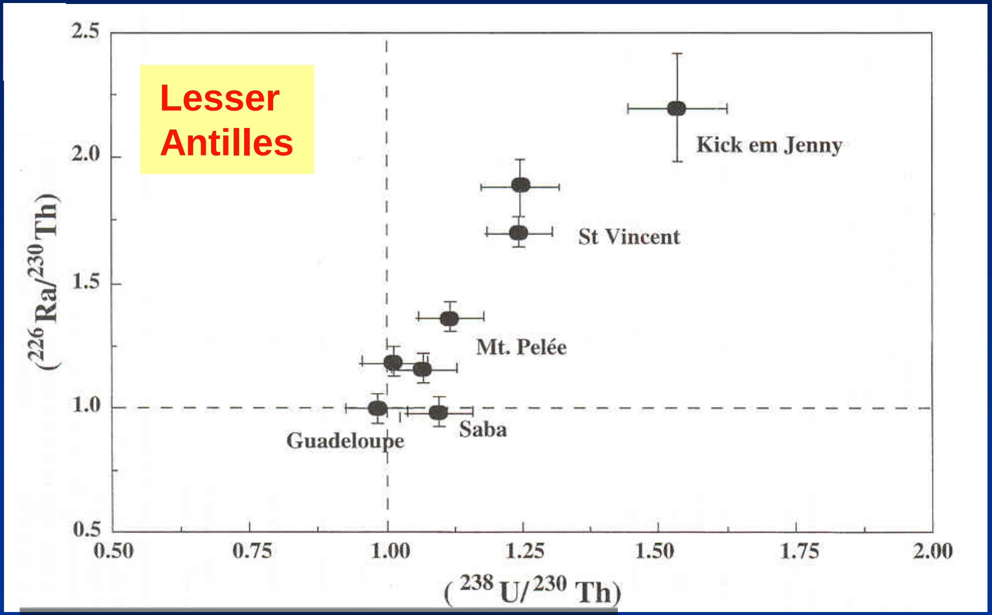


Sigmarsson et al. (1998) Nature 394

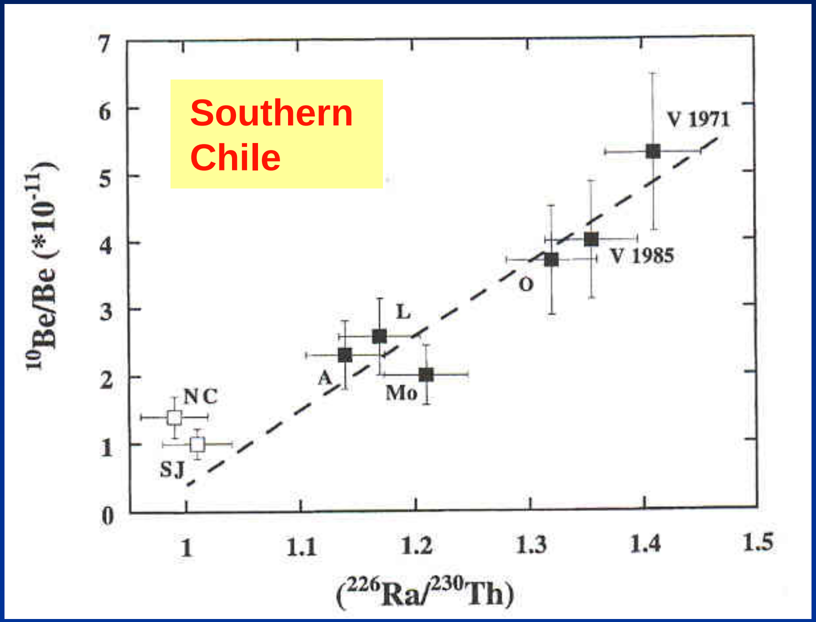
Timescales of melt transport

$^{238}U \rightarrow {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{206}Pb$ (excluding some "shorties")

$T_{1/2}$ = 75 ka **$T_{1/2}$ = 1.6 ka**



Chabaux et al. (1999) Chem Geol 153



Sigmarsson et al. (2002) EPSL 196

Ultrafast source to surface movement: 10-100 m/year

Adakites (High Mg-andesites)

Geochemical characteristics

- intermediate to acidic calc-alkaline volcanic rock
- Anomalously steep rare-earth-element pattern, low HREE
- High Al_2O_3 and Sr contents
- High Sr/Y ratios
- Enriched in compatible elements such as Mg, Cr and Ni
- Defant and Drummond (1990) defined it as having Yb < 1.8 ppm, Y < 15-20 ppm, Sr/Y >40 and it may be of low-, medium- or high-K_2O type

Petrogenesis, Tectonic setting

- derives from high pressure partial melting of subducted oceanic crust,

….subducted oceanic ridges or underplated mafic material

- A fractional crystallization origin of calc-alkaline basaltic magma is precluded

….by its trace element characteristics

Slab melting process also proposed for formation of Archean crust (→TTGs)

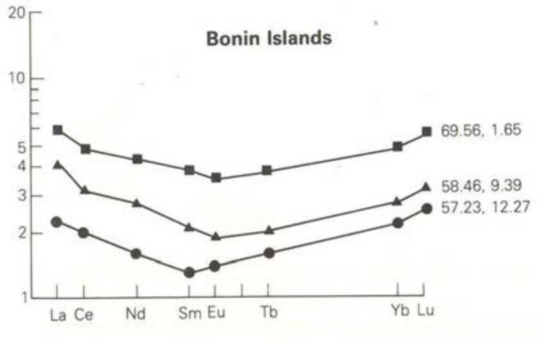
Boninites (High-Mg andesites & dacites)

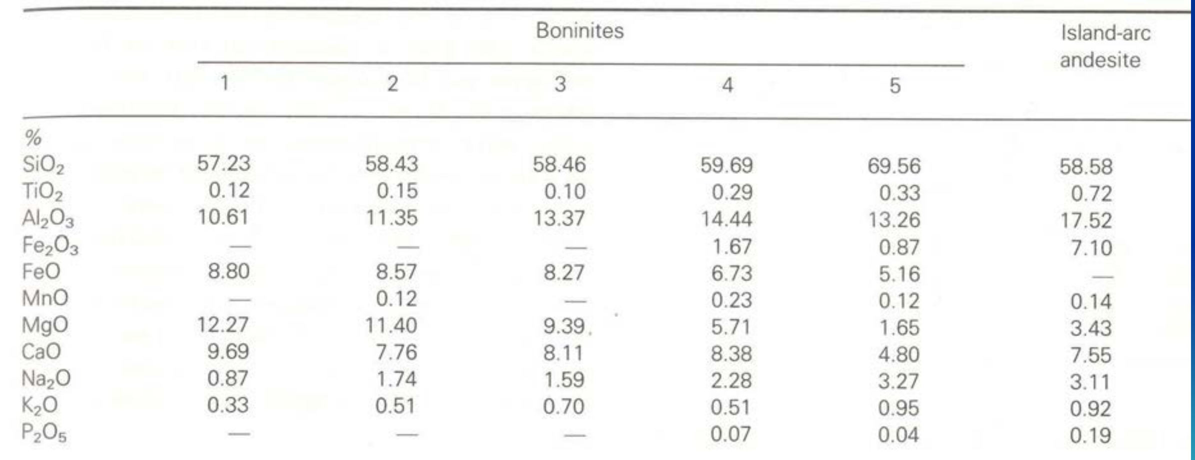
Geochemical characteristics

- ► high SiO_2 (>55%), high-MgO (~9%), low Al_2O_3, low TiO_2 lavas
- ► Enriched in compatible elements such as Cr and Ni
- ►‘V’-shaped REE pattern (as in metasomatized harzburgite xenoliths)

Petrogenesis, Tectonic setting

- ► derivation from strongly depleted mantle sources under hydrous conditions
- ► near-primary partial melts (not fractionated)
- ► occur often during start of subduction





	Boninites					Island-arc andesite
	1	2	3	4	5	
%						
SiO_2	57.23	58.43	58.46	59.69	69.56	58.58
TiO_2	0.12	0.15	0.10	0.29	0.33	0.72
Al_2O_3	10.61	11.35	13.37	14.44	13.26	17.52
Fe_2O_3	—	—	—	1.67	0.87	7.10
FeO	8.80	8.57	8.27	6.73	5.16	—
MnO	—	0.12	—	0.23	0.12	0.14
MgO	12.27	11.40	9.39	5.71	1.65	3.43
CaO	9.69	7.76	8.11	8.38	4.80	7.55
Na_2O	0.87	1.74	1.59	2.28	3.27	3.11
K_2O	0.33	0.51	0.70	0.51	0.95	0.92
P_2O_5	—	—	—	0.07	0.04	0.19

Adakites - references

Defant MJ, Drummond MS (1990) Derivation of some modern arc magmas by melting of young subducted lithosphere. *Nature* **347**, 662-665

Castillo PR (2006) An overview of adakite petrogenesis. Chinese Science Bulletin 51, 257-268

Boninites - references

Crawford AJ, Beccaluva L, Serri G (1981) Tectono-magmatic evolution of the West Philippine-Mariana region and the origin of boninites. *Earth Planet Sci Lett* **54**, 346-356

Hickey RL, Frey FA (1982) Geochemical characteristics of boninite series volcanics: implications for their source. *Geochim Cosmochim Acta* **46**, 2099-2115

Arc magmatic tempos

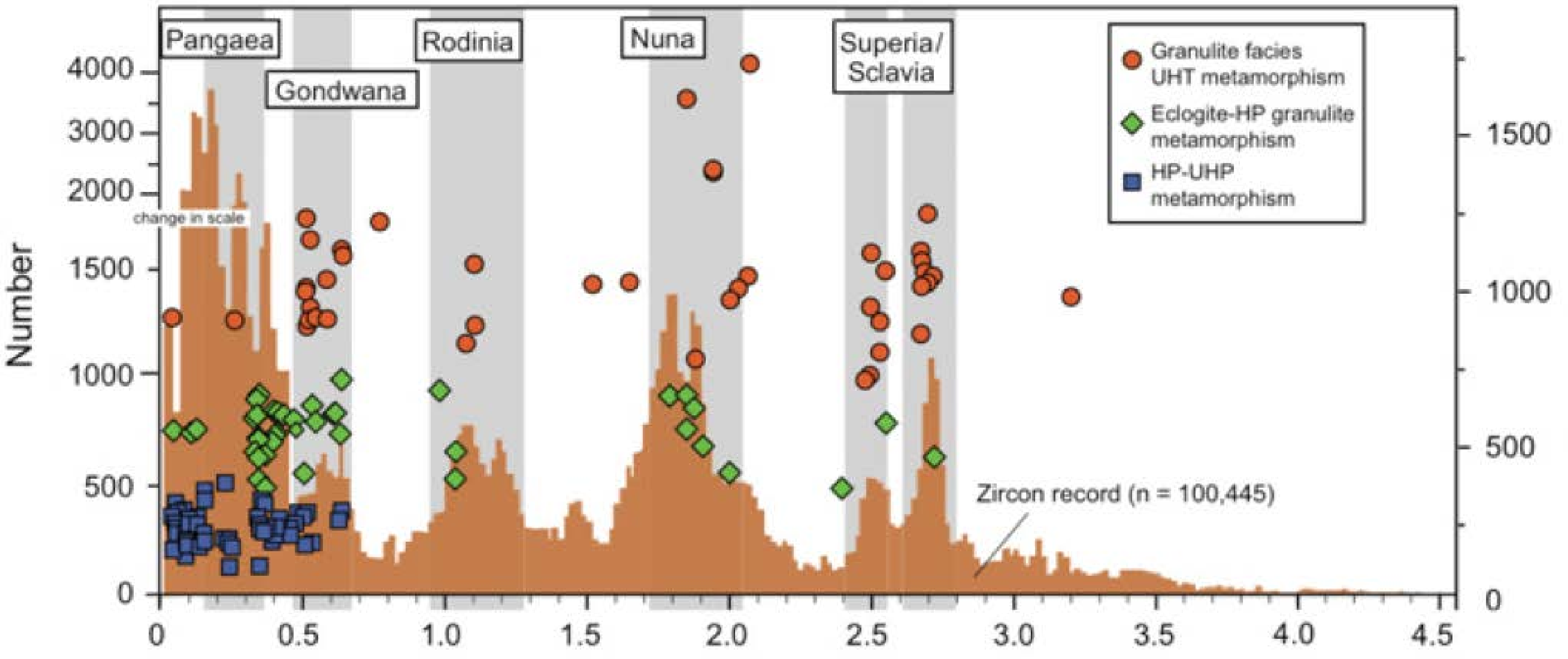
Looking at the temporal behavior of arc magmatism

central portion of the Sierra Nevada Batholith (Late Cretaceous) showing its voluminous nature (Photo: Scott Paterson)

Ducea et al (2015) Elements

Arc magmatic tempos

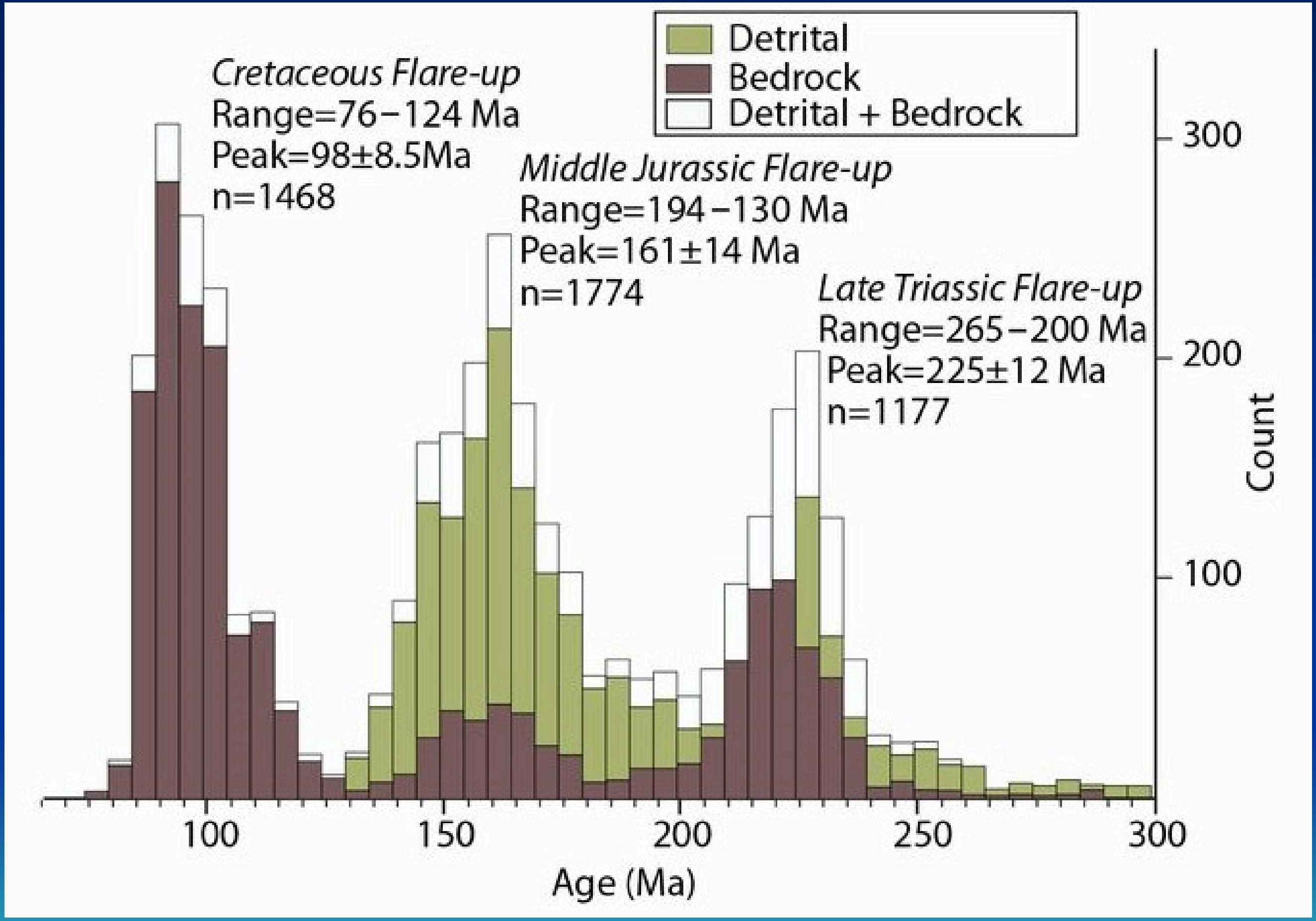
U–Pb crystallization ages for over 100,000 detrital zircon grains (Voice et al. 2011). The zircon peaks and occurrences of ultra-high temperature metamorphism correlate to the ages of supercontinent assembly (Cawood et al. 2013).



John Valley (2015) Elements

Arc magmatic tempos

Exposed bedrock U–Pb zircon ages & detrital zircon U–Pb LA-ICP MS ages from the Sierra Nevada Batholith (California)

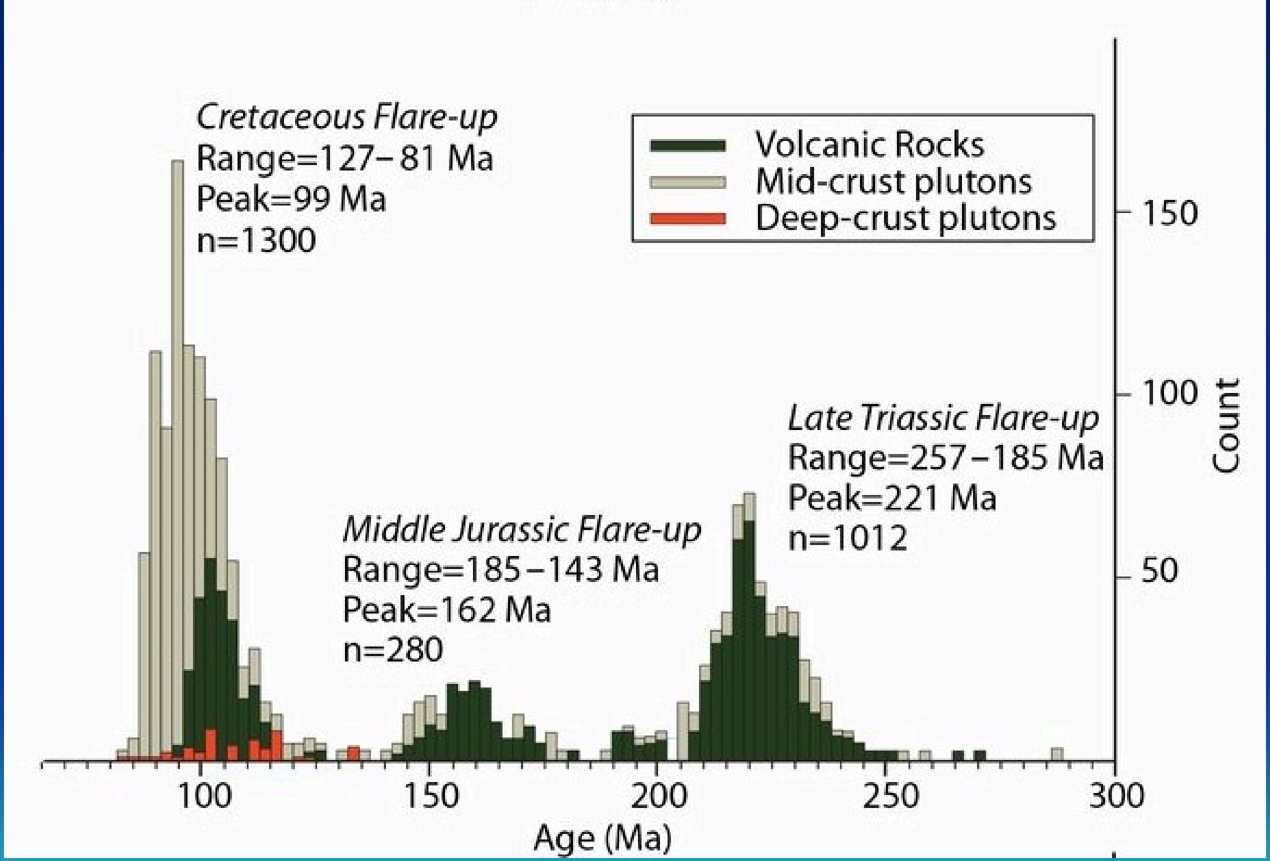


Both data sets temporally define the beginning (~250 Ma) and cessation (~85 Ma) of Mesozoic magmatism plus timing of three magmatic flare-ups and four lulls

Paterson & Ducea (2015) Elements

Arc magmatic tempos

Depth comparison of bedrock Sierran U–Pb igneous ages, with ages separated into surface volcanic, shallow plutons (emplaced above 6 kbar), and deep plutons (>6 kbar emplacement).

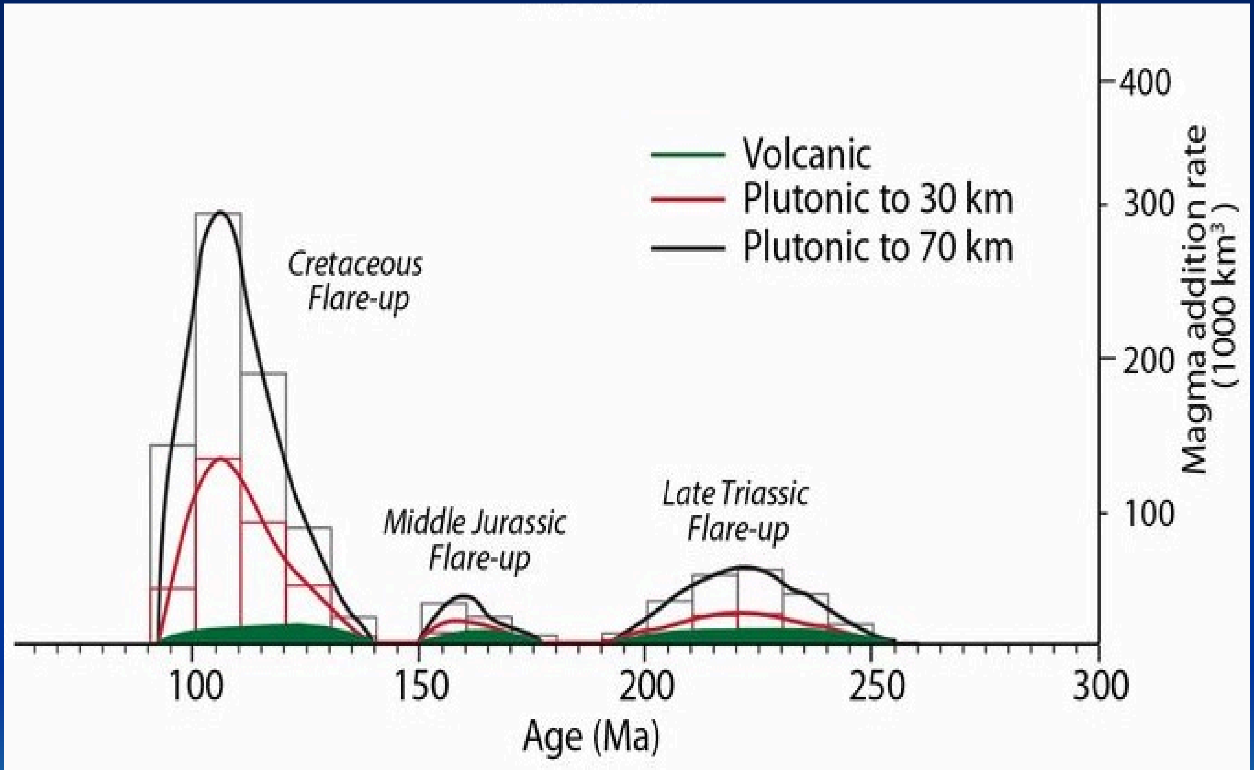


Timing of flare-ups and lulls appears depth independent, although volcanism may peak slightly earlier than plutonism in the Jurassic and Cretaceous flare-ups.

Paterson & Ducea (2015) Elements

Arc magmatic tempos

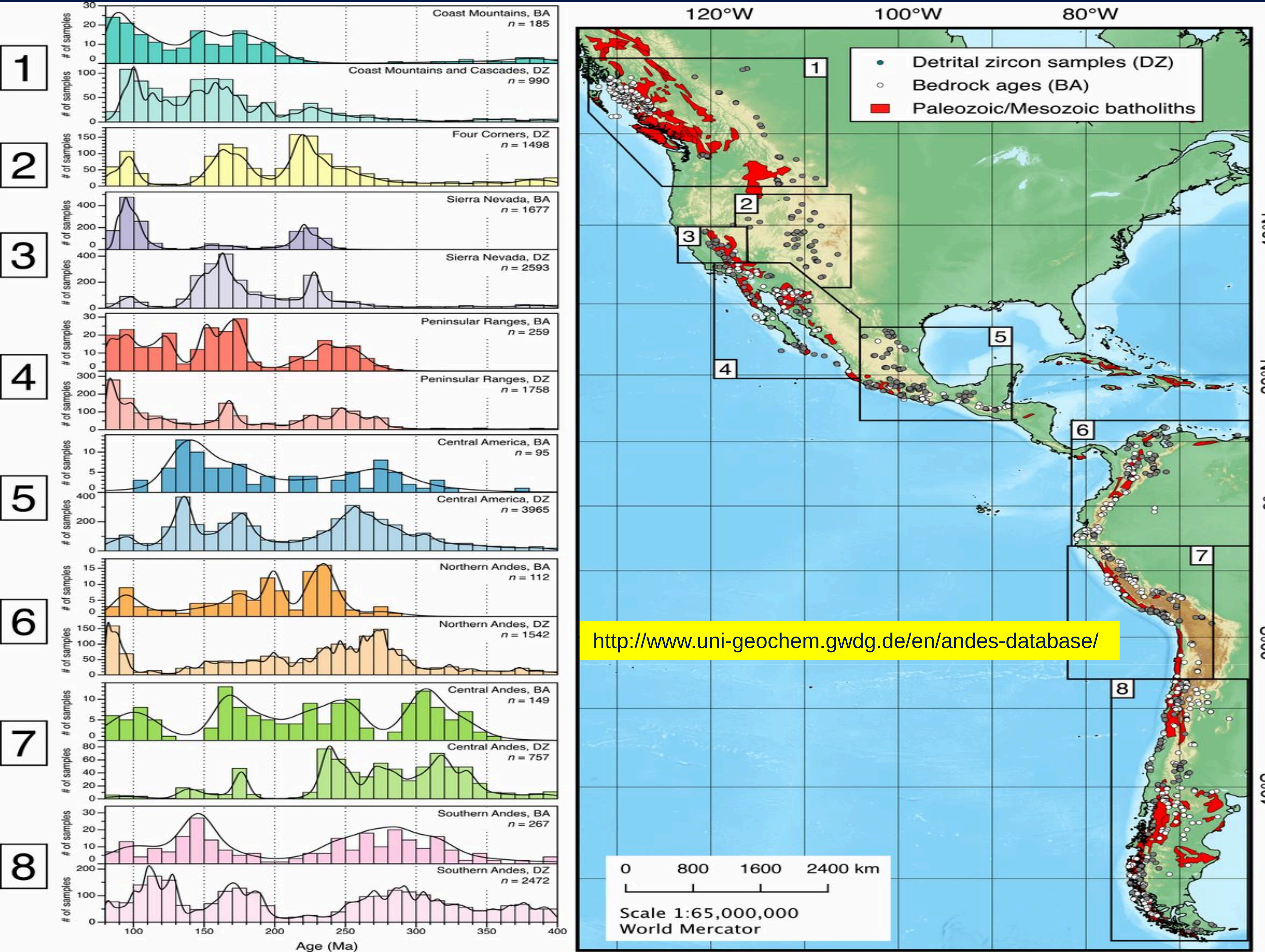
Calculated magma addition rates, measured in km^3 for 10 My age bins for both plutonic and volcanic materials in a 110 km wide corridor, central Sierra Nevada



curves show huge (100 to 1000) increases of magma added during flare-ups versus lulls resulting in plutonic/volcanic ratios of ~30/1

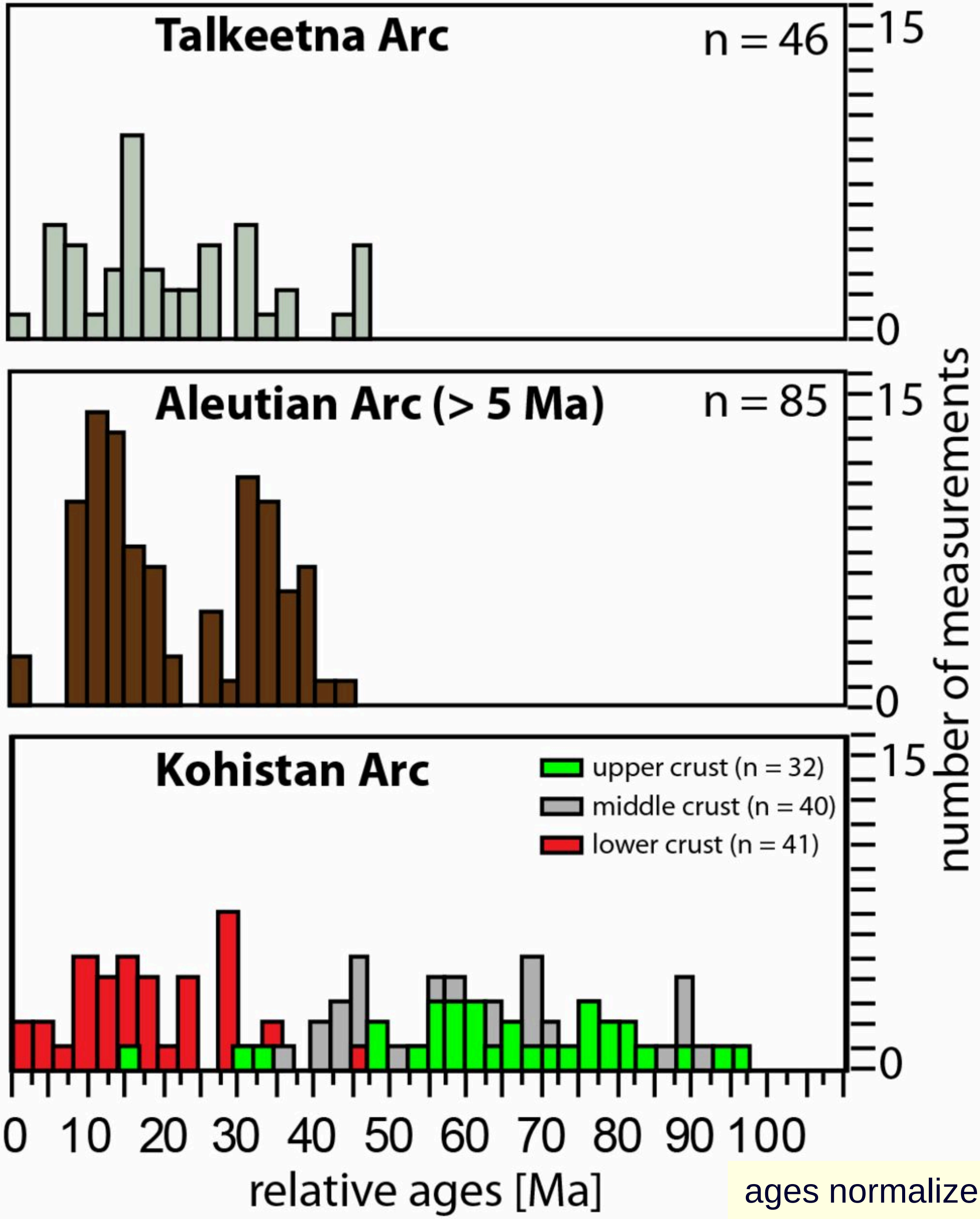
Paterson & Ducea (2015) Elements

flare-ups and lulls display apparent wave-like patterns of waxing and waning magmatism



http://www.uni-geochem.gwdg.de/en/andes-database/

Arc magmatic tempos in oceanic arcs

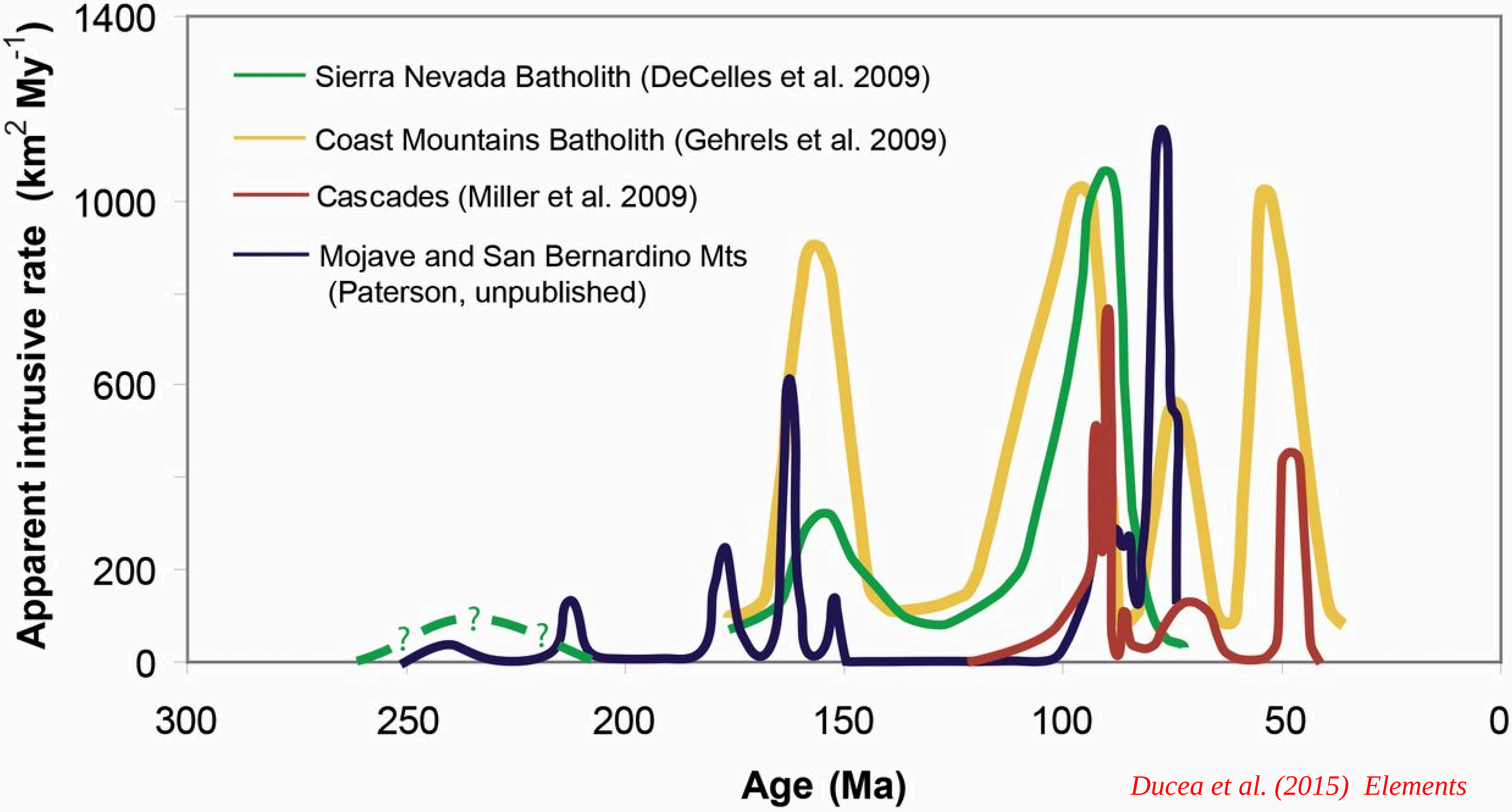


Paterson & Ducea (2015)
Elements

ages normalized to when arc magmatism started

Arc magmatic tempos

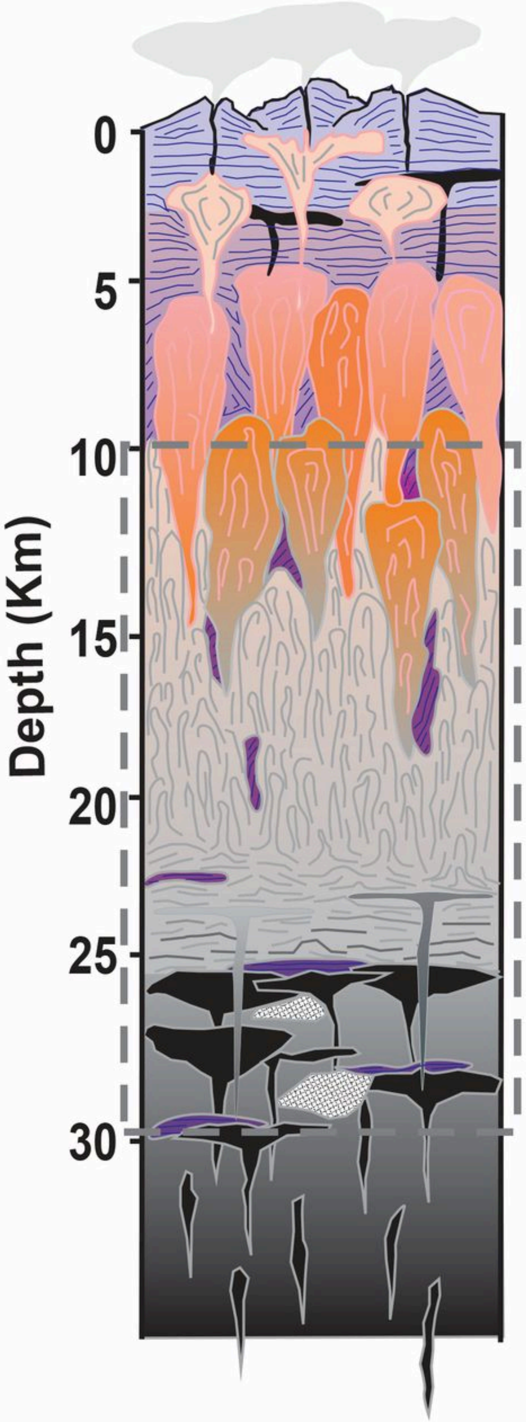
intrusive rates versus age for various segments of the Mesozoic to early Cenozoic magmatic arcs in the western North American Cordillera



Ducea et al. (2015) Elements

Schematic crustal column though the Ordovician Famatinian arc (Argentina)

Vertical “wall” of rocks that show the same age range from the surface to the dept is a characteristic of most arcs. This attests to the verticality of magma transport, petrogenetic processes, and the emplacement in arc rocks.



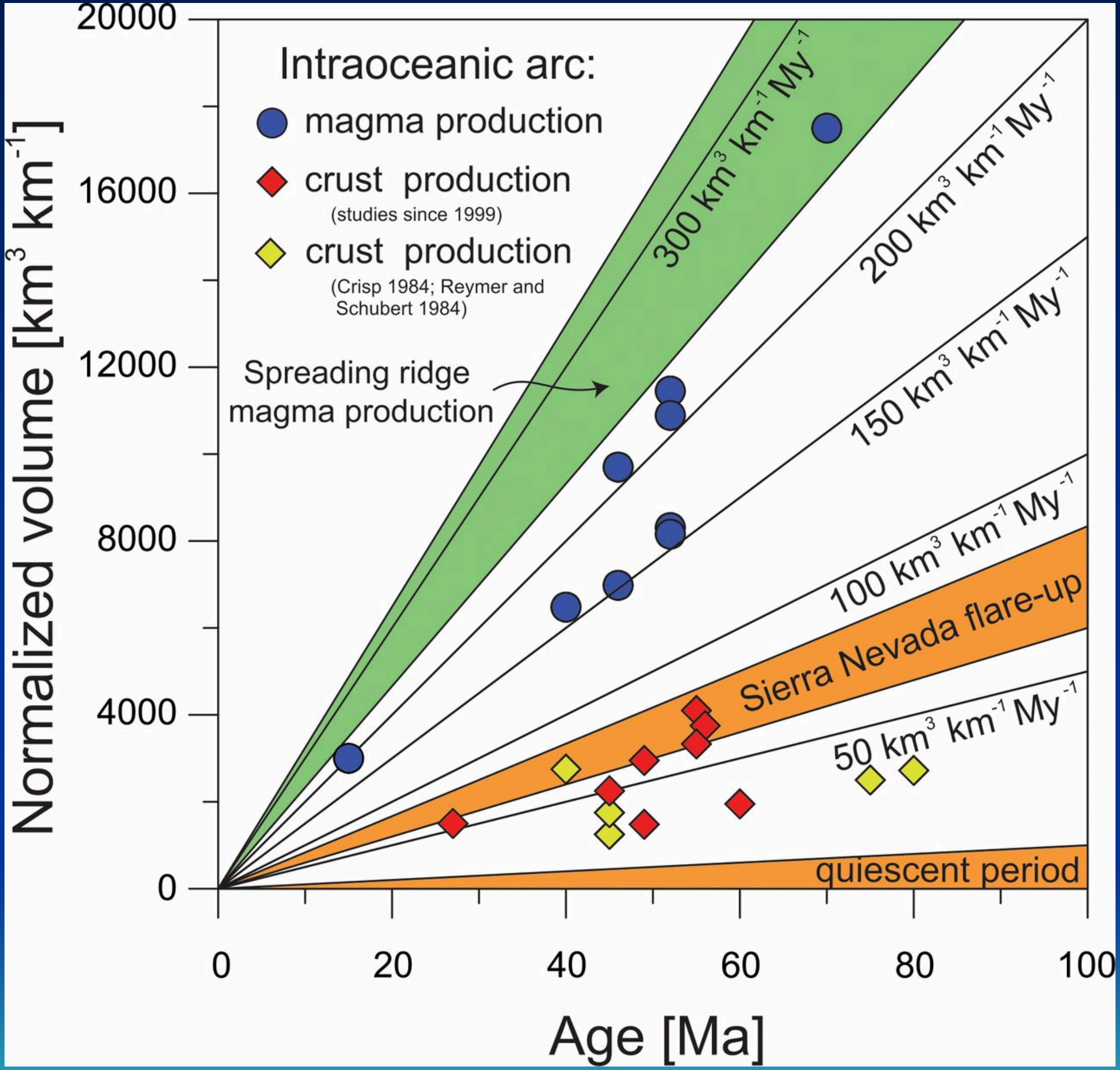
Ducea et al. (2015) Elements

- arc compositions become more mafic and richer in cumulate/restite assemblages (residues) with depth.

- magmatic arc products dominate everywhere in the crust.

- intrusive and/or volcanic ages and their relative distribution typical of the upper crust are identical with those in the lower crust.

Magma and crust production rates



Jicha & Jagoutz (2015) Elements