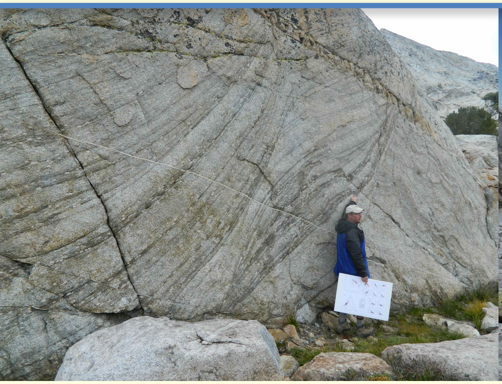
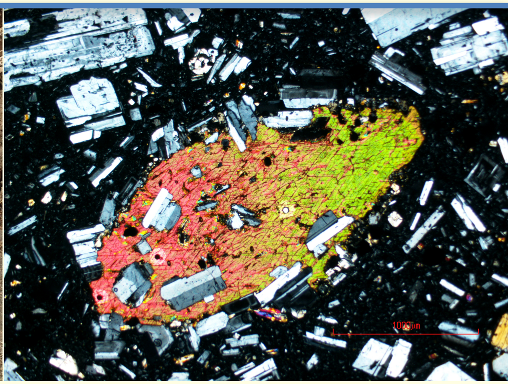
Formation Of Volcanic arcs



Adam Kent

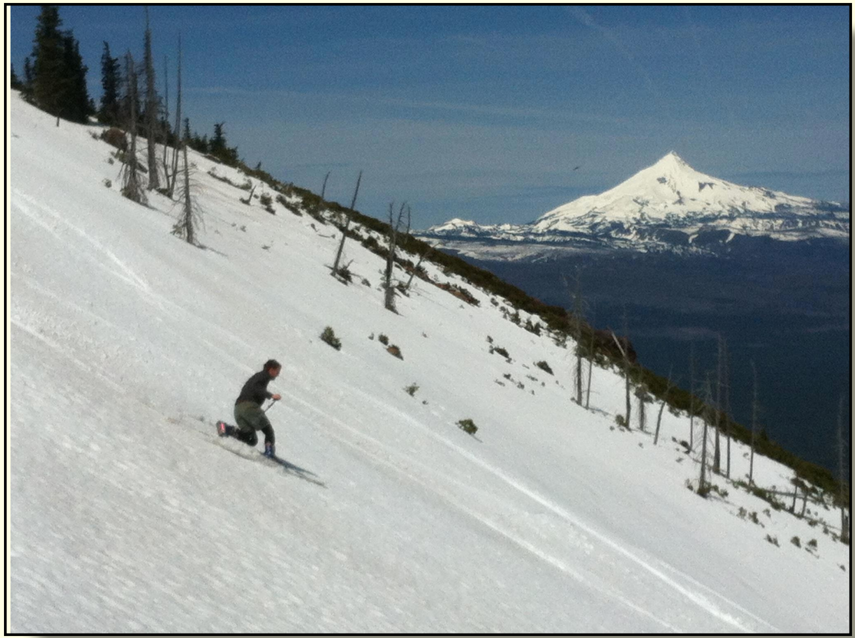
Oregon State University

Gunung Agung, Bali

Adam Kent

(@geowhateverist)

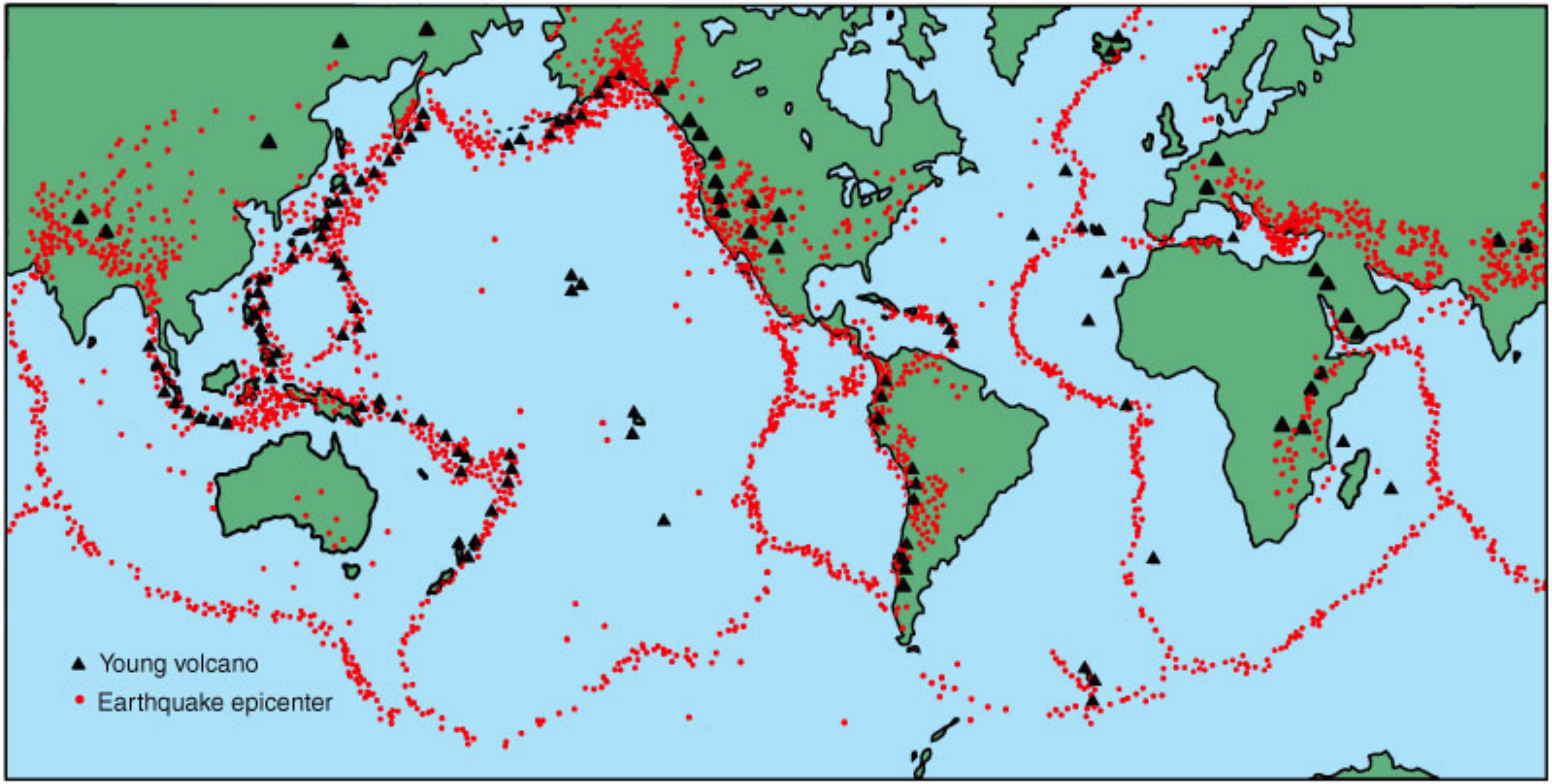
- Use the tools of petrology & geochemistry to study magmatic systems
- Interaction between magmatic and volcanic processes
- Projects in Cascades, New Zealand, Saudi Arabia
- Applications of laser ablation ICP-MS



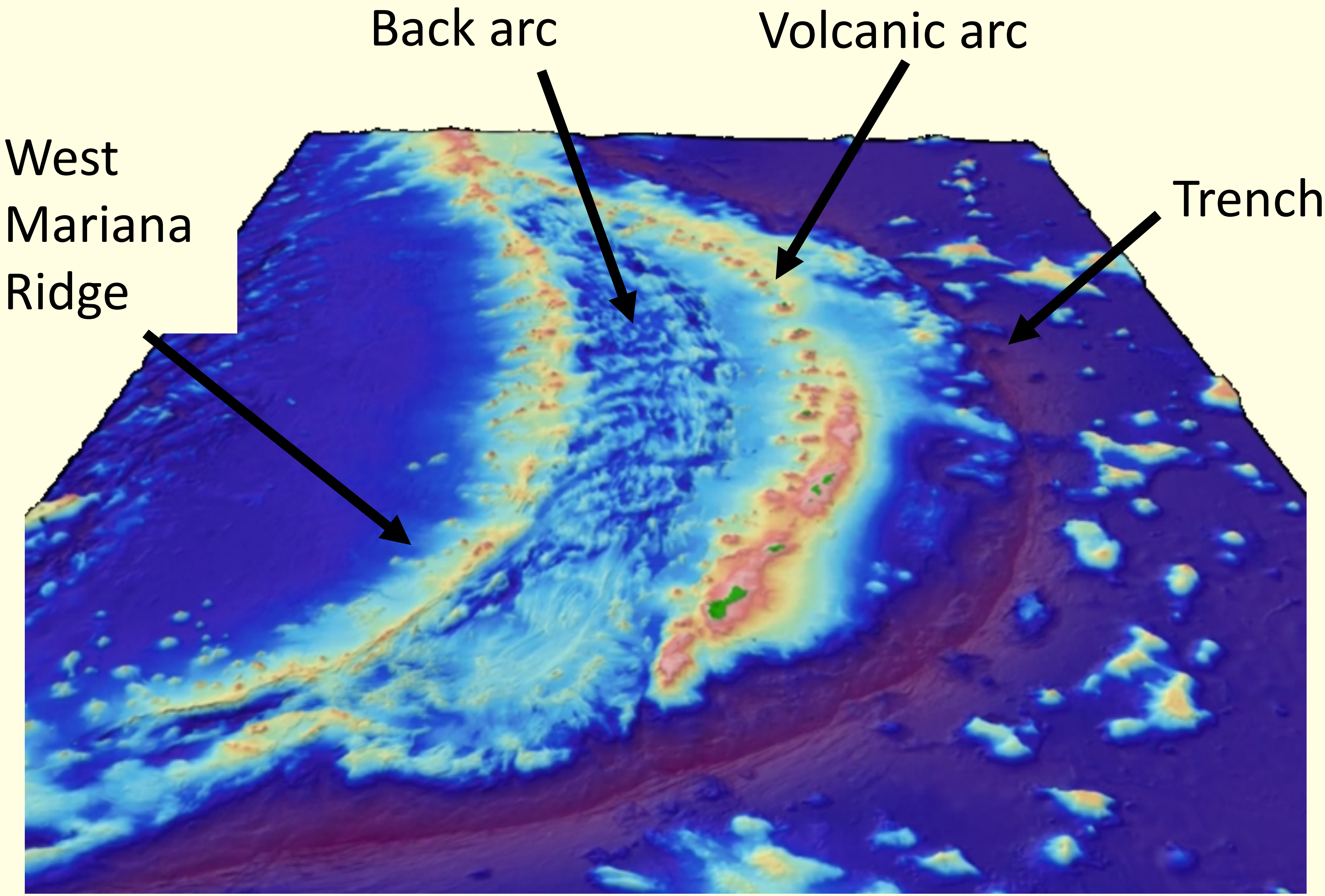
Black Butte, Mount Jefferson

Saudi Arabia

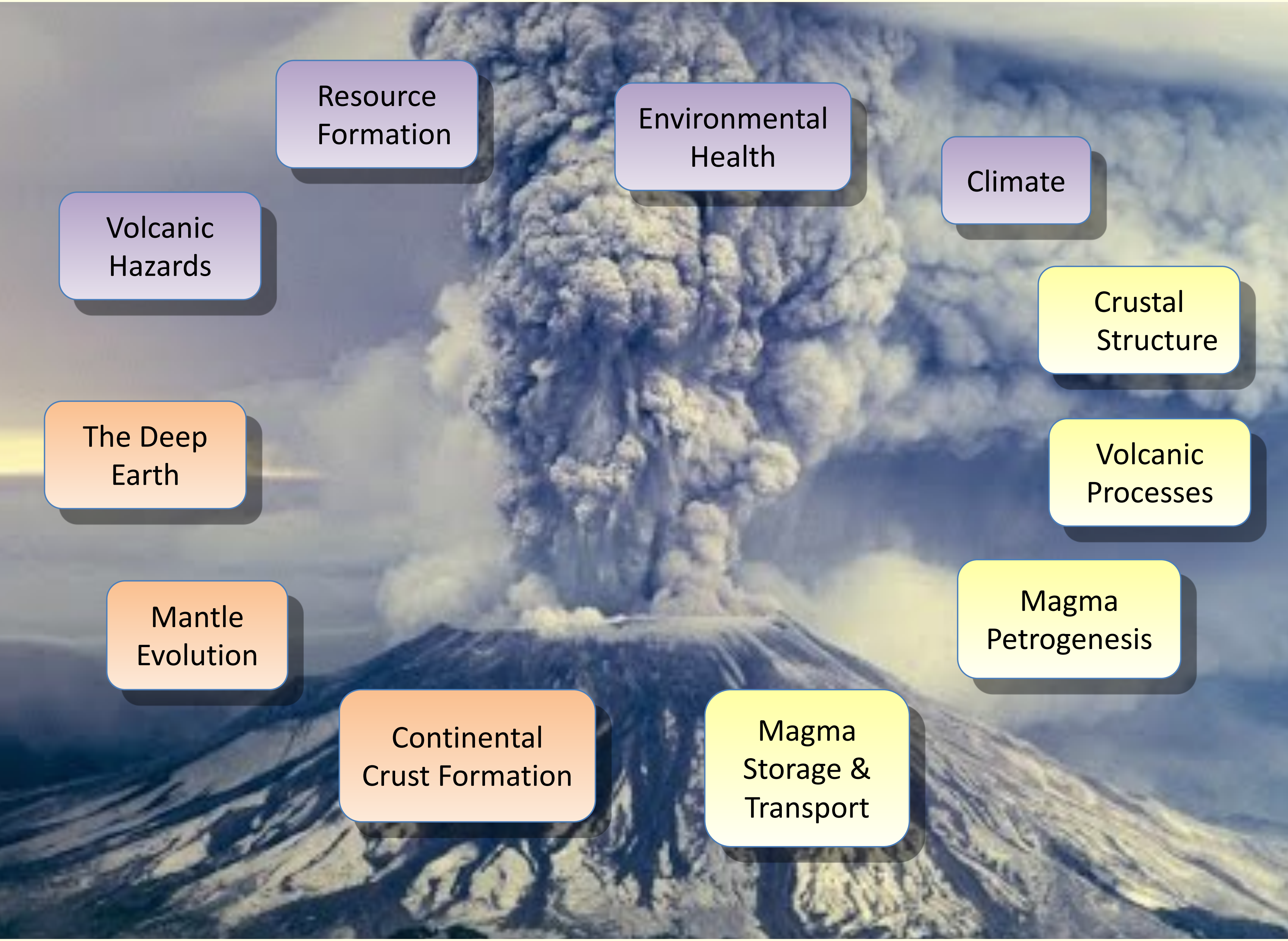
Montserrat

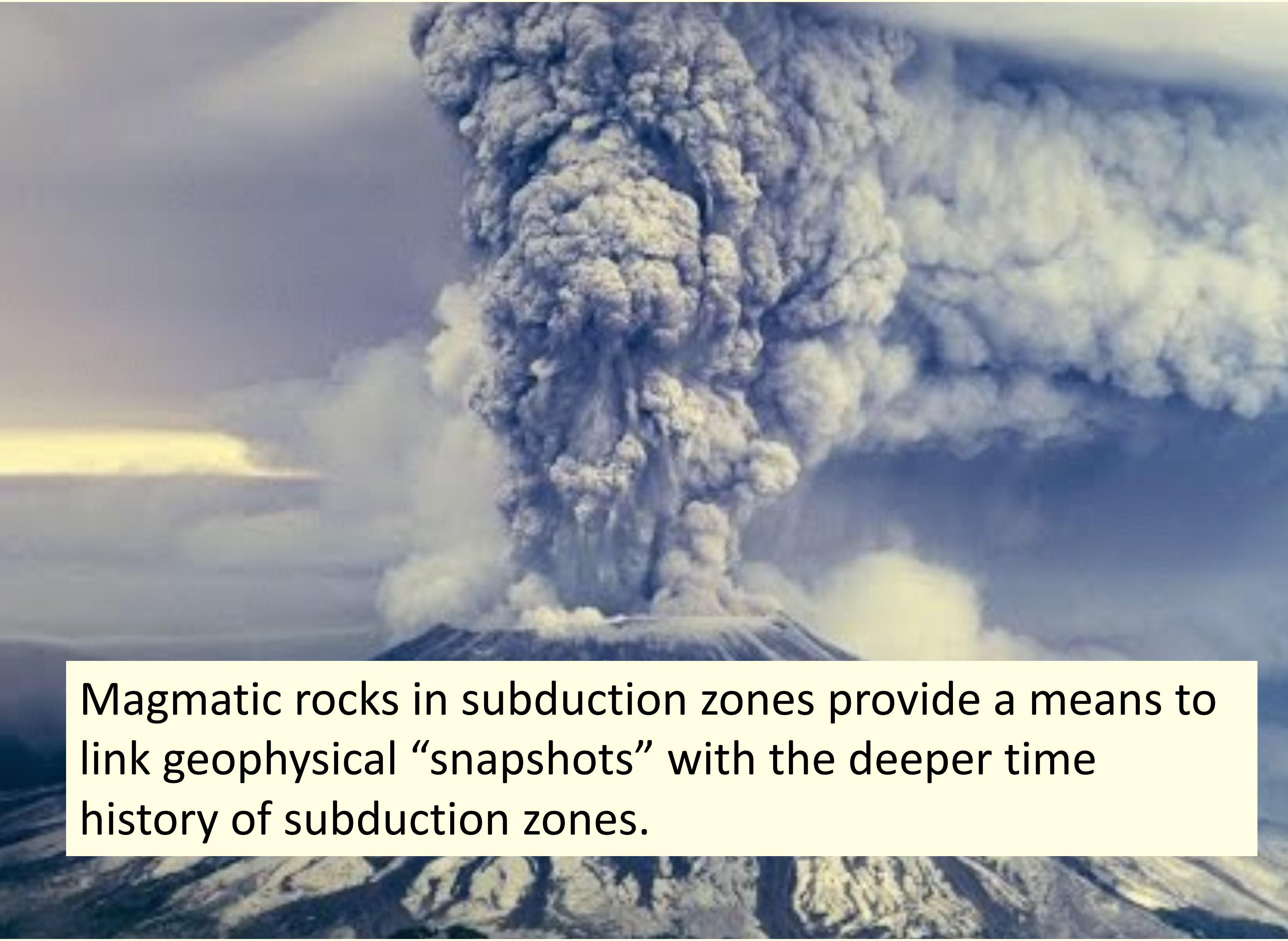


Volcanic arc: An arcuate chain of volcanoes formed above a subducting plate, and typically parallel to an oceanic trench.

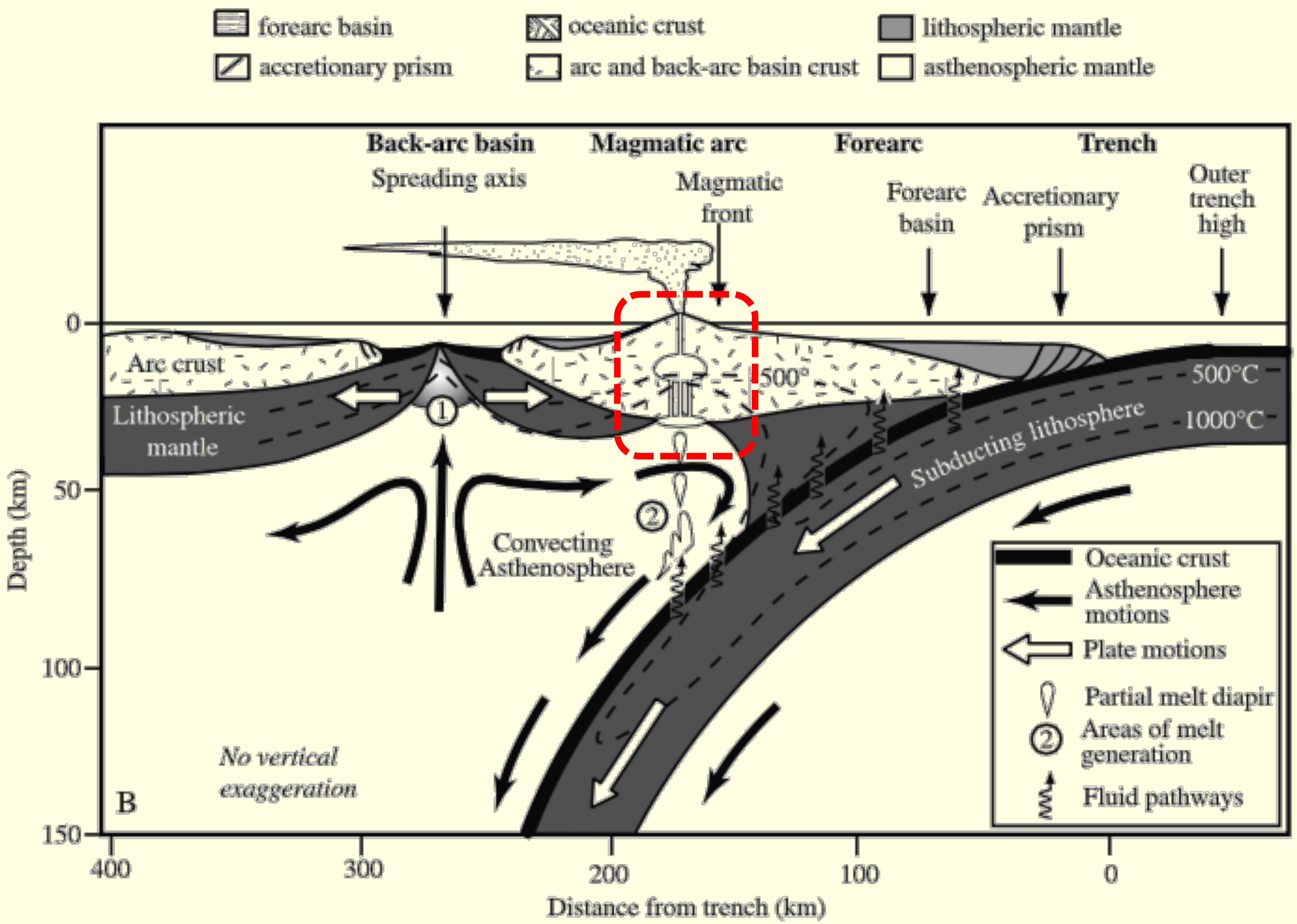


Mariana arc (NOAA)


Resource Formation
Environmental Health
Climate
Volcanic Hazards
Crustal Structure
The Deep Earth
Volcanic Processes
Mantle Evolution
Magma Petrogenesis
Continental Crust Formation
Magma Storage & Transport



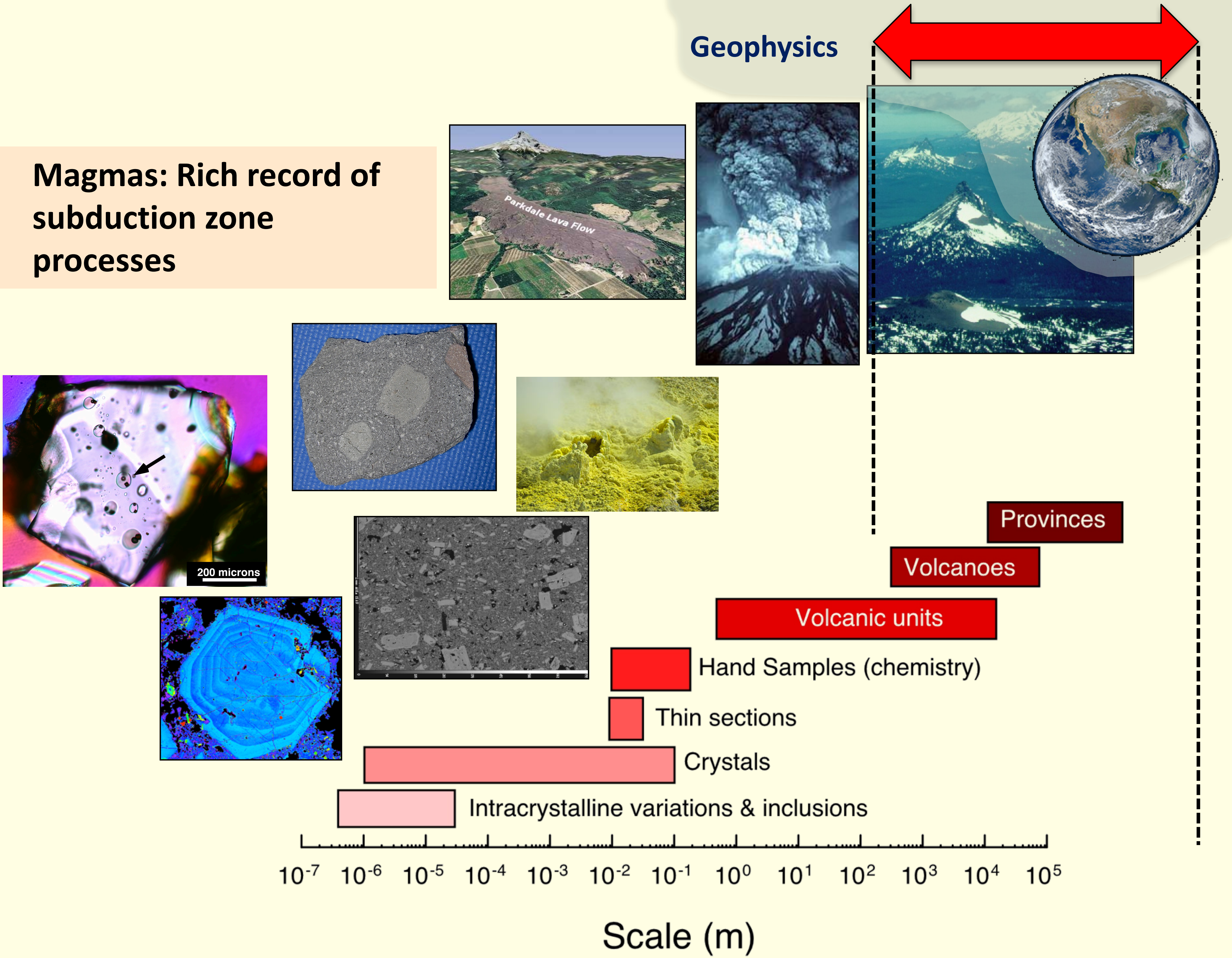
Magmatic rocks in subduction zones provide a means to link geophysical “snapshots” with the deeper time history of subduction zones.



Today: Discussion of the role of the upper plate in forming volcanic arcs

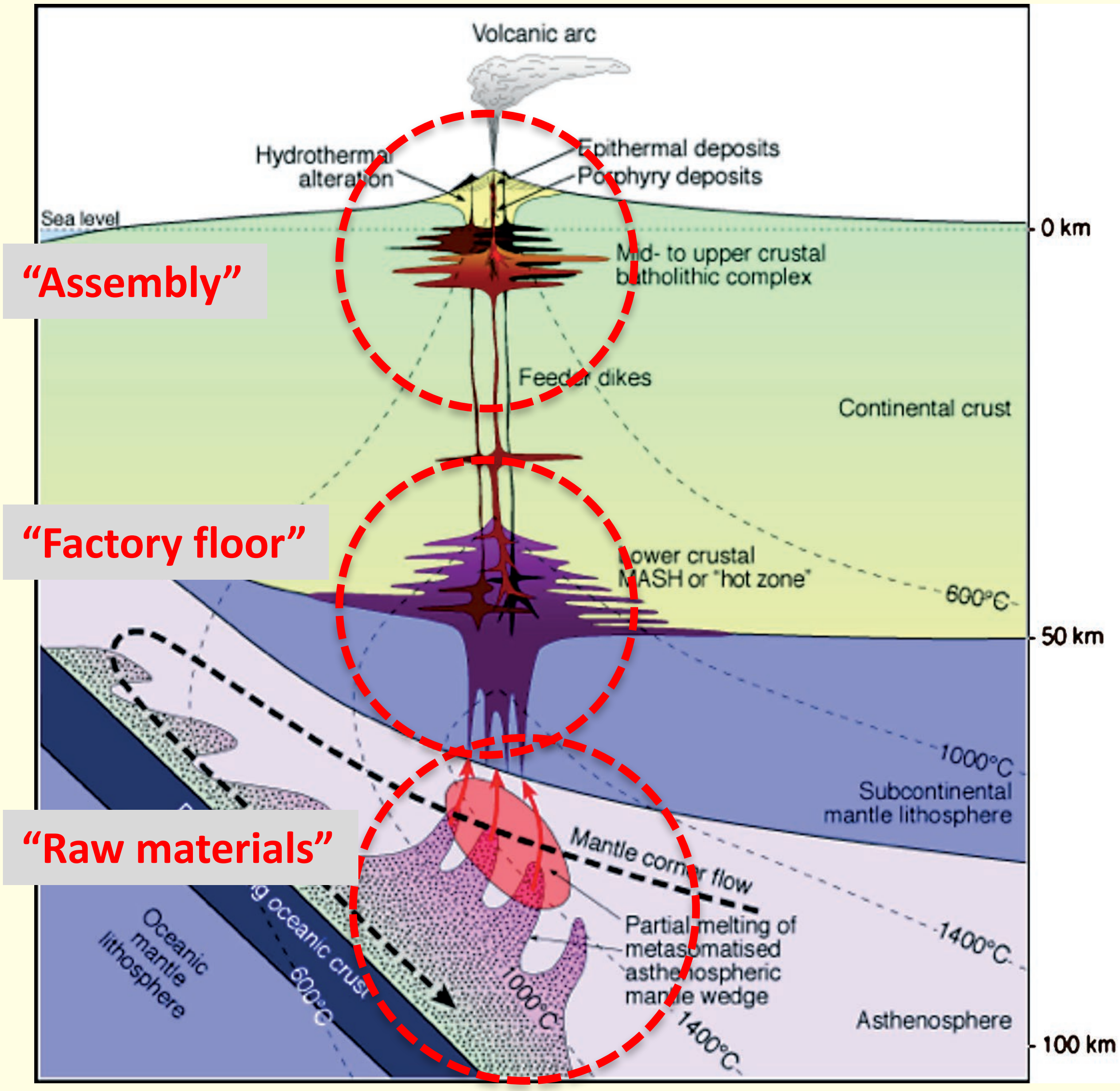
Stern 2002

- **Magmas: Rich record of subduction zone processes**



The Upper Plate

- Transformation of mantle derived magmas to the broad array of observed arc magmas
  - Production of intermediate and evolved magma compositions
  - Formation of crystals and their inclusions – important reserve of information
- Substantial magma residence
  - "Freezing" to form pluton, or transit to eruption
- Degassing and loss of volatiles to atmosphere or hydrothermal systems.
- Spatial and temporal modulation from plate tectonic rates to volcanic rates, and from continuous to episodic



Richards, 2011

KEEP CALM

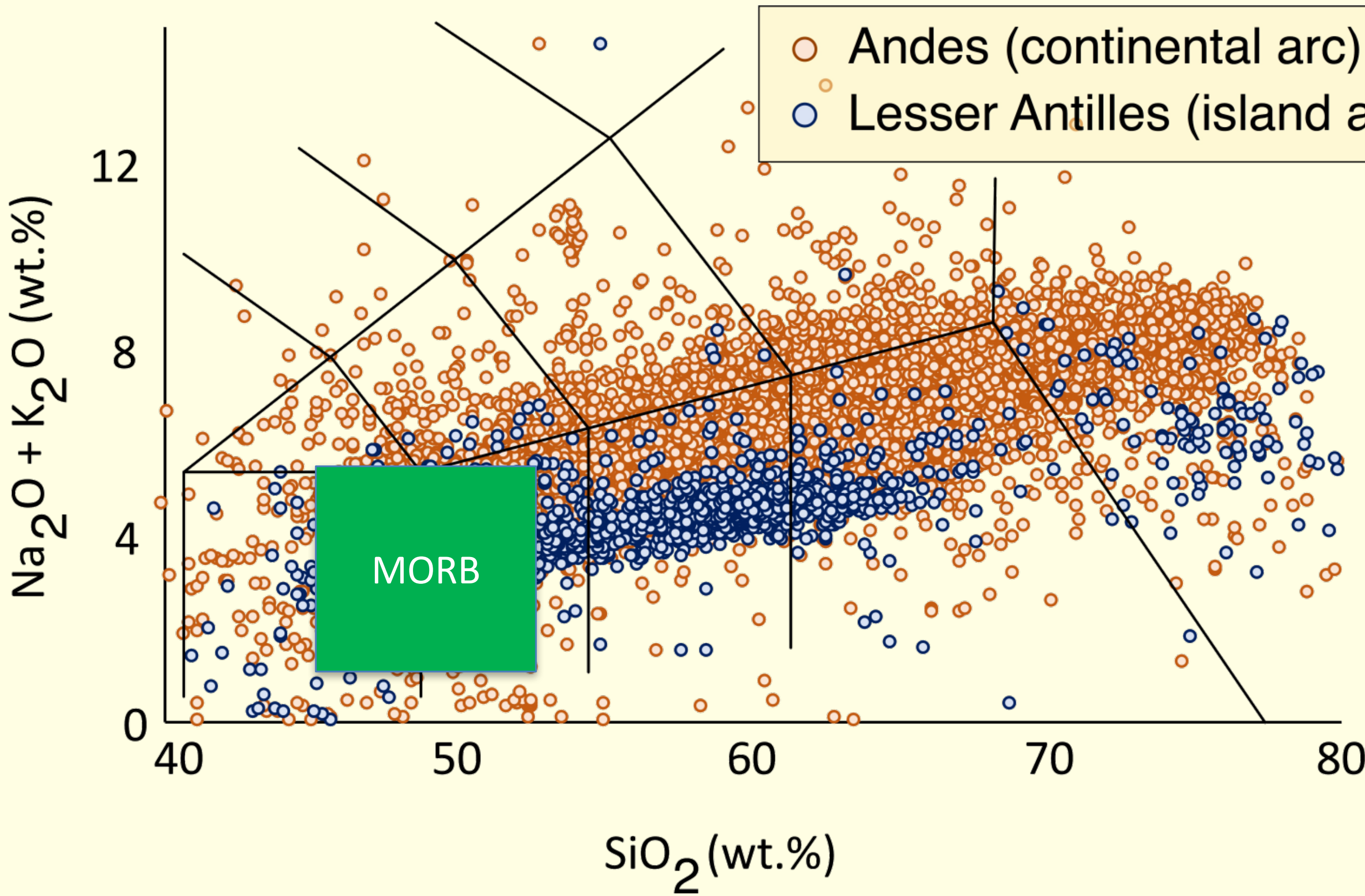
ITS

QUIZ TIME

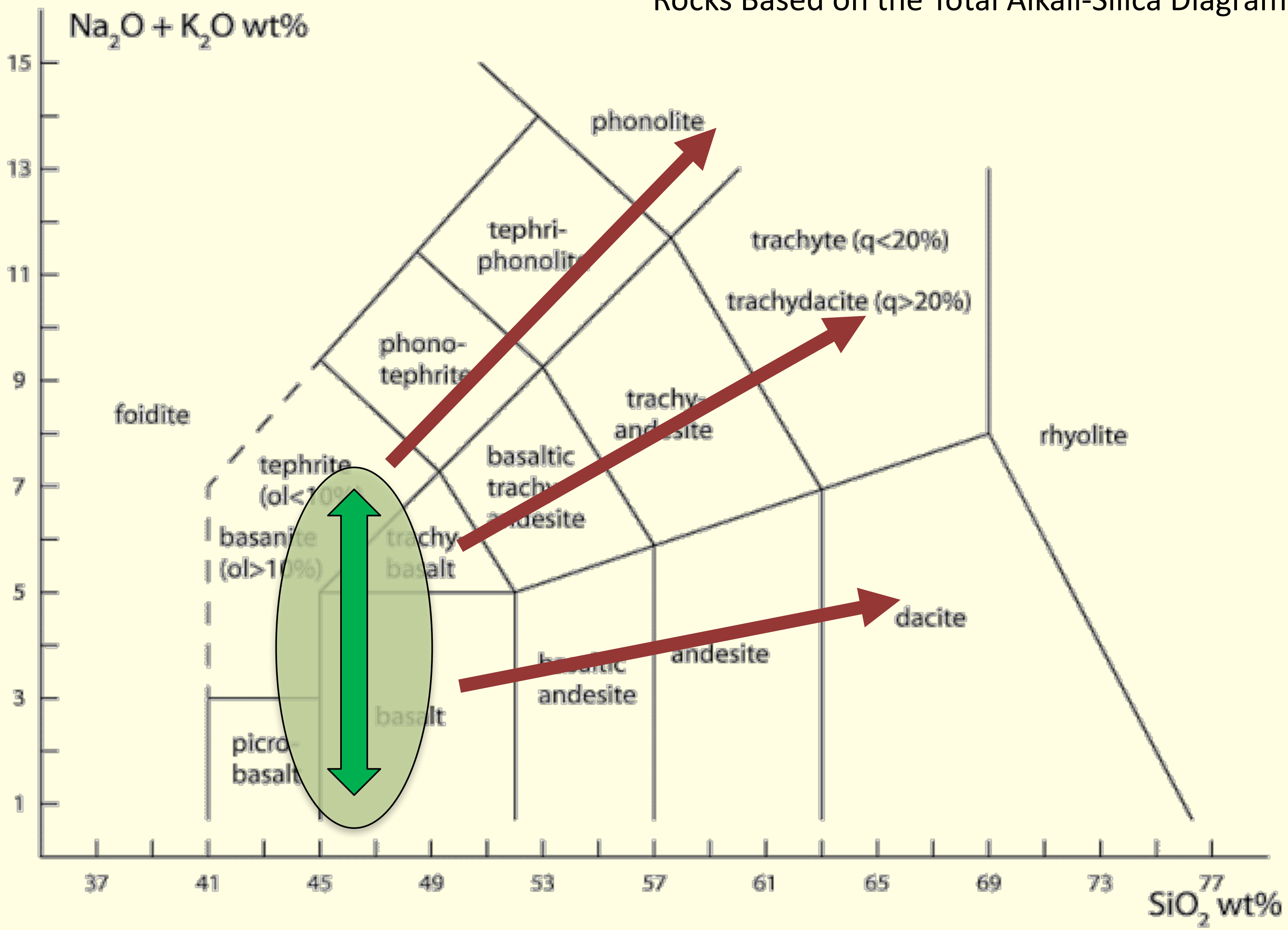
What most defines subduction zone magmatism?

1. Mafic (primitive) magmas
2. Intermediate magmas (andesites)
3. Evolved magmas (dacites, rhyolites)

Global Characteristics of Arc Volcanics



Le Bas et al. 1986 A Chemical Classification of Volcanic Rocks Based on the Total Alkali-Silica Diagram

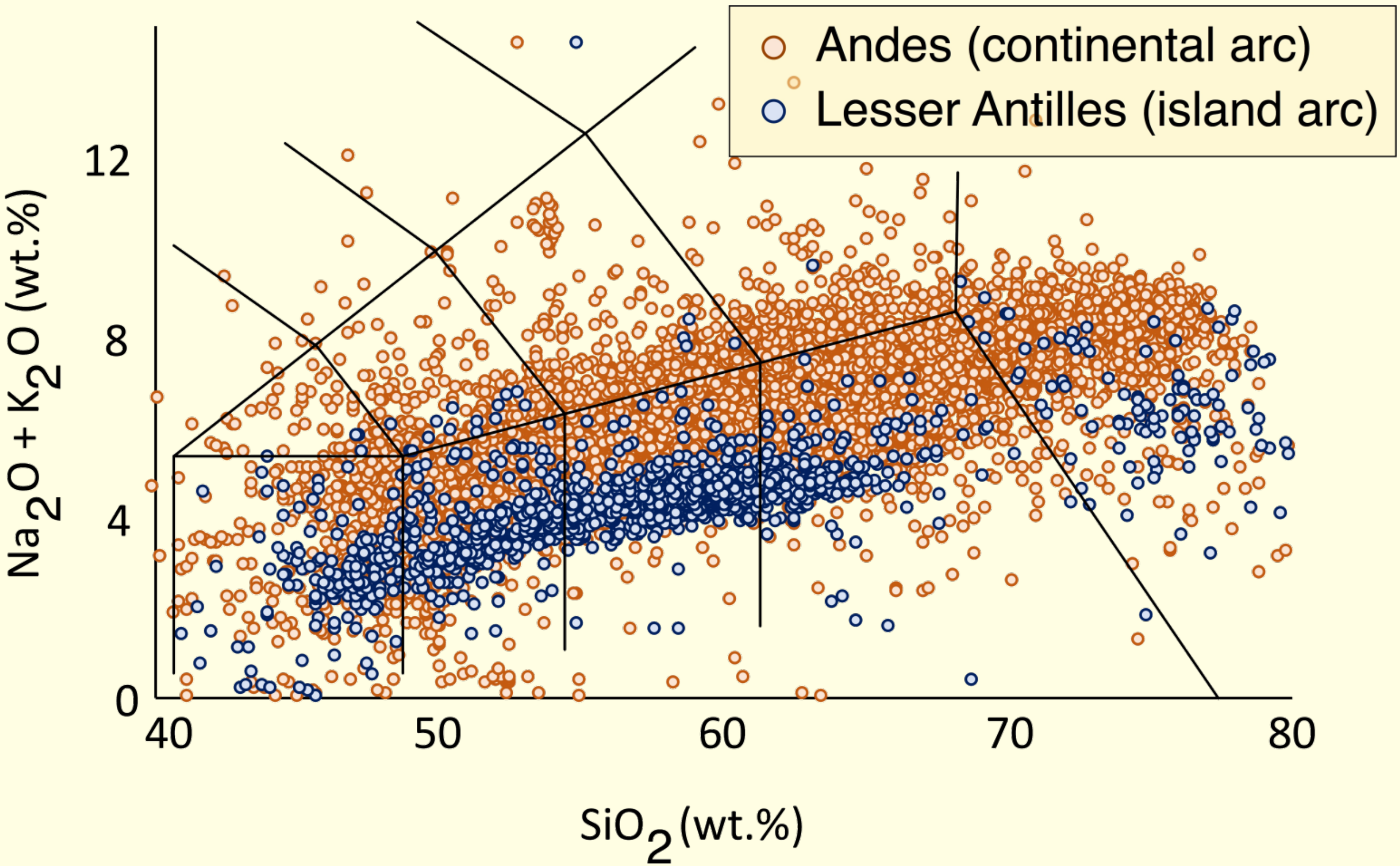


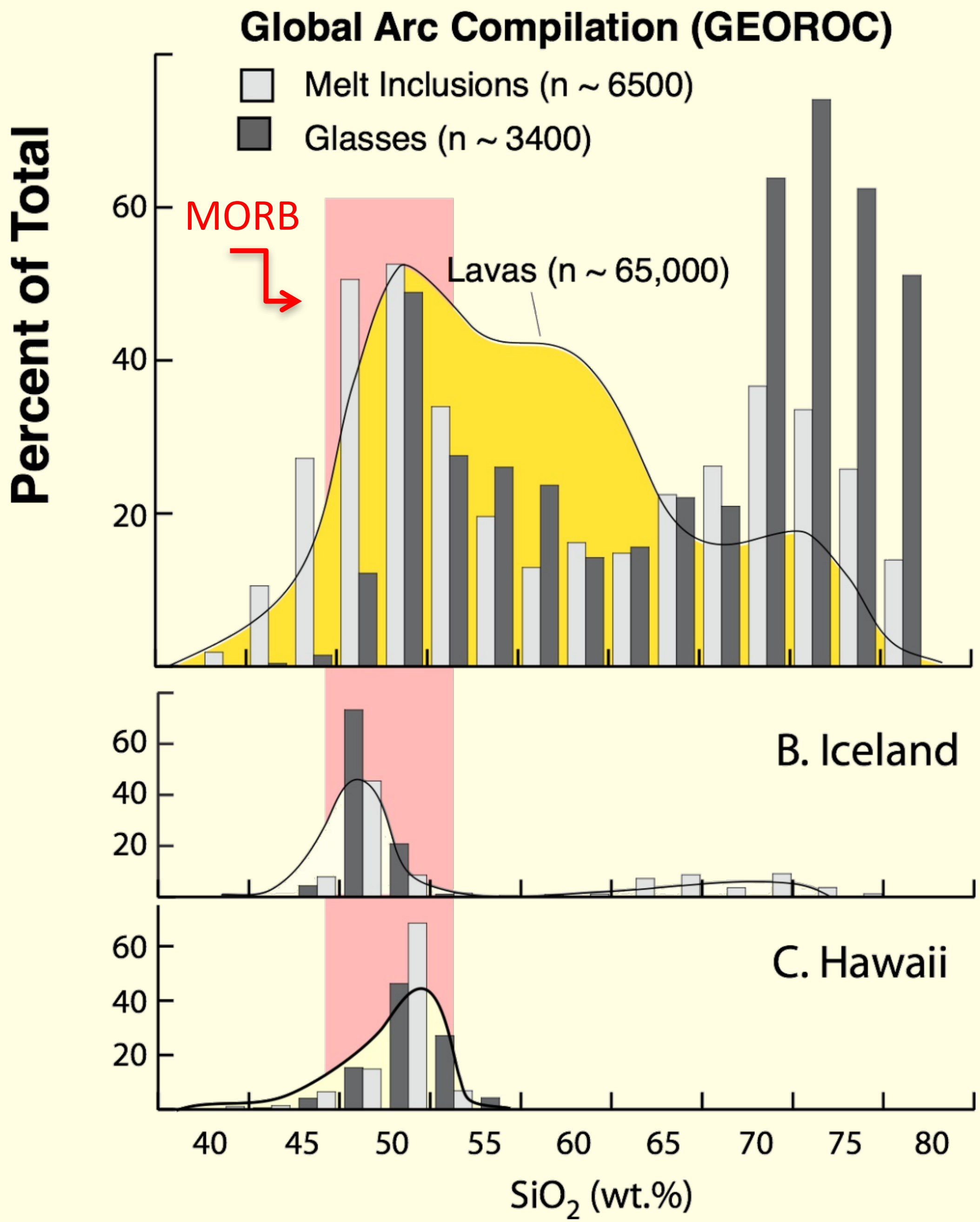
Mafic (Basic)
Primitive

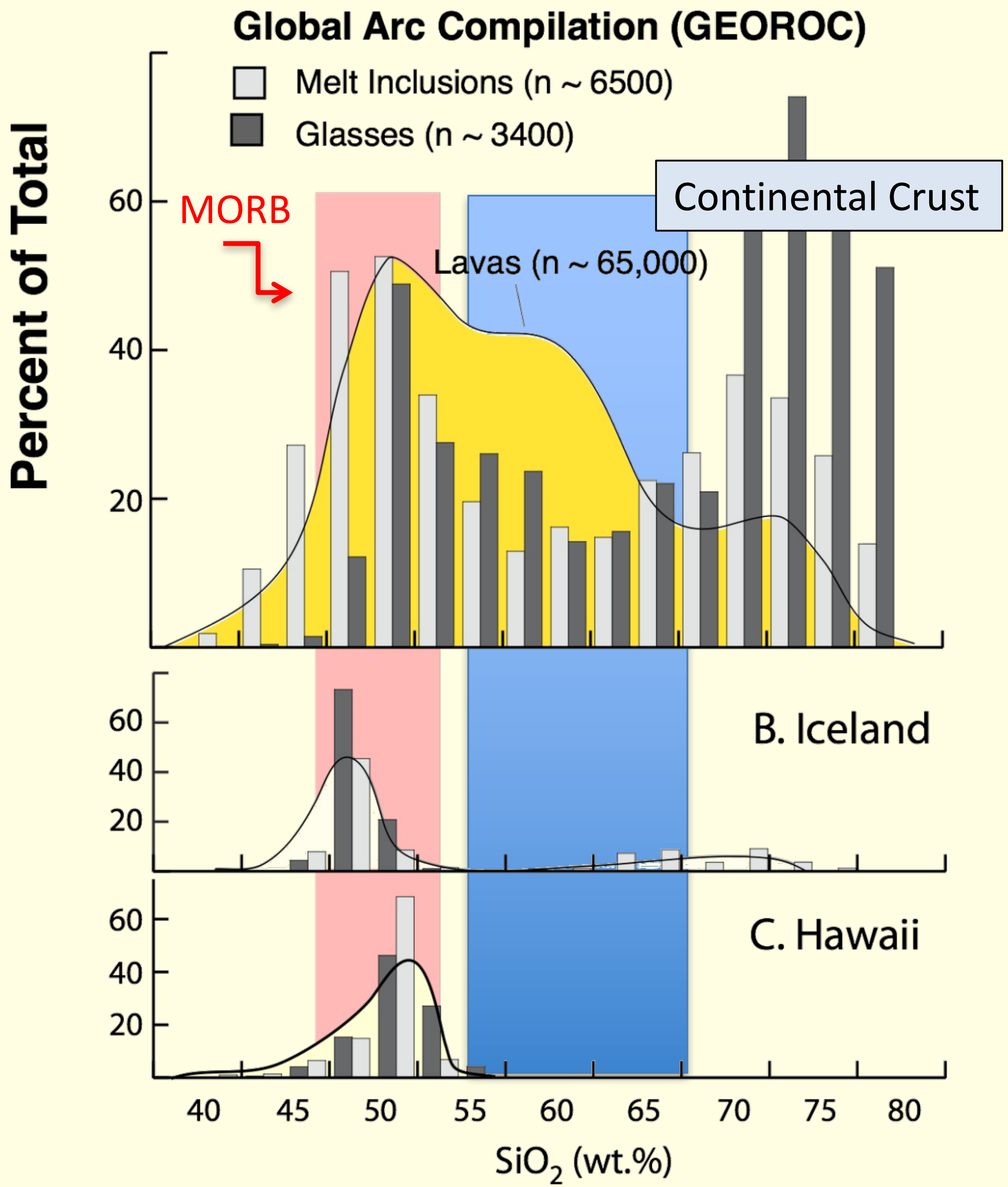
Intermediate

Felsic (Acid)
Evolved

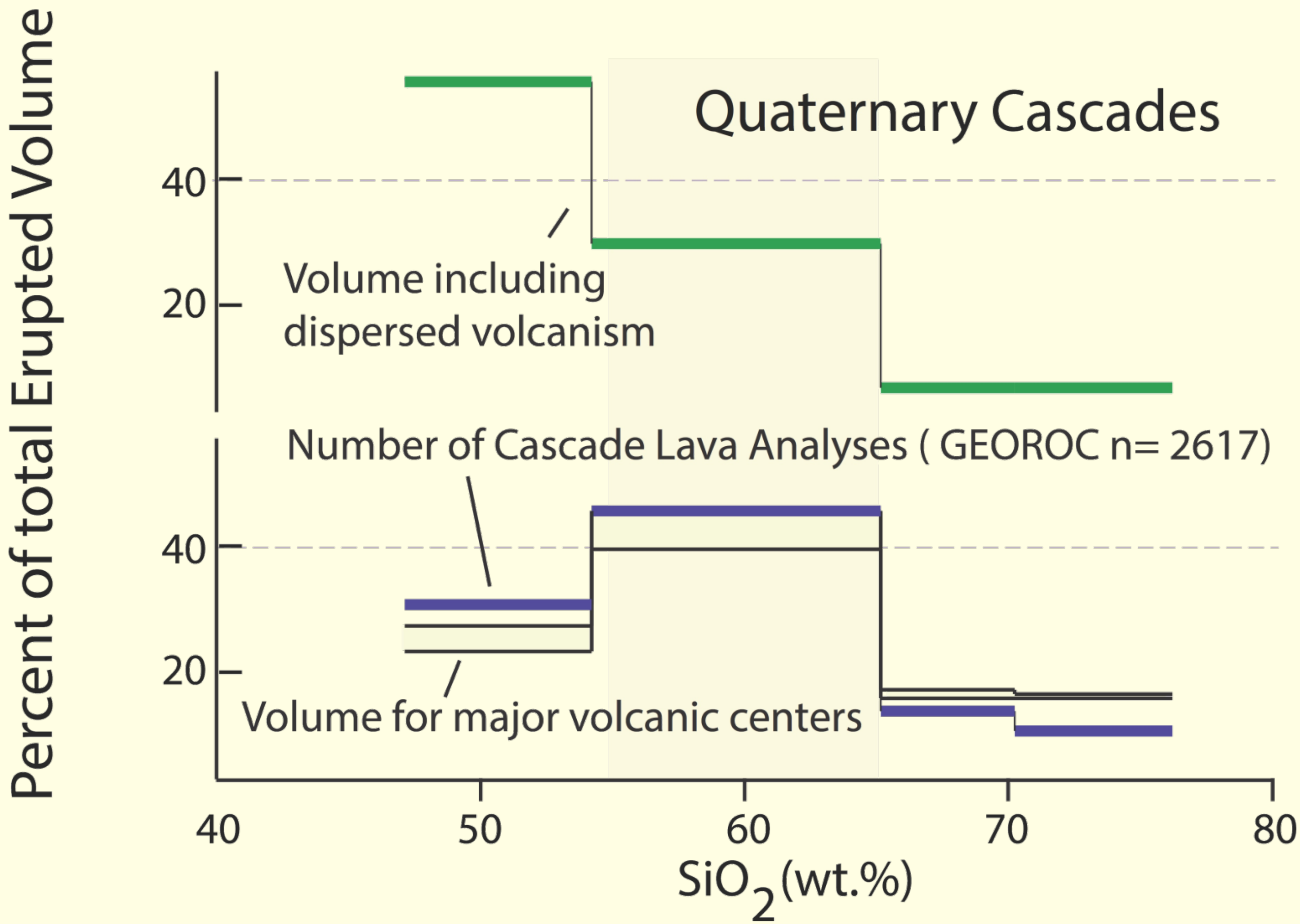
Global Characteristics of Arc Volcanics




Global Arc Compilation (GEOROC)
Melt Inclusions (n ~ 6500)
Glasses (n ~ 3400)
Lavas (n ~ 65,000)
MORB
Percent of Total
60
40
20
B. Iceland
C. Hawaii
40
45
50
55
60
65
70
75
80
SiO2 (wt.%)

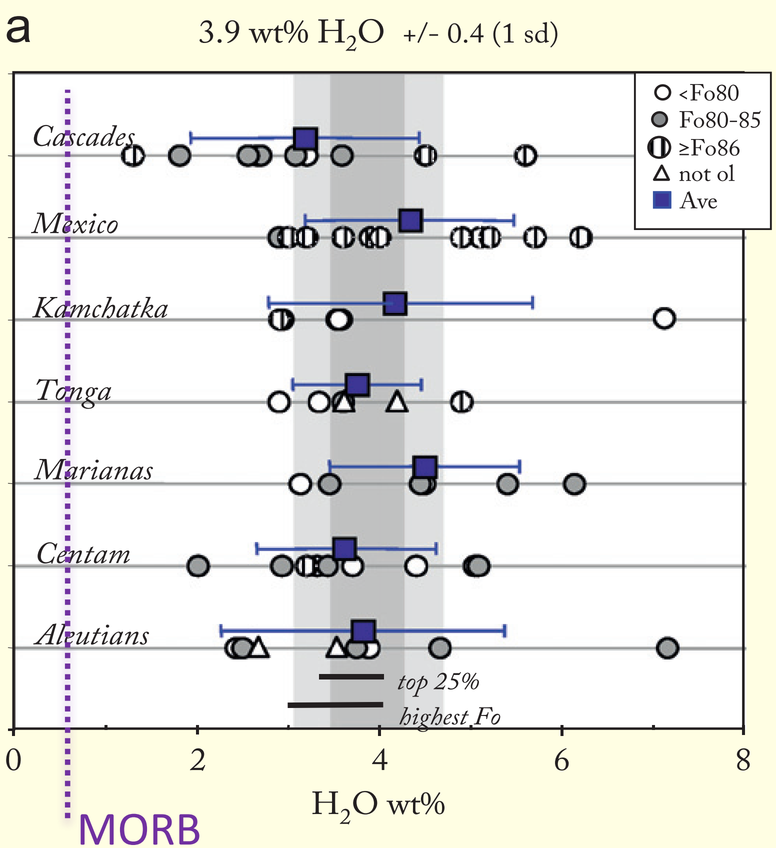


Global Arc Compilation (GEOROC)
Melt Inclusions (n ~ 6500)
Glasses (n ~ 3400)
Continental Crust
MORB
Lavas (n ~ 65,000)
Percent of Total
60
40
20
B. Iceland
60
40
20
C. Hawaii
60
40
20
40
45
50
55
60
65
70
75
80
SiO2 (wt.%)



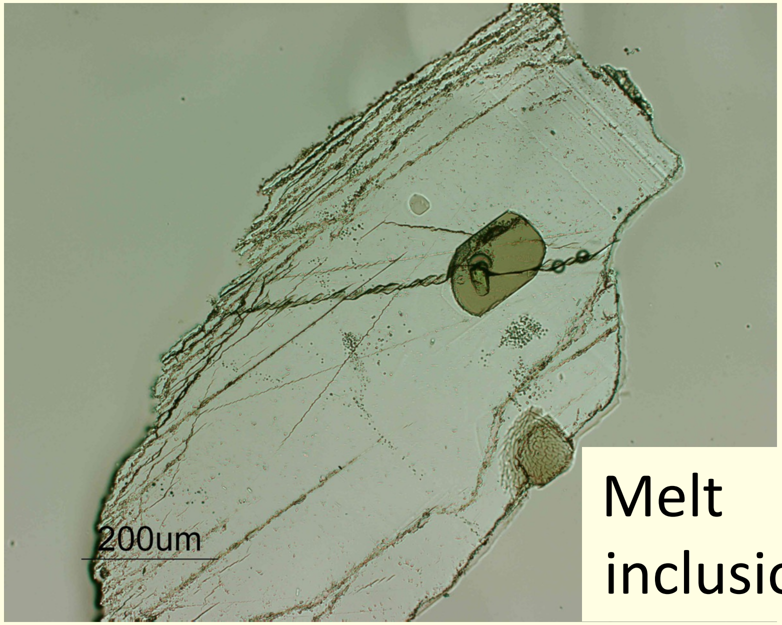
Kent, 2013; after Hildreth, 2008

Arcs: Water-rich magmas

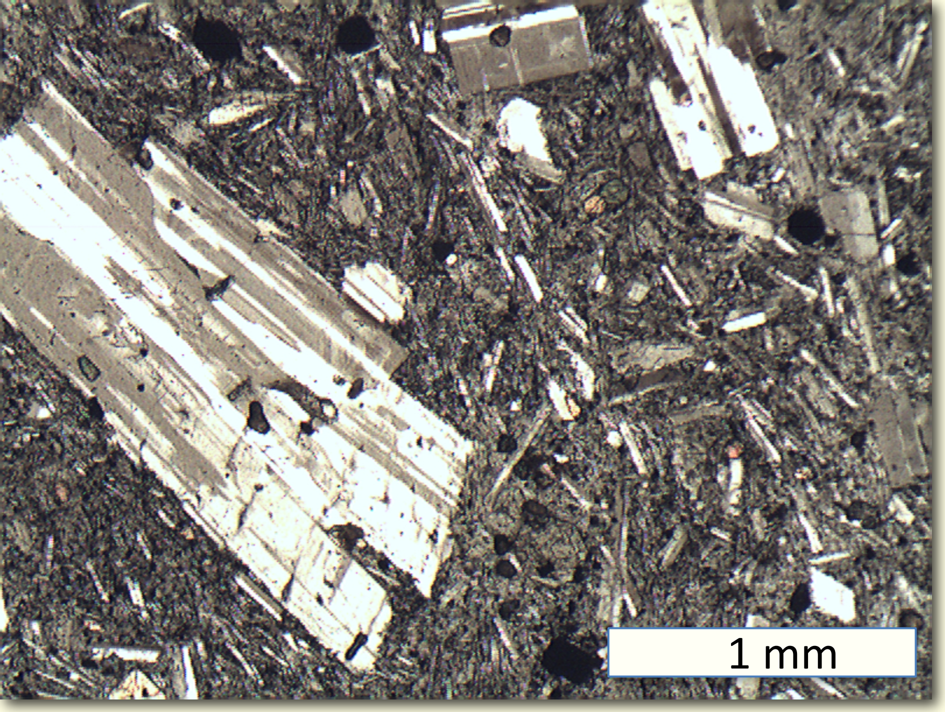


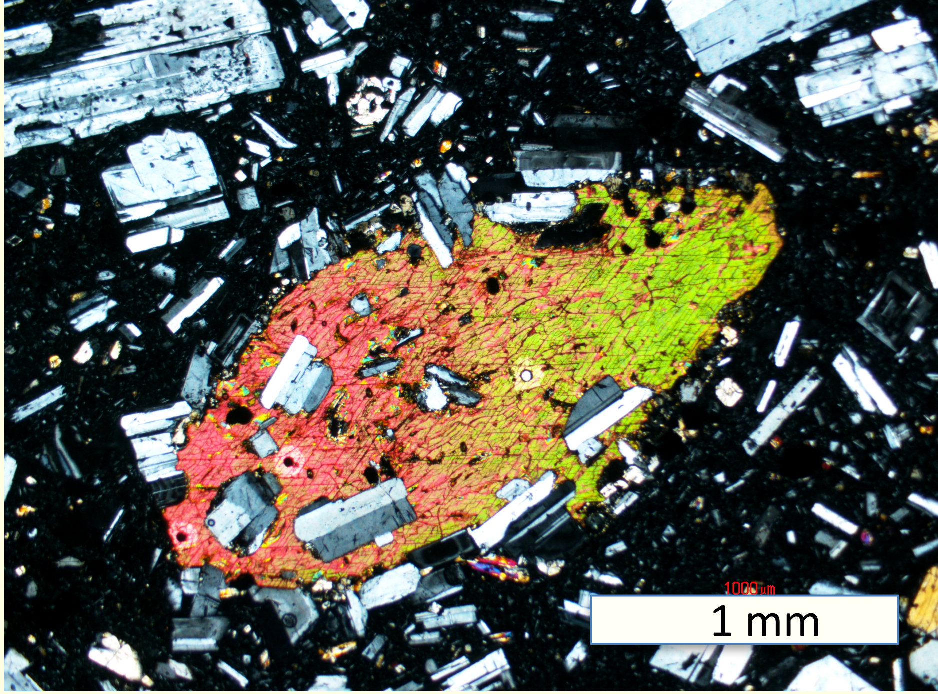
Water in melt inclusions
Plank et al. 2013

Mount Pinatubo, 1991



Melt inclusions

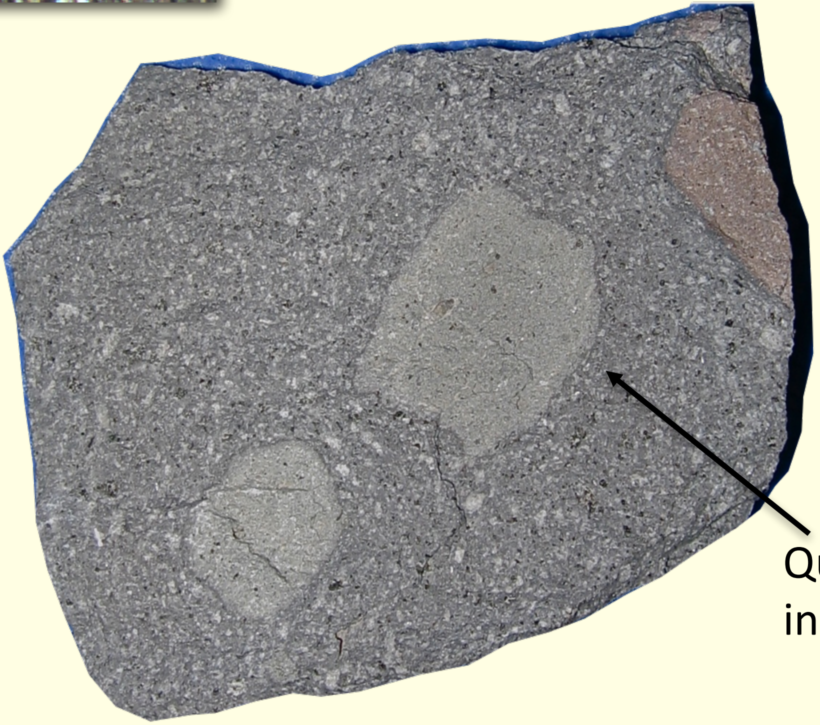




Amphibole, Mount Hood
Kent et al. 2010

Andesites (intermediate magmas)

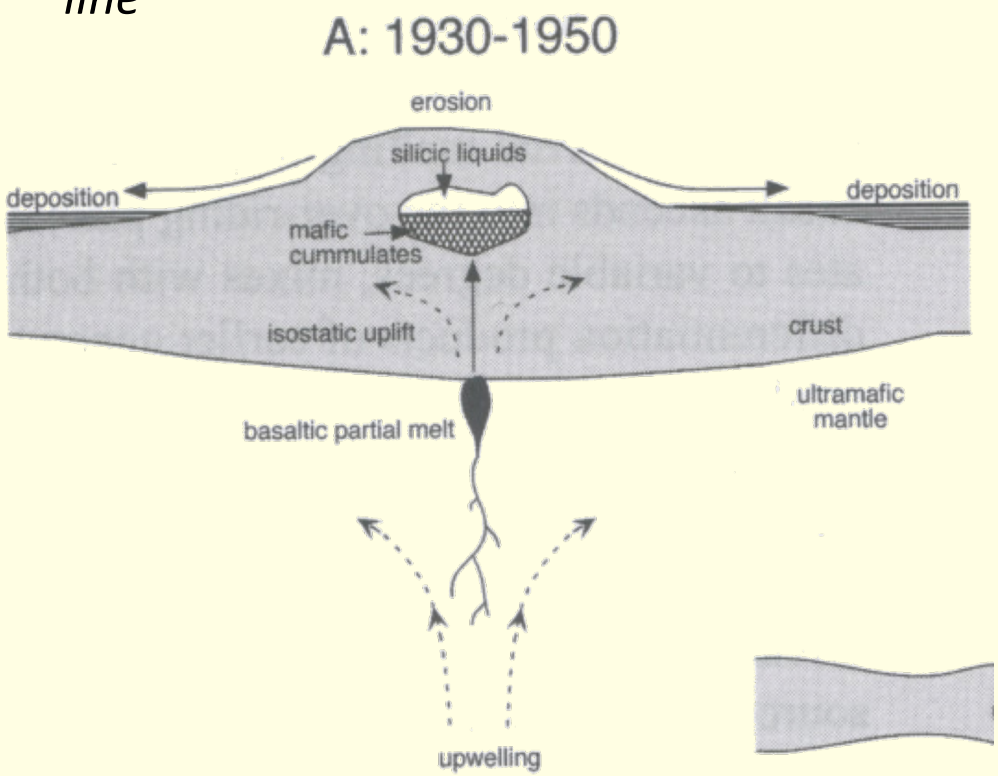
Intermediate (~55-65 wt.% SiO_2)
Plagioclase ± Fe Mg mineral (olivine, pyroxene, hornblende) + oxides ± quartz ± zircon etc.



Quenched mafic inclusions

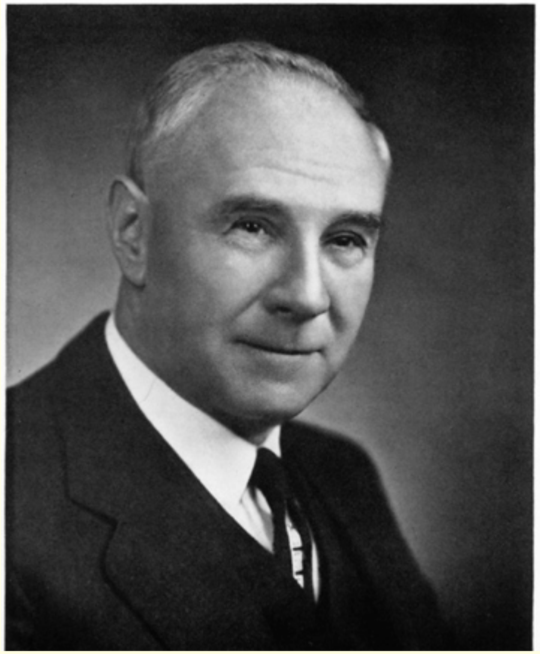
History of Ideas: The Andesite Line

In the early 20th century it was recognized that andesitic rocks (intermediate) occurred in circum-pacific region at the margins of continents – the *Andesite line*



Eiler, 2003

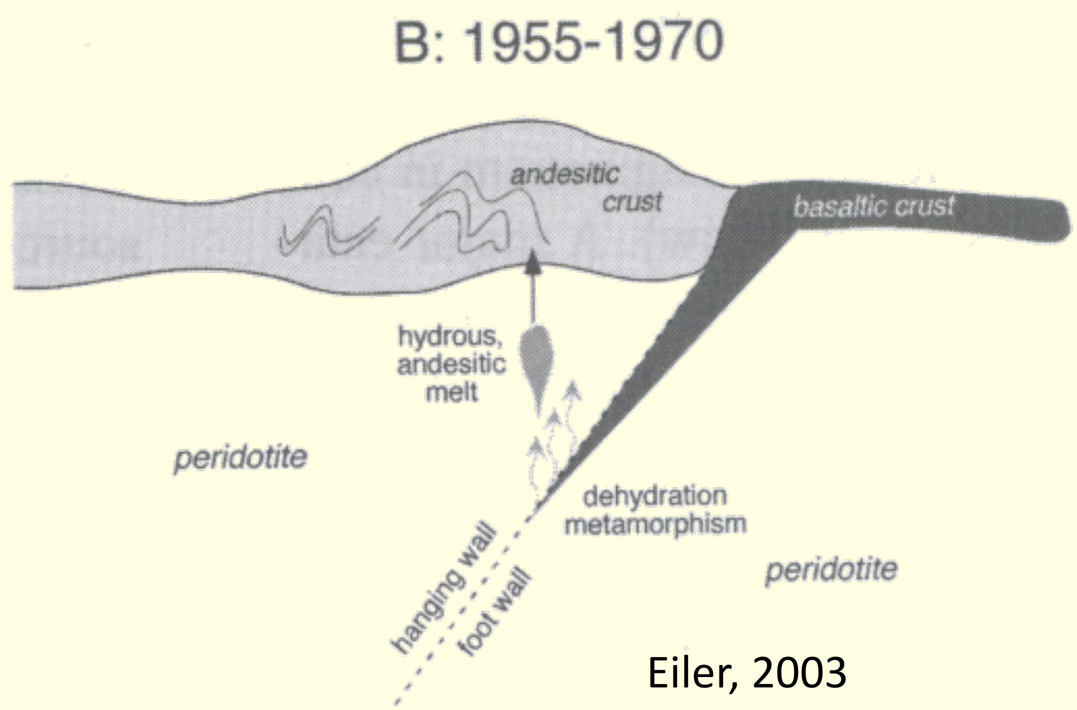
Bowen (1928) showed andesite could be produced by differentiation from basaltic parent



Norman L Bowen

History of Ideas: The Andesite Line

- 1950's: Links recognized between seismicity (Wadati-Benioff), continental margins and the "andesite line".
- Growing evidence that mafic magma produced by melting peridotite AND that H_2O lowers the peridotite melting point

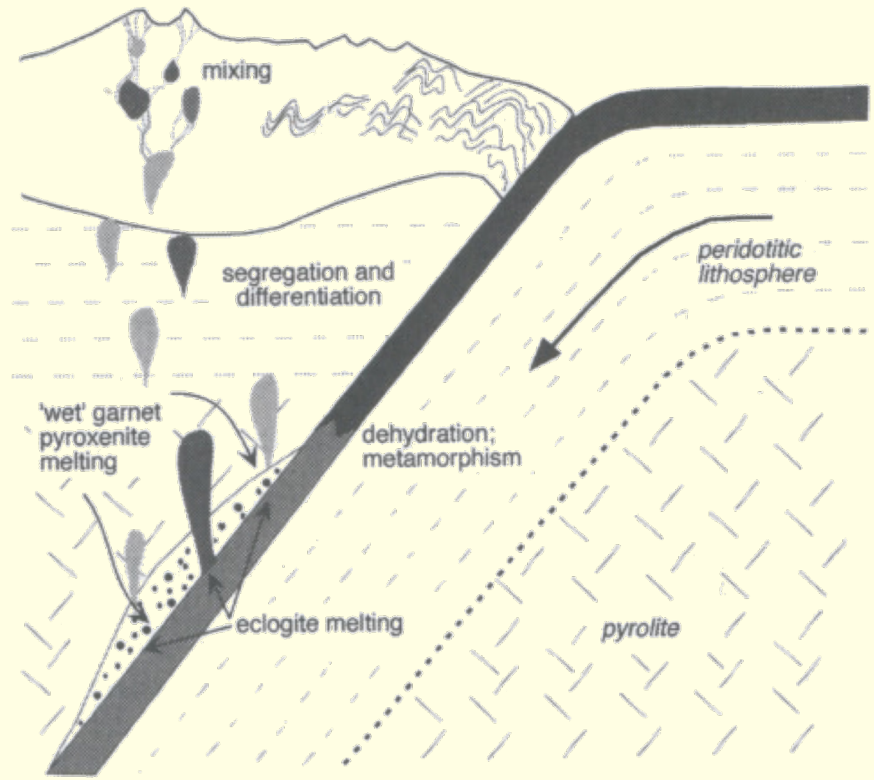


Eiler, 2003

History of Ideas: The Andesite Line

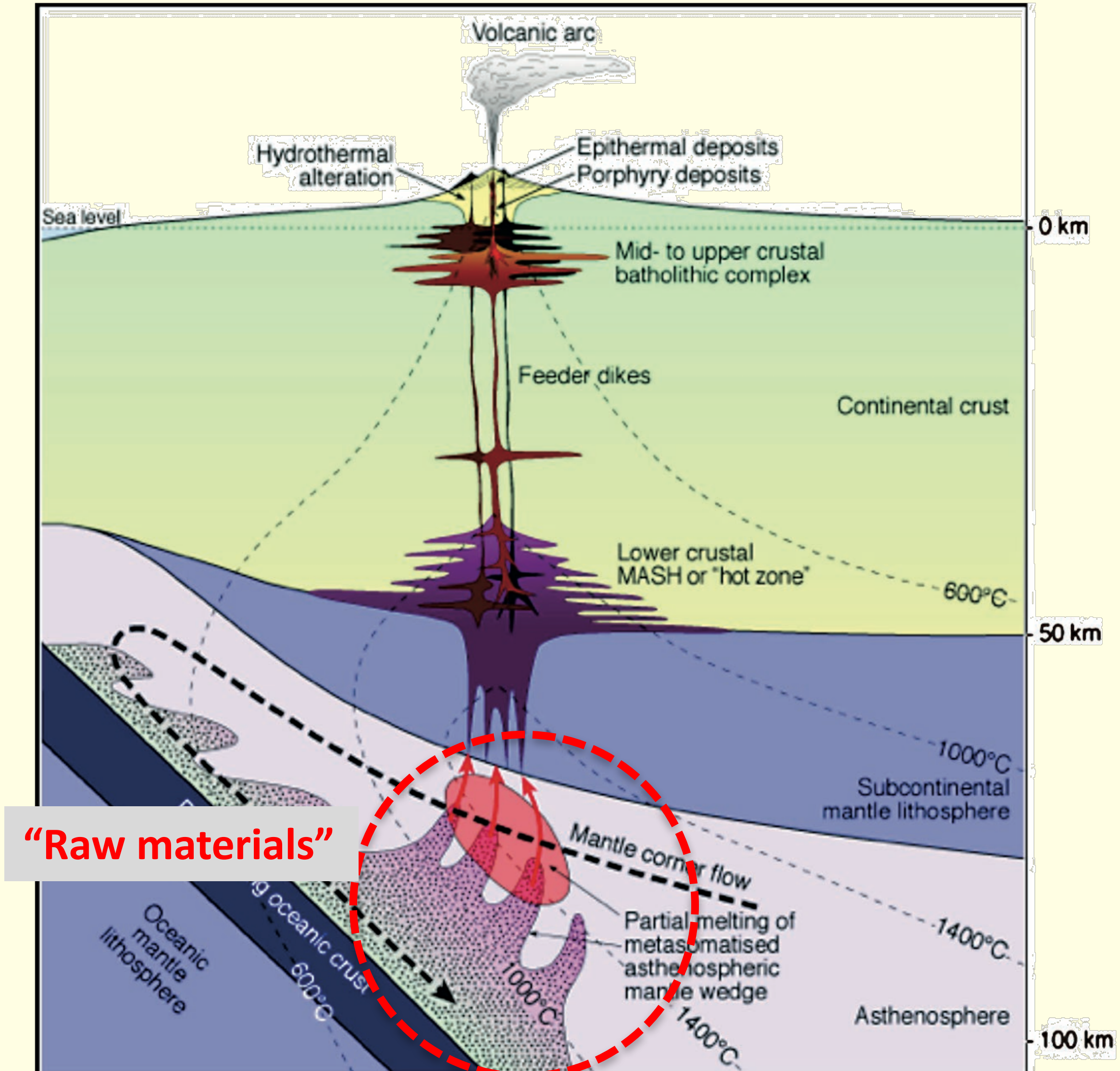
AE Ringwood 1930-1993

C: 1975



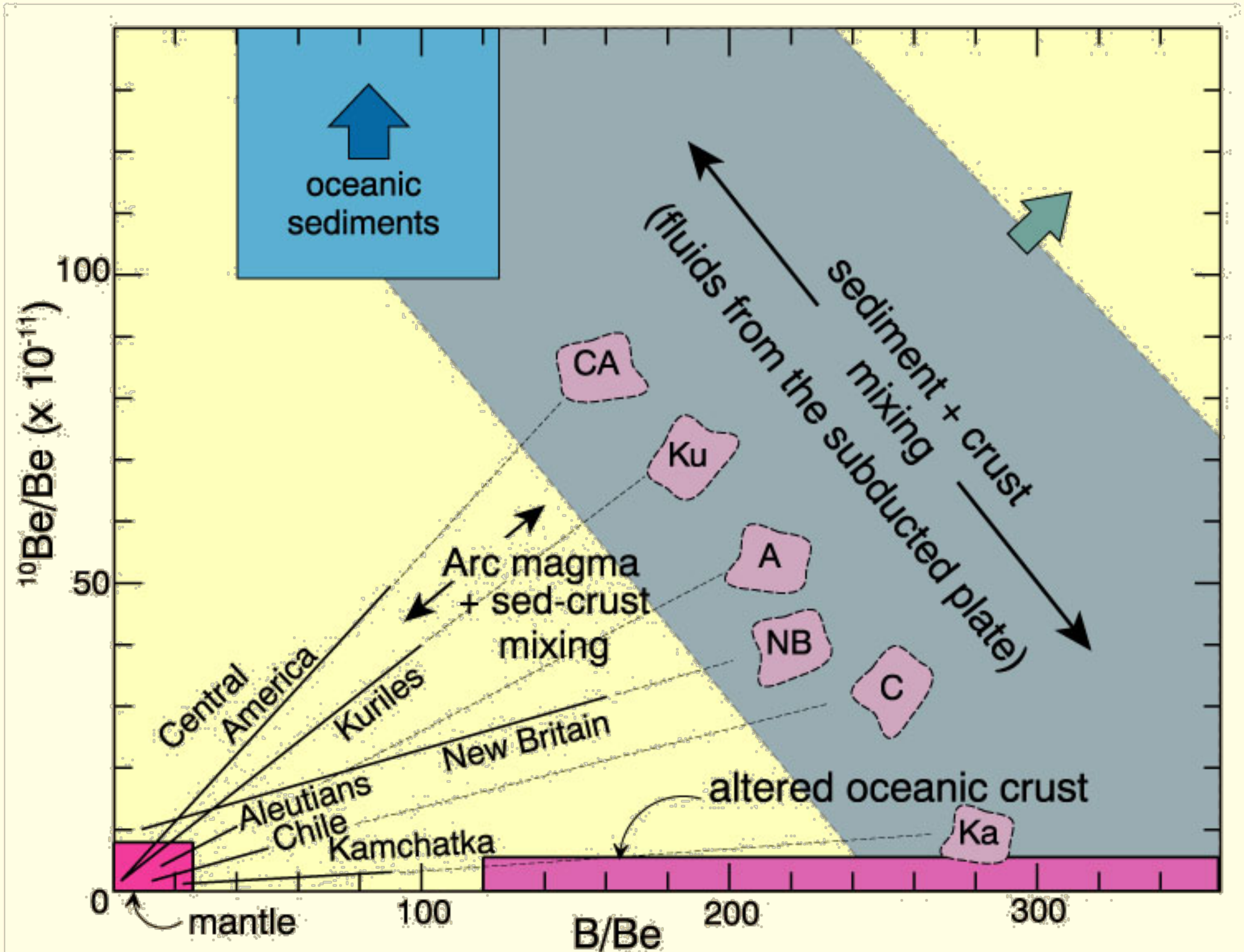
(After Ringwood, 1975)

Ringwood (and others): Melting within the slab produces andesite, subsequent differentiation and mixing produces array of arc magmas



Richards, 2011

The Mantle

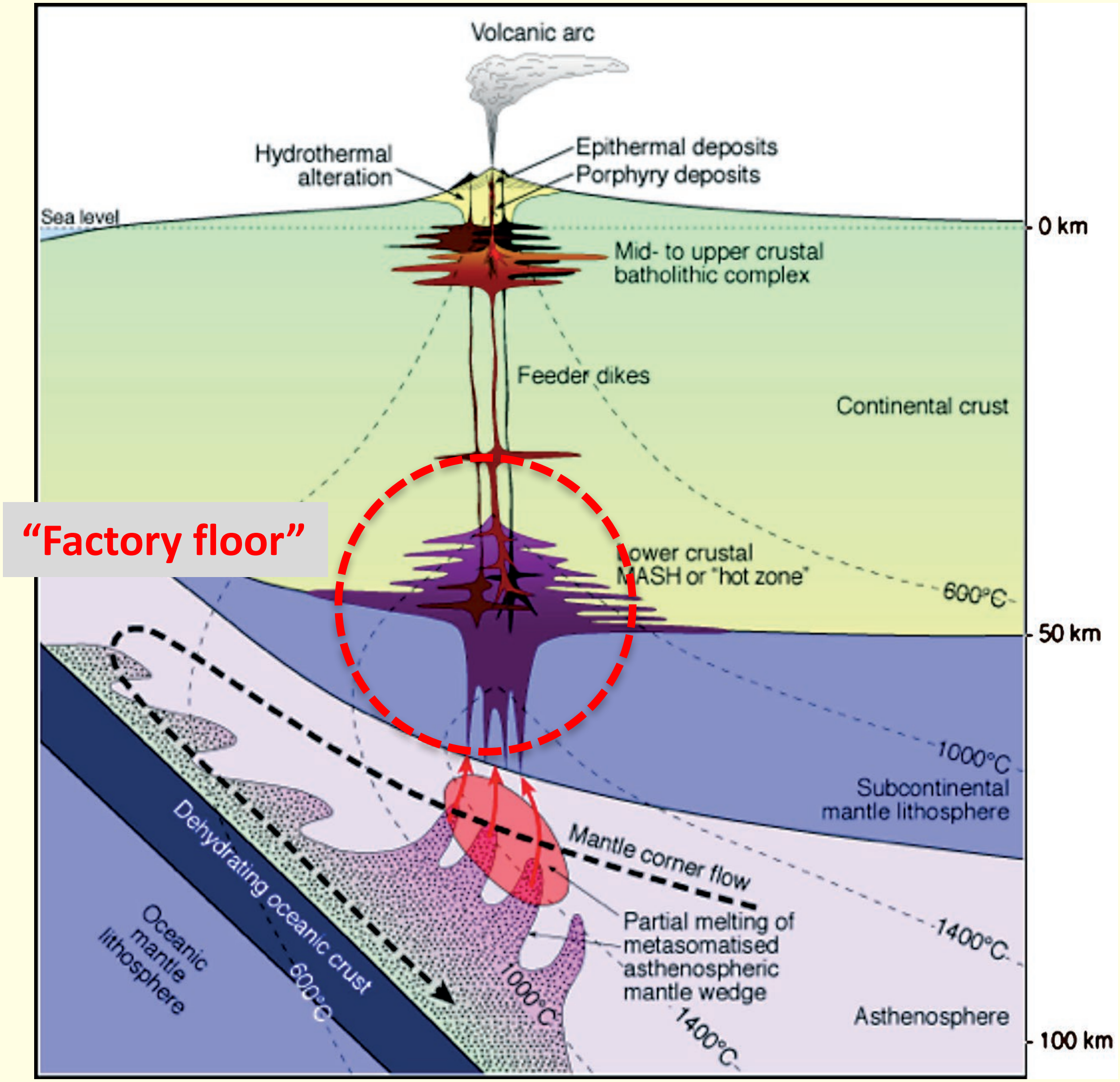


Morris and Tera, 1989 (Figure from Winter, 2001)

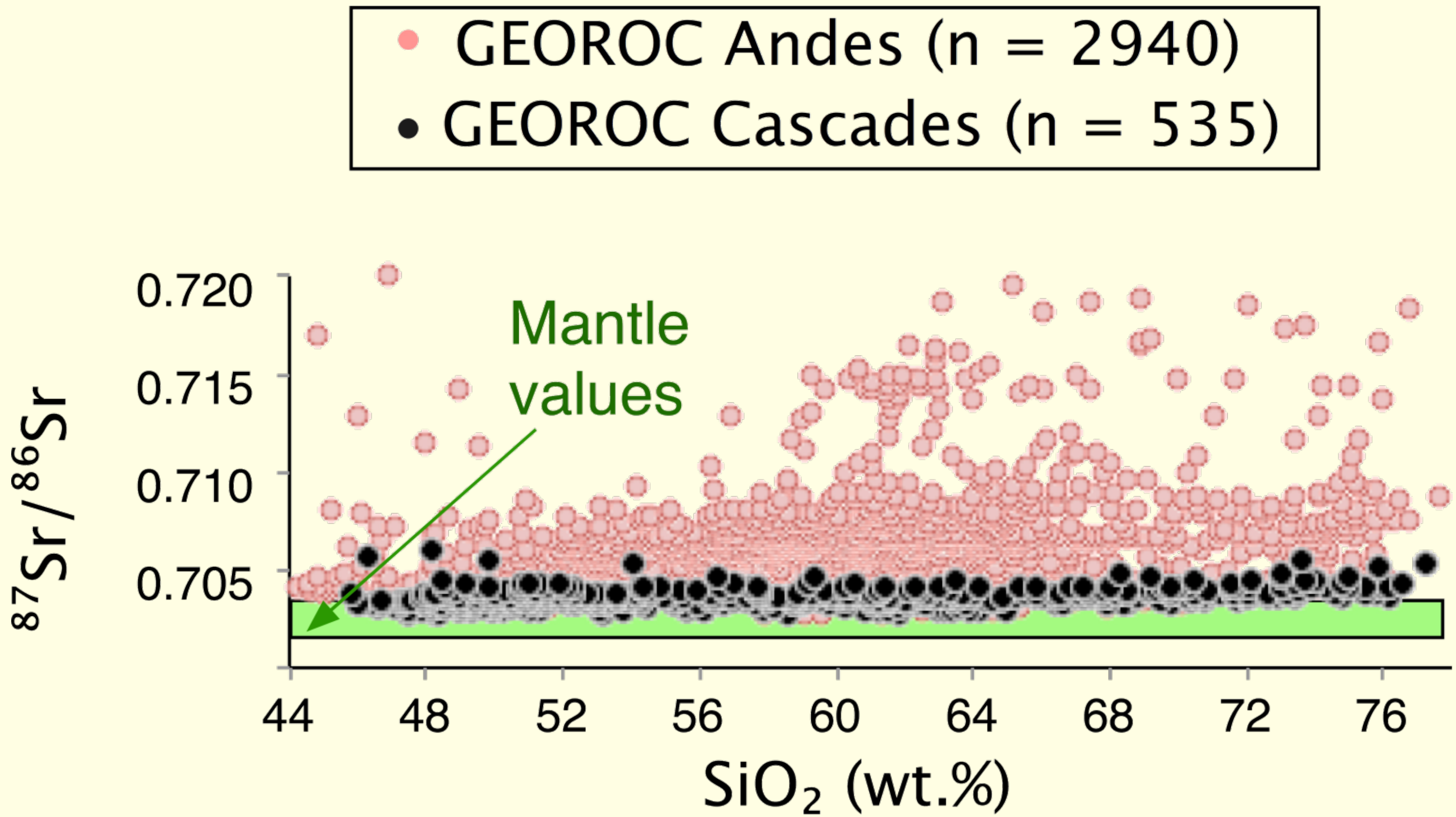
^{10}Be and ^{9}Be in mineral separates and whole rocks from volcanic arcs: Implications for sediment subduction

Where do we produce most intermediate and evolved magmas?

1. Upper crust
2. Lower crust
3. Mantle



Richards, 2011



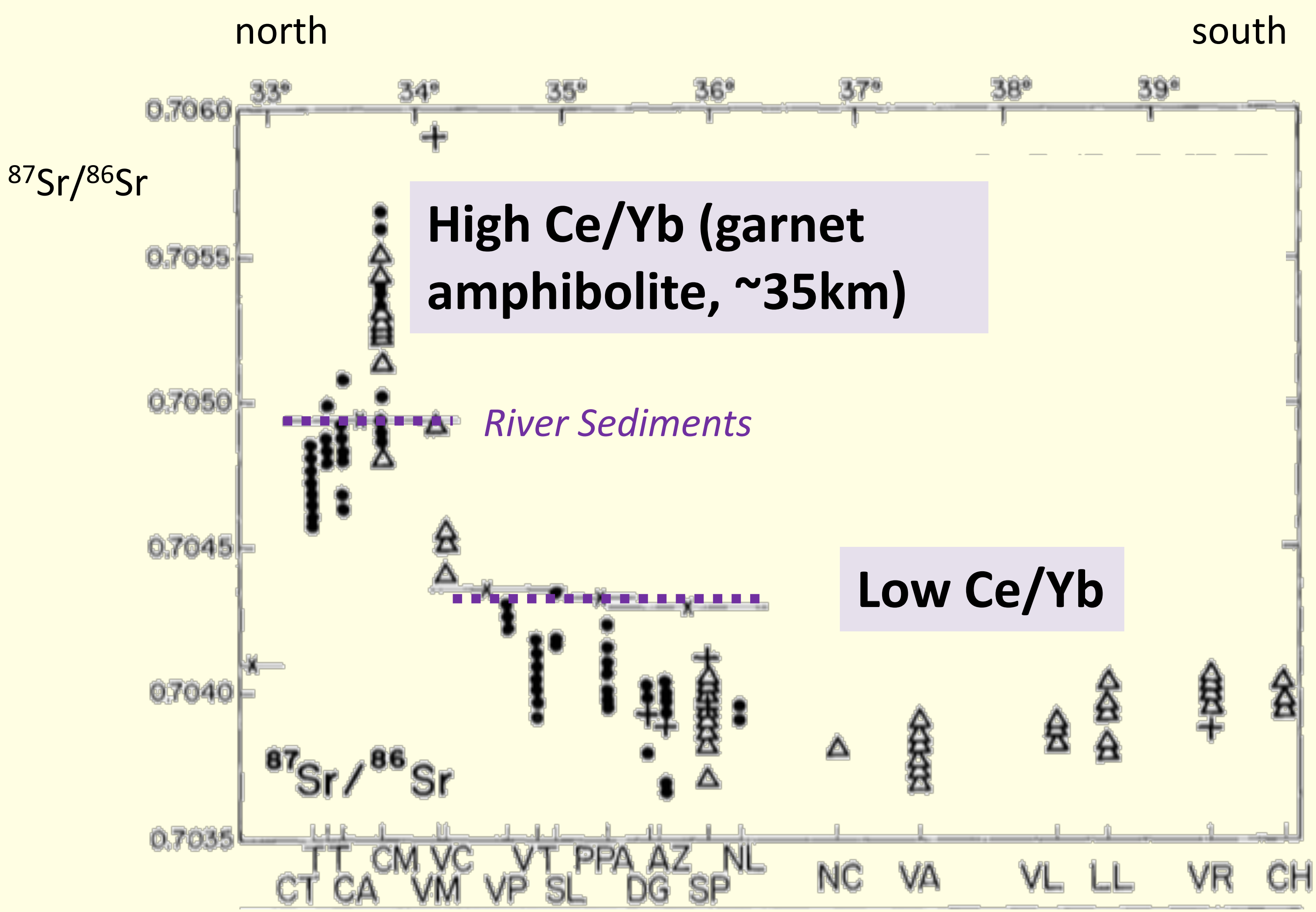
$^{87}Rb \rightarrow {}^{87}Sr$ ($T_{1/2}$ = 49 Ga), high $^{87}Sr/^{86}Sr$ = high Rb/Sr through time. Continental crust has high Rb/Sr

Contrib Mineral Petrol (1988) 98:455–489

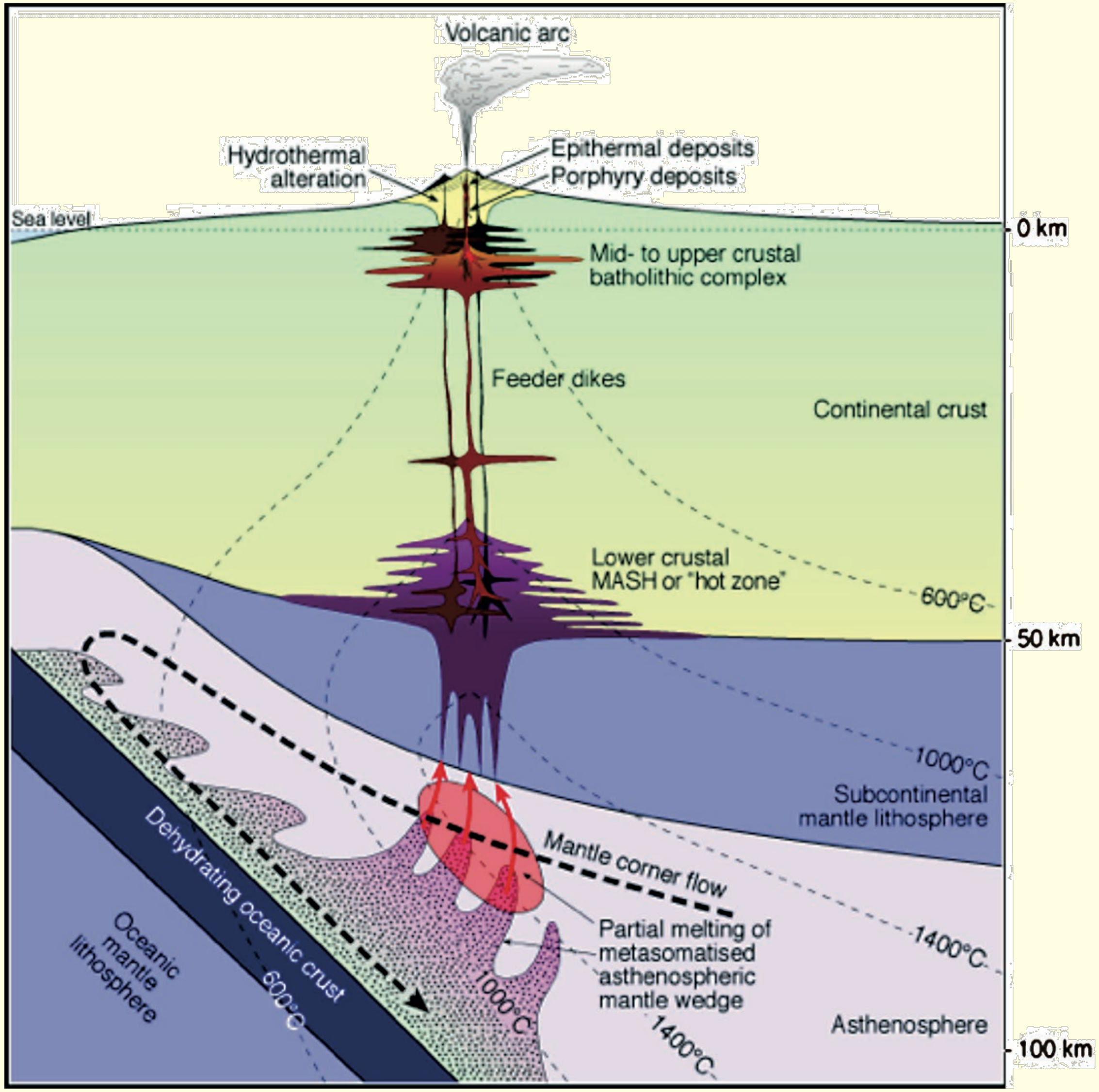
Contributions to Mineralogy and Petrology

Crustal contributions to arc magmatism in the Andes of Central Chile

Wes Hildreth[1] and Stephen Moorbath[2]
[1] USGS, Menlo Park, California 94025, USA
[2] Department of Earth Sciences, University of Oxford, OX1 3PR, UK

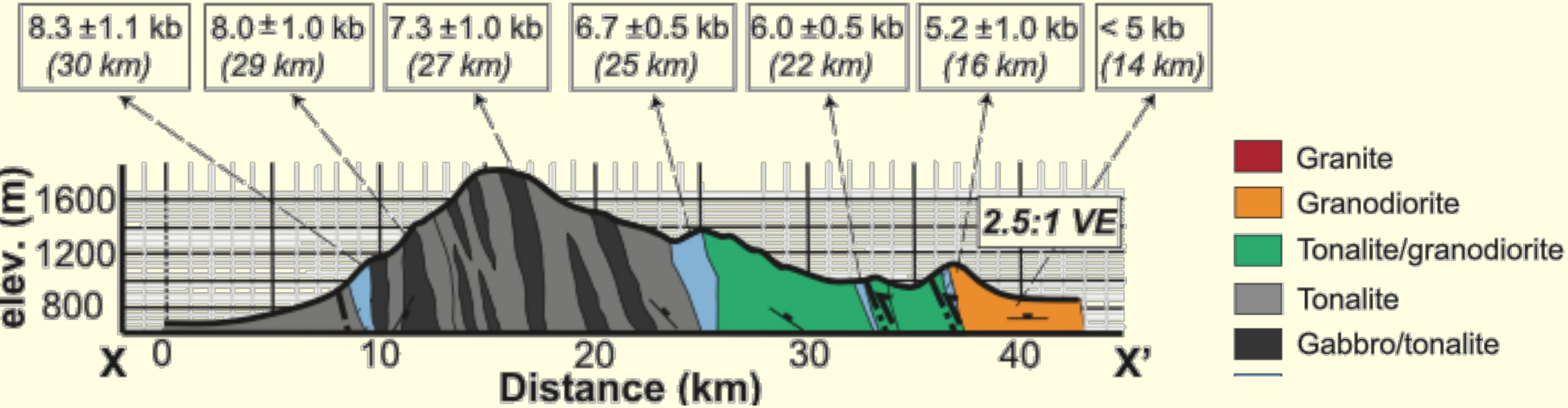


Hildreth and Moorbath, 1988

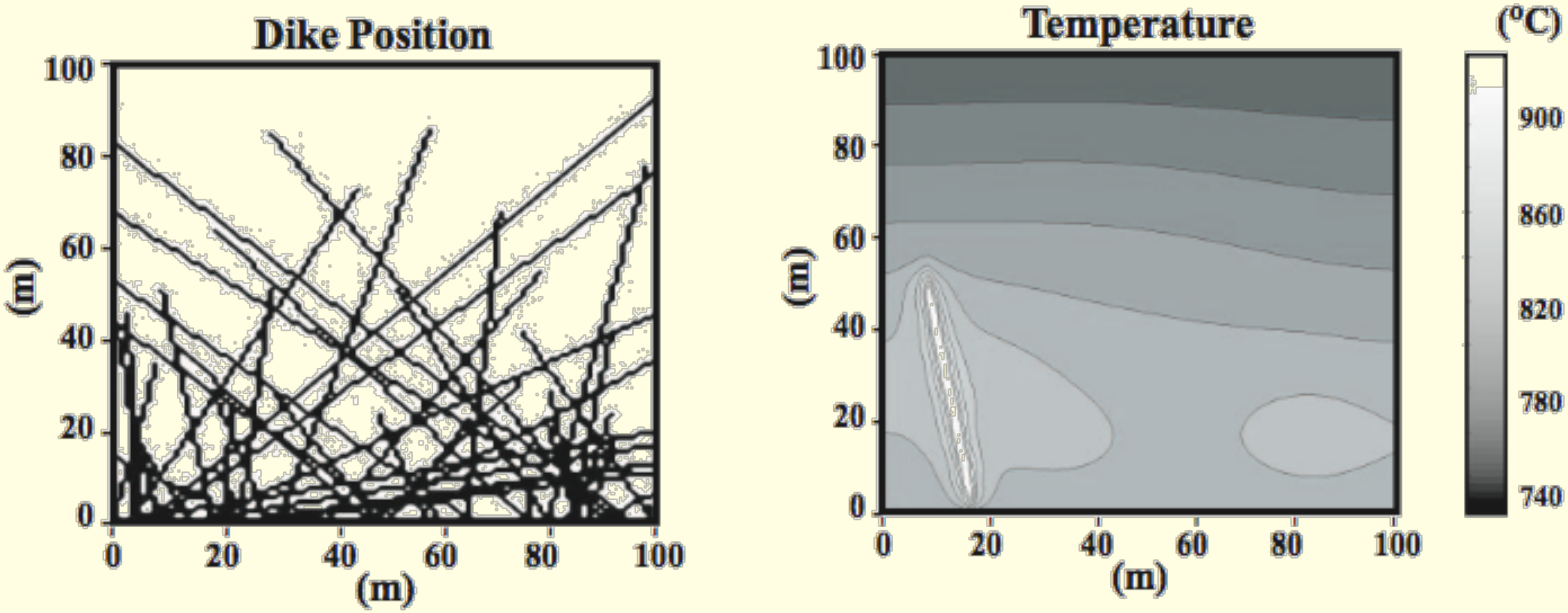


MASH* Zone, Hot Zone: Intrusion of dykes into lower crust

**mixing, assimilation, storage, hybridization*

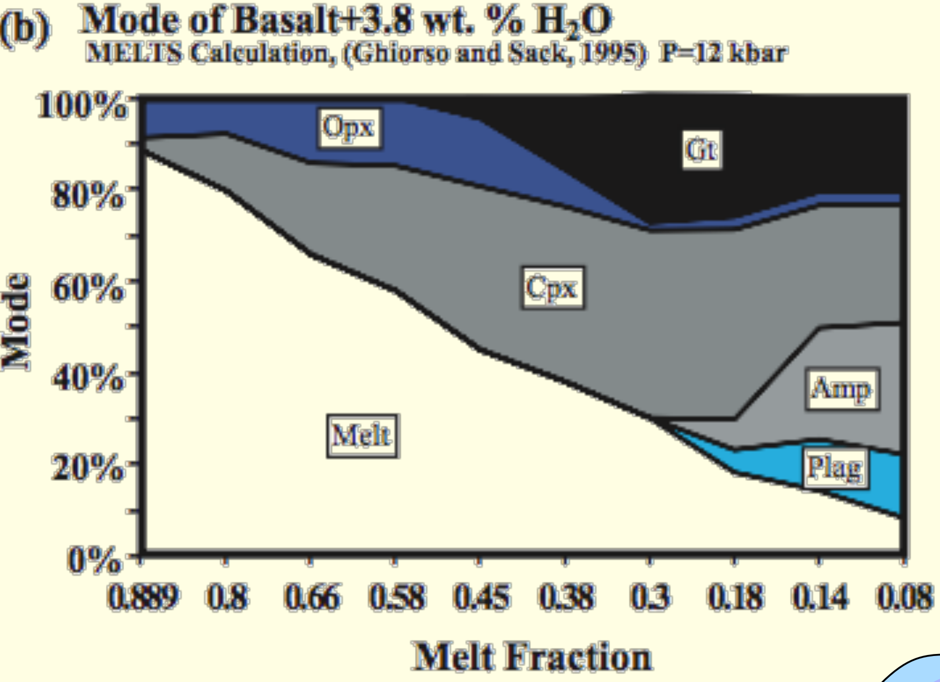


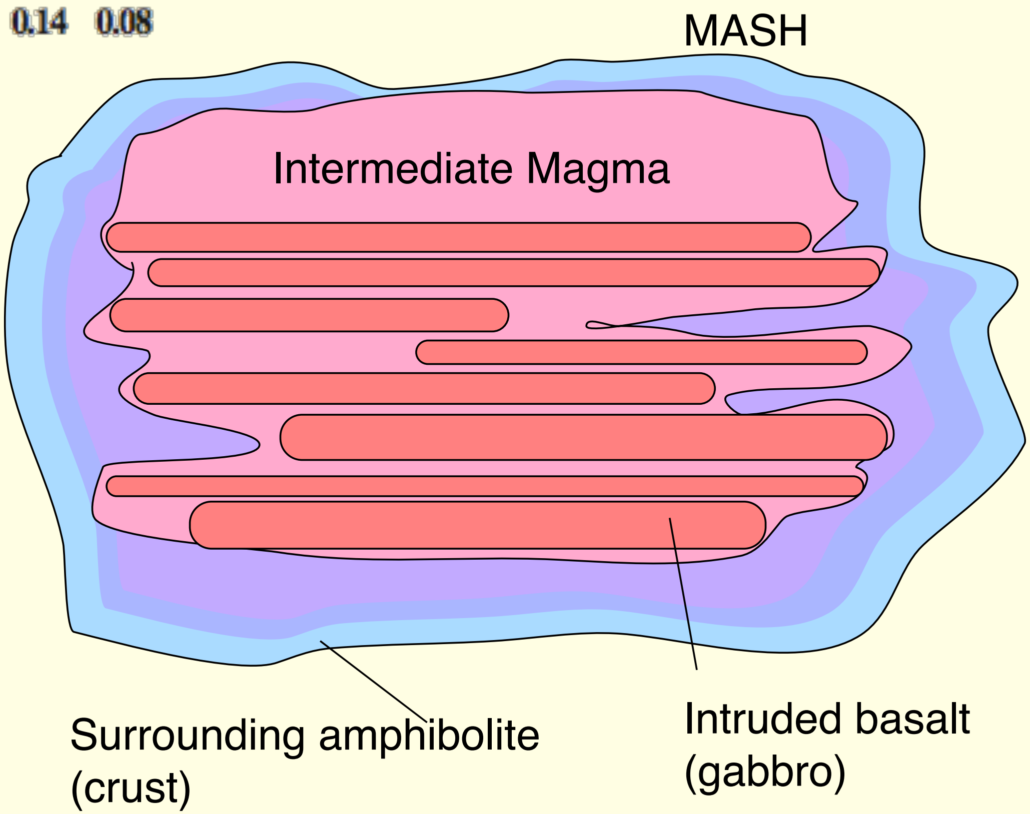
Walker et al., 2015, Sierra Valle Fértil, Argentina



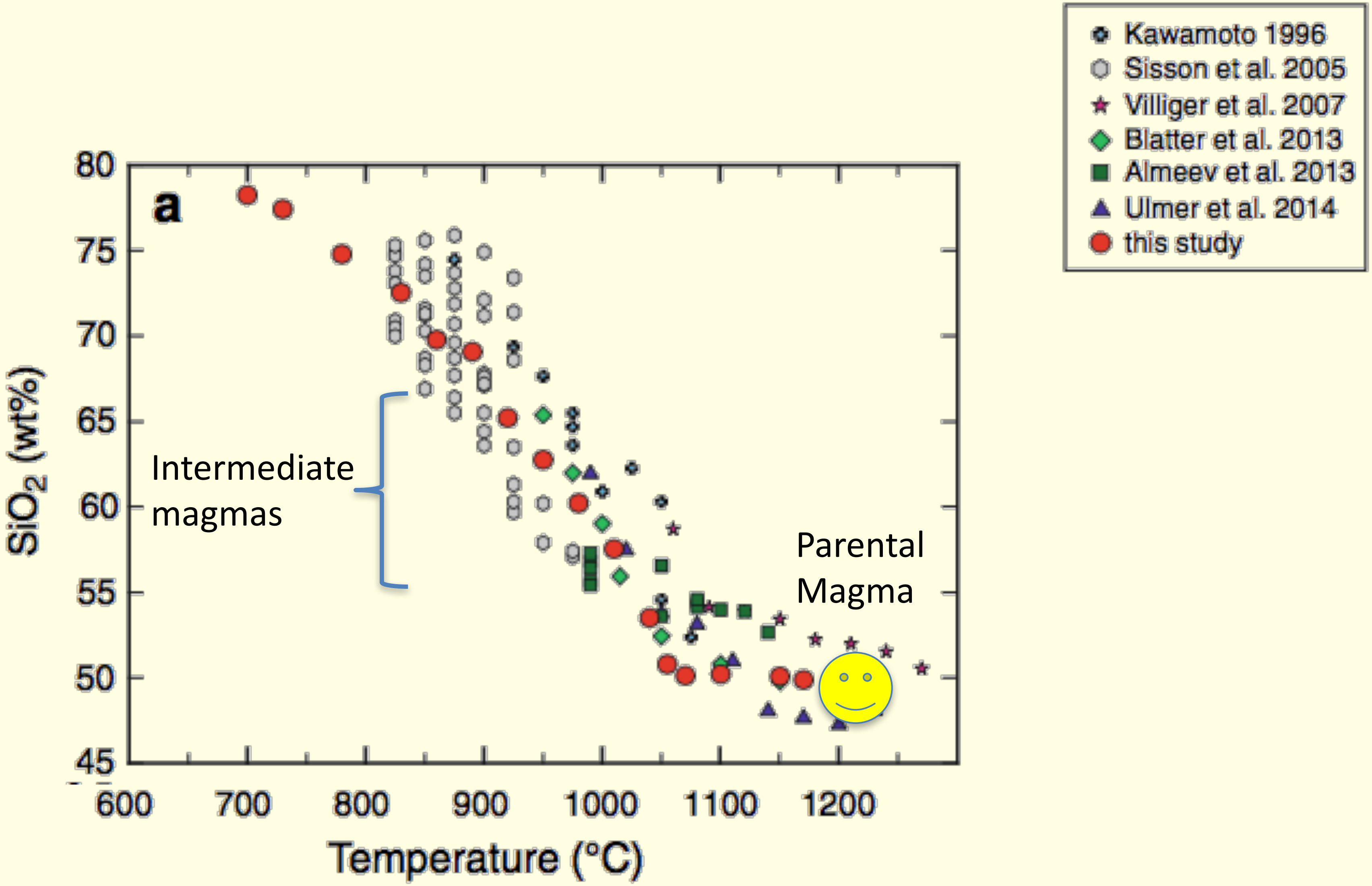
- Intrusion of mafic magma into the lower crust forms a **MASH/Hot zone**
  - A region of heated crust where intruded magmas cool and surrounding crust heats up

Dufek and Bergantz, 2005
Annen et al., 2006

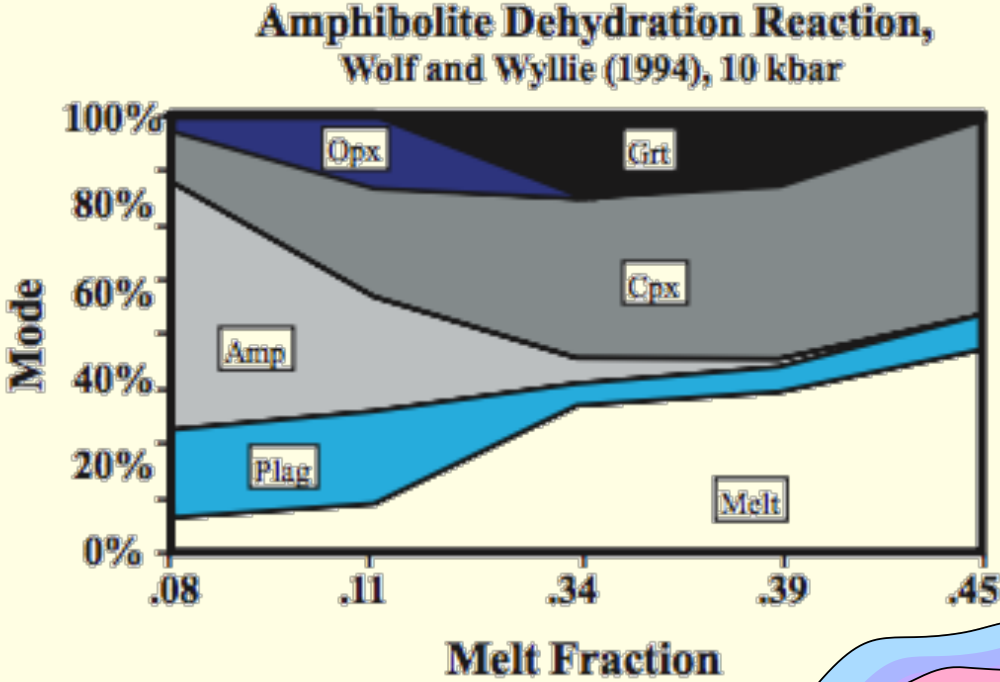


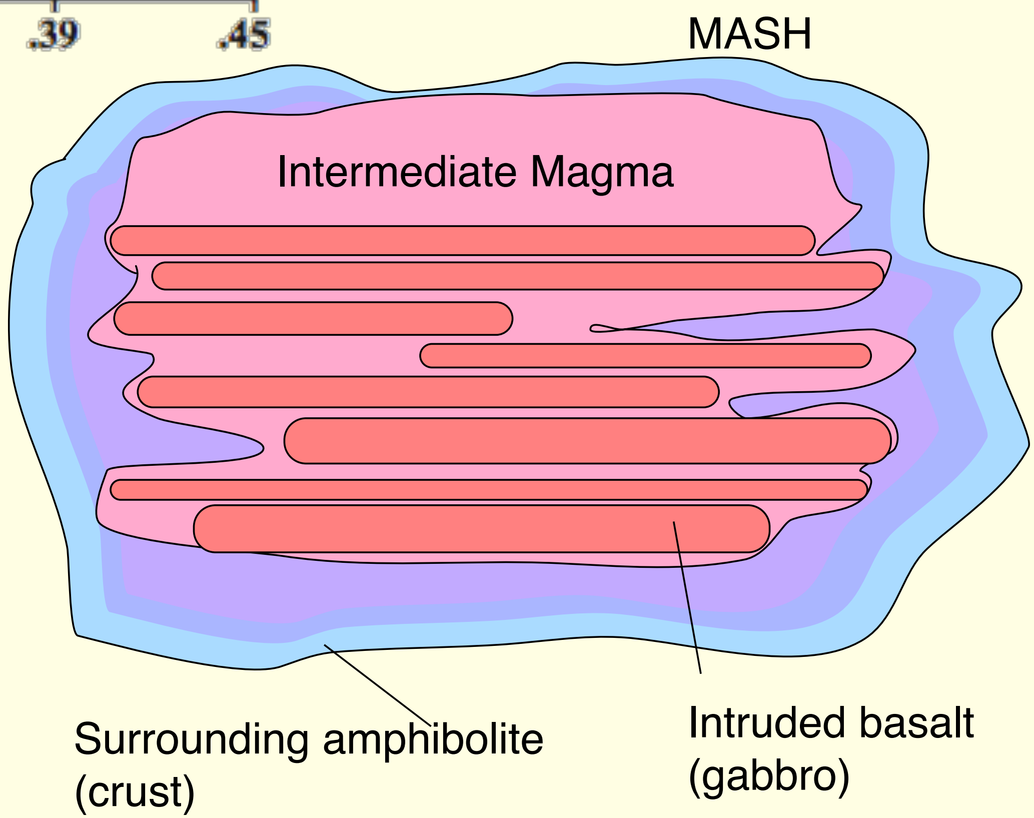


Dufek and Bergantz, 2005



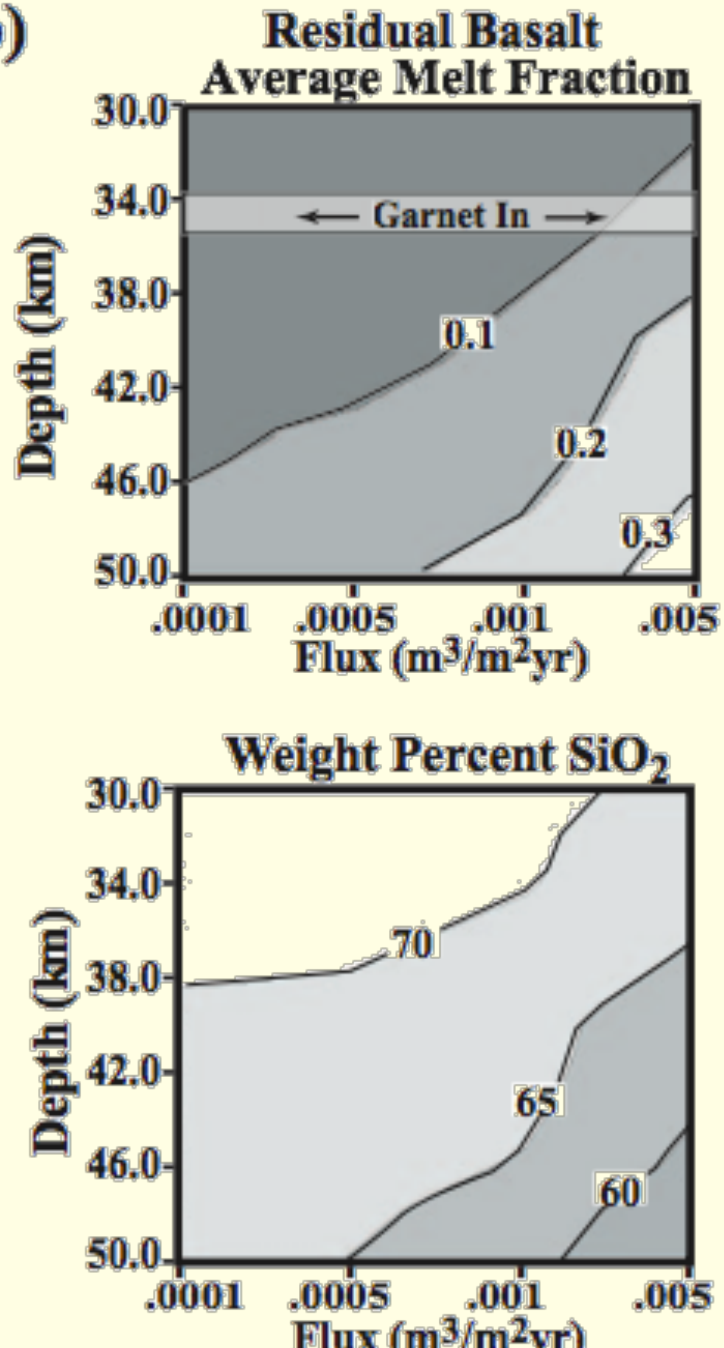
Nandedkhar et al., 2013



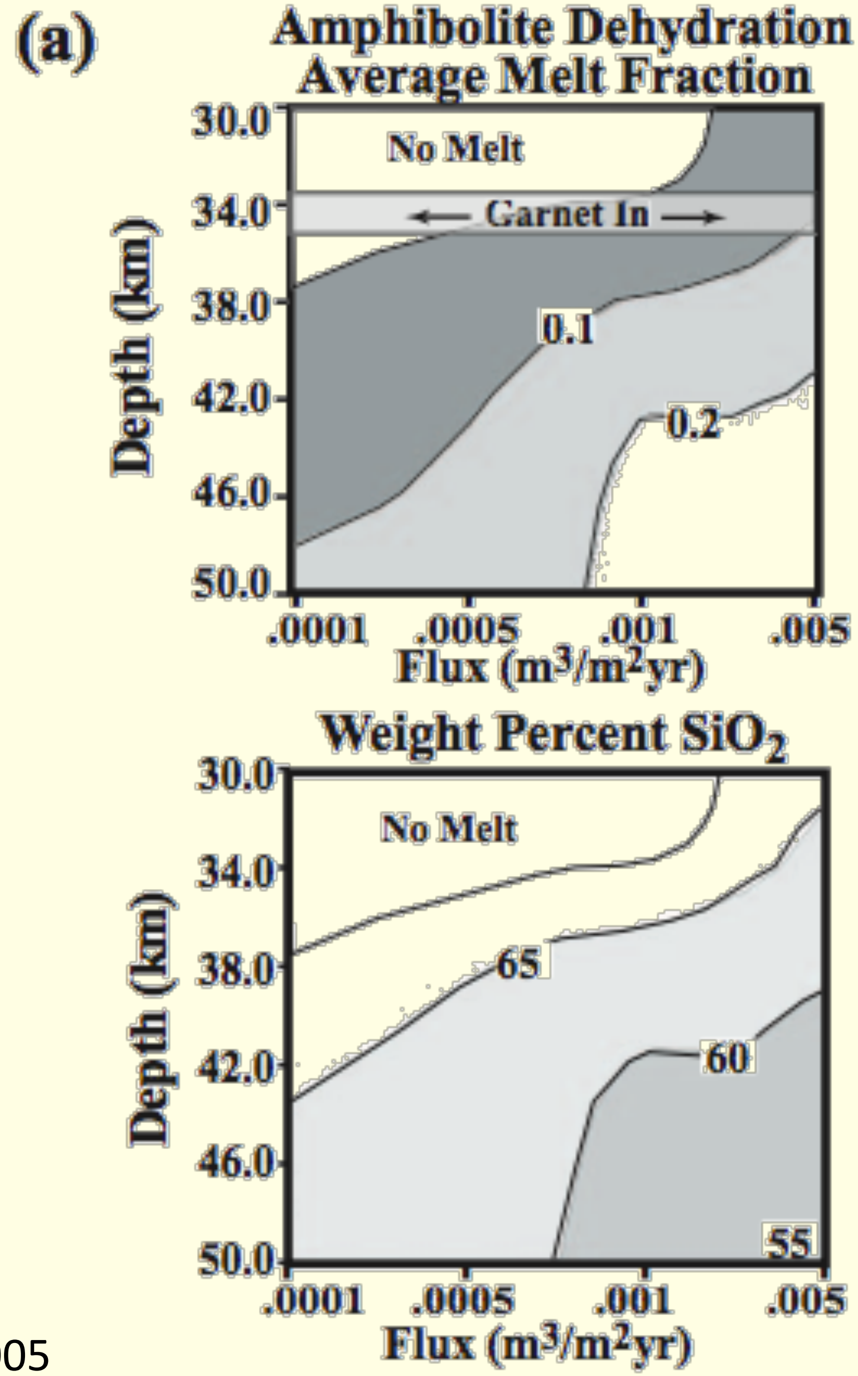


Dufek and Bergantz, 2005

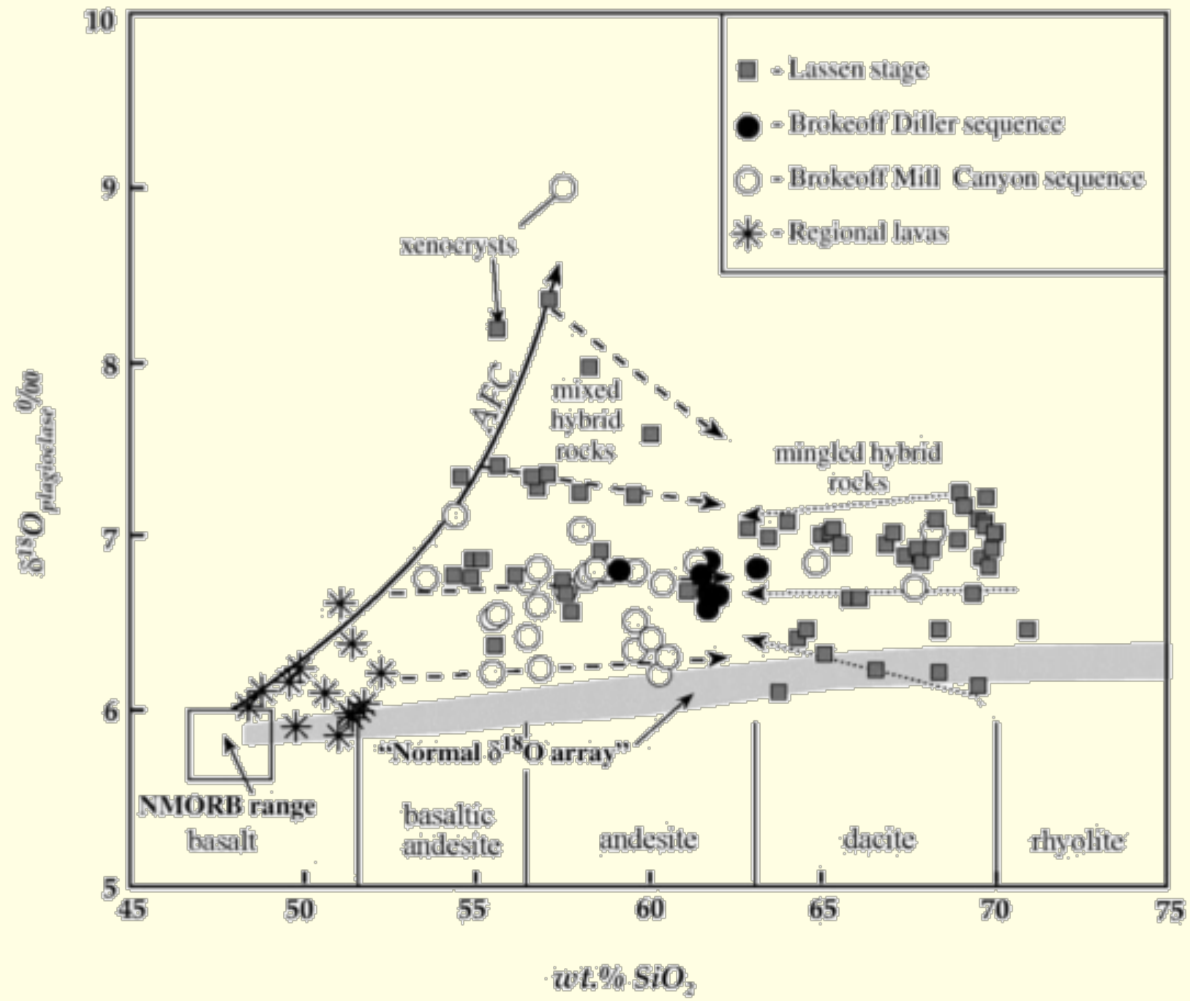
(b)



Dufek and Bergantz, 2005

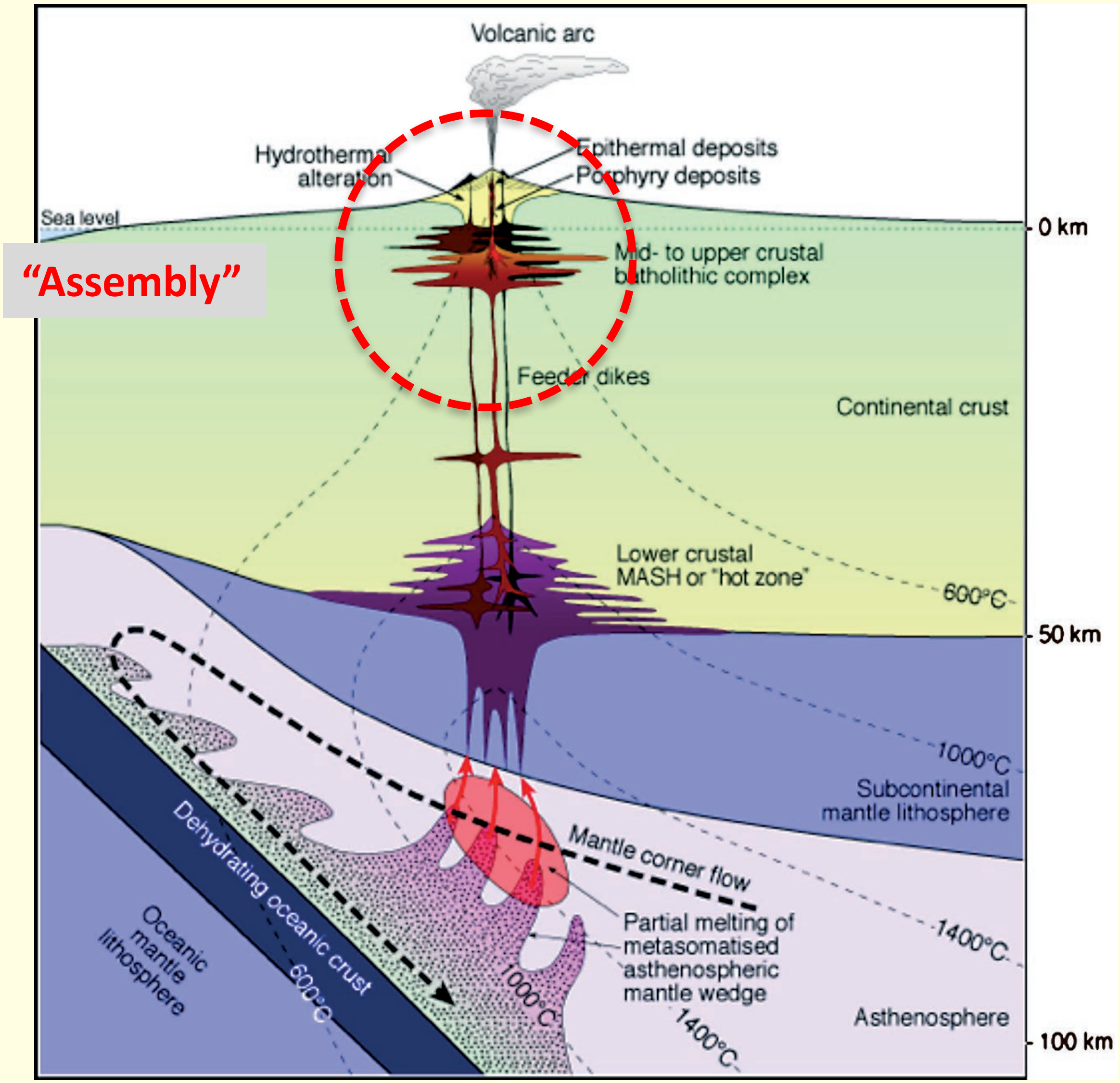


Dufek and Bergantz, 2005



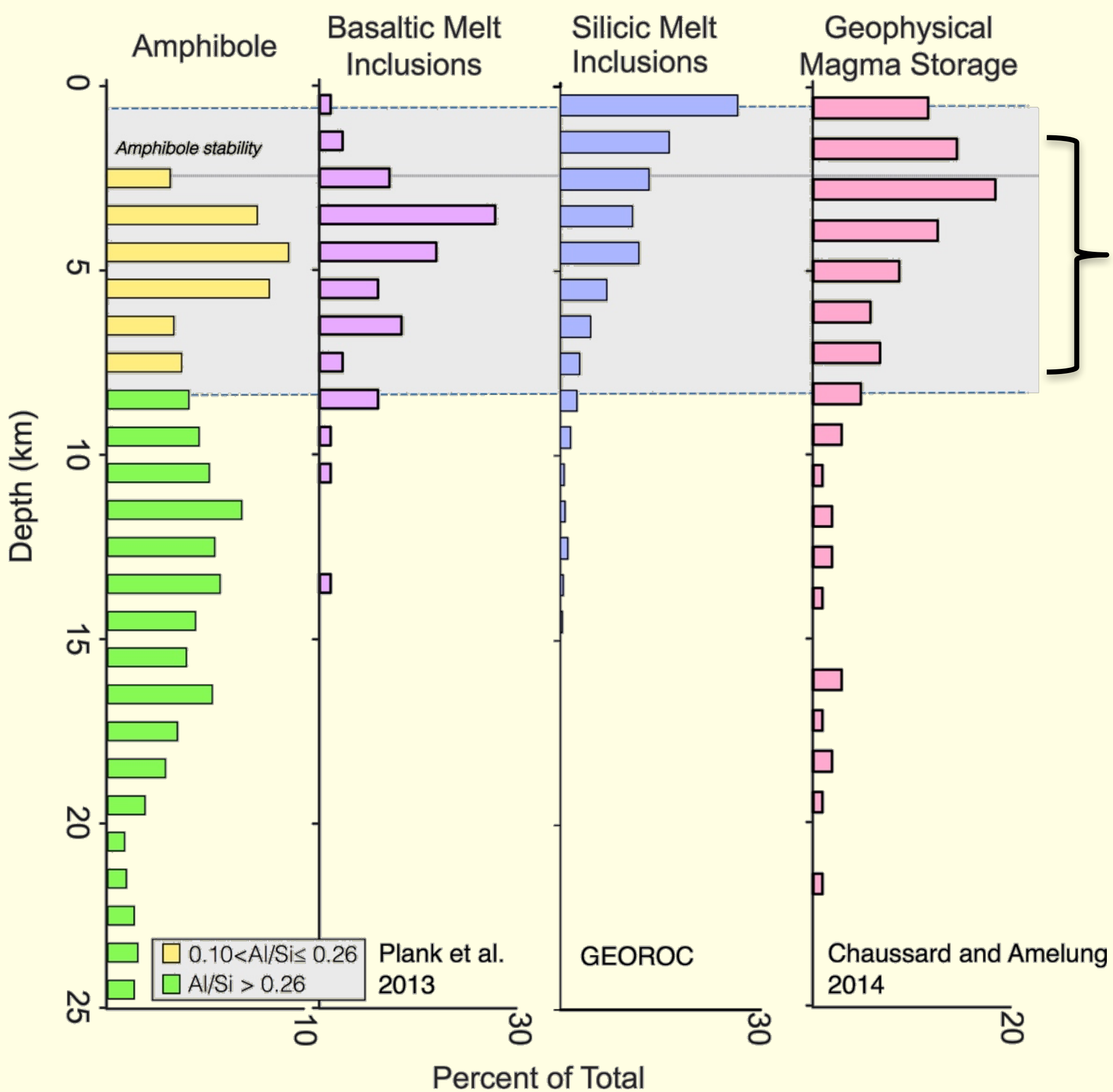
Oxygen isotope compositions at Mount Lassen

Feeley et al., 2008



Richards, 2011

Shallow Magma Storage

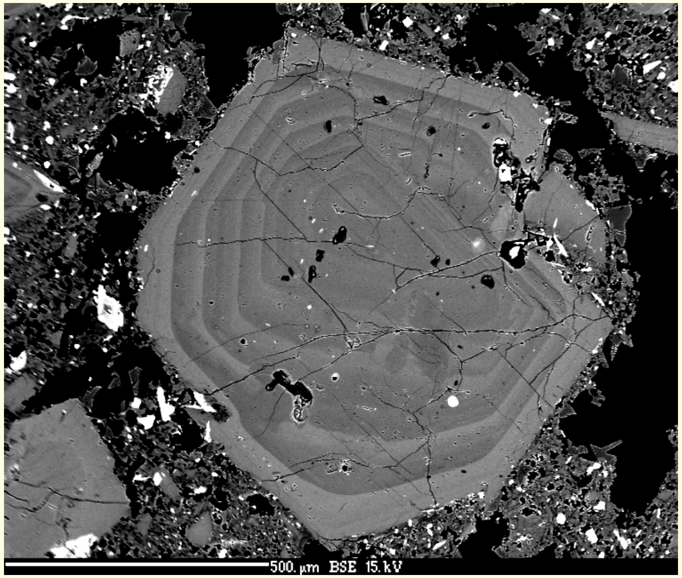


Upper crustal magma storage zones

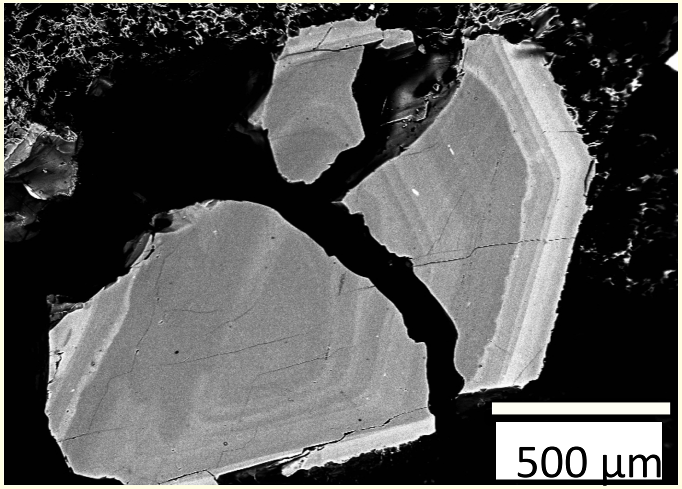
- Areas of magma assembly
- Strong control on volcanic processes

Why does so much magma residence occur in the shallow crust?

- Trapping magma at brittle ductile transition?
- Stalling of ascending magmas?
- Density/viscosity?

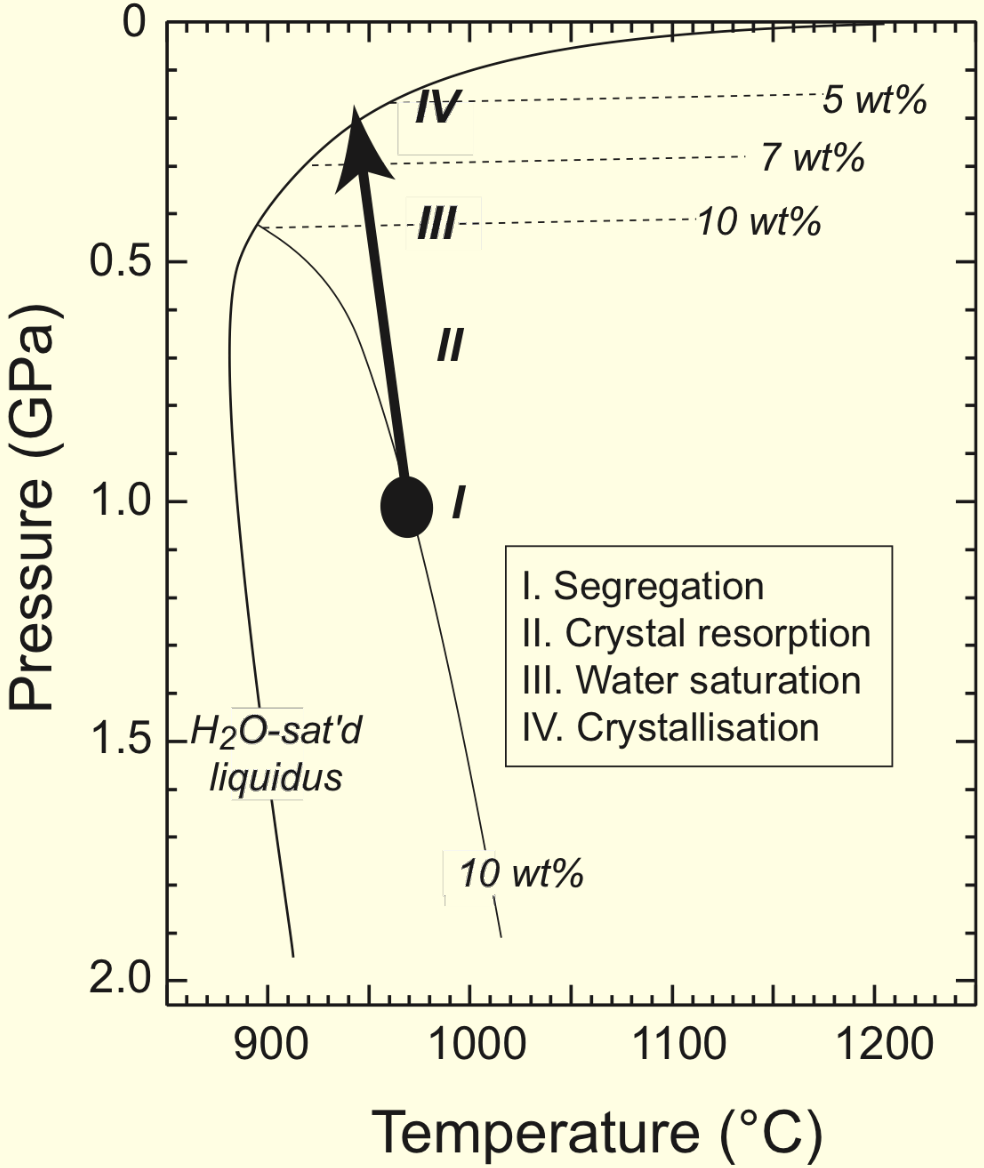


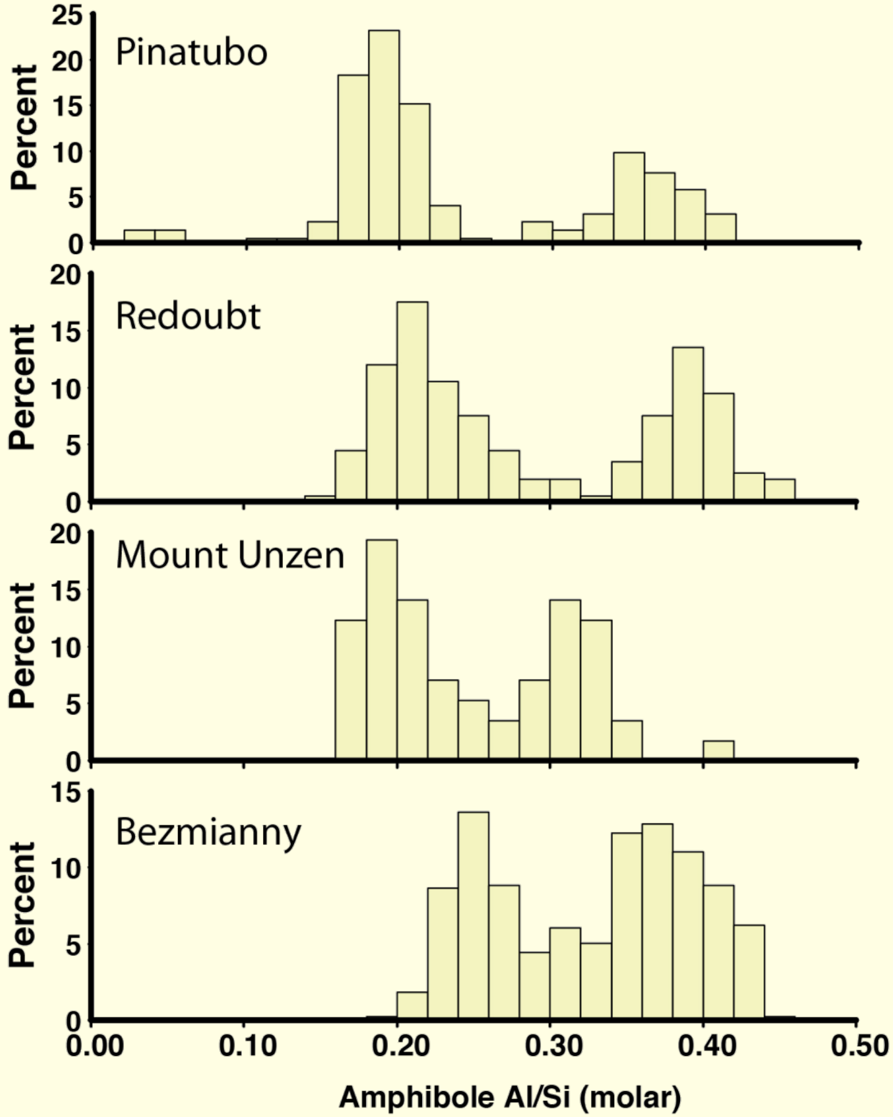
Mount Hood



Mount Pinatubo

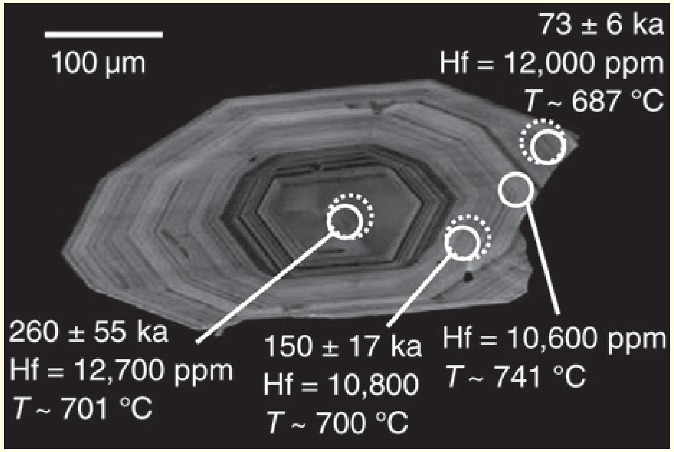
Annen et al., 2006

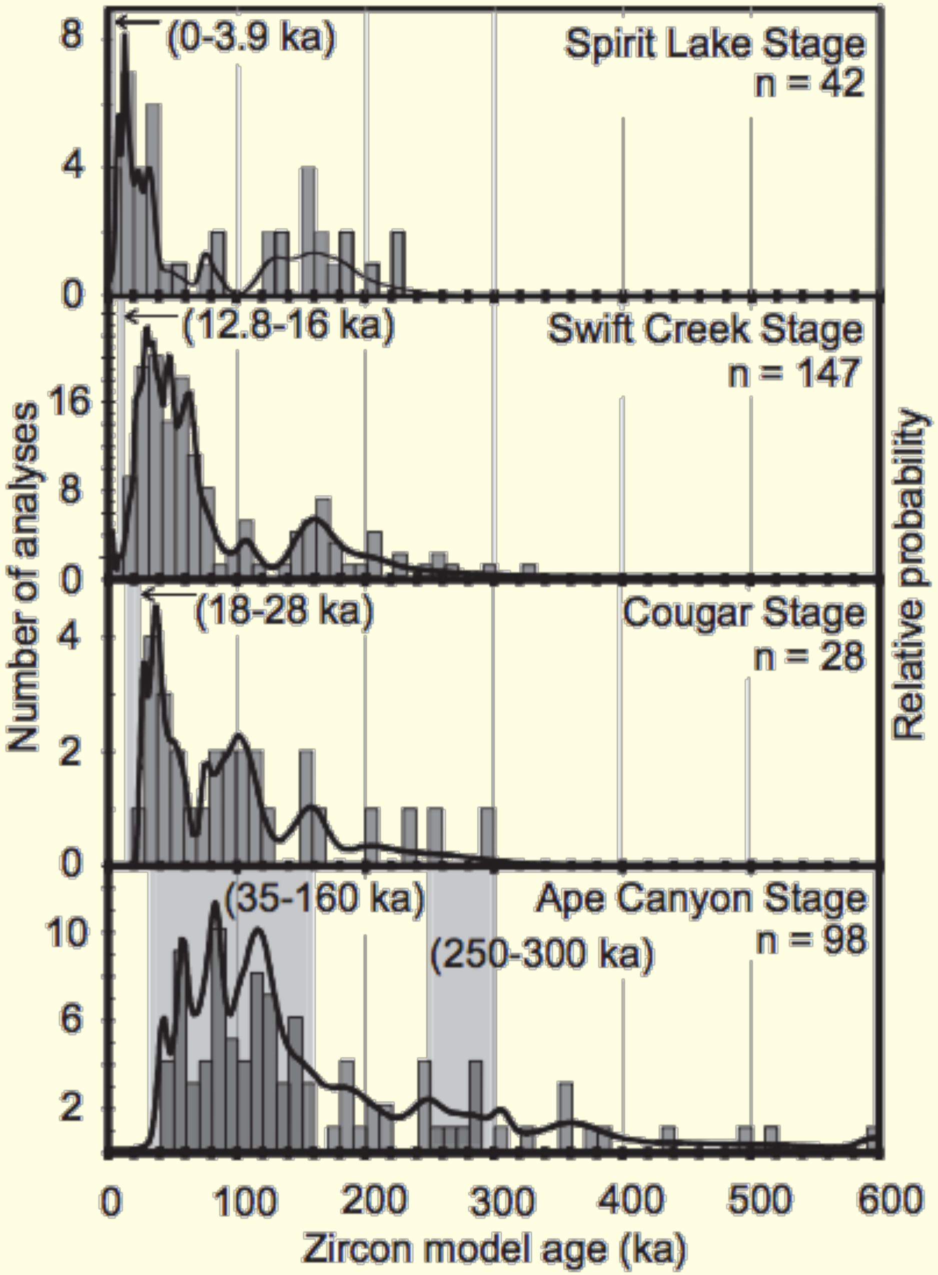




Bimodal Mineral compositions appear to be an important feature of many arc volcanoes

Data: Coombs et al. 2012, Loewen, 2013; Turner et al. 2013; GEOROC





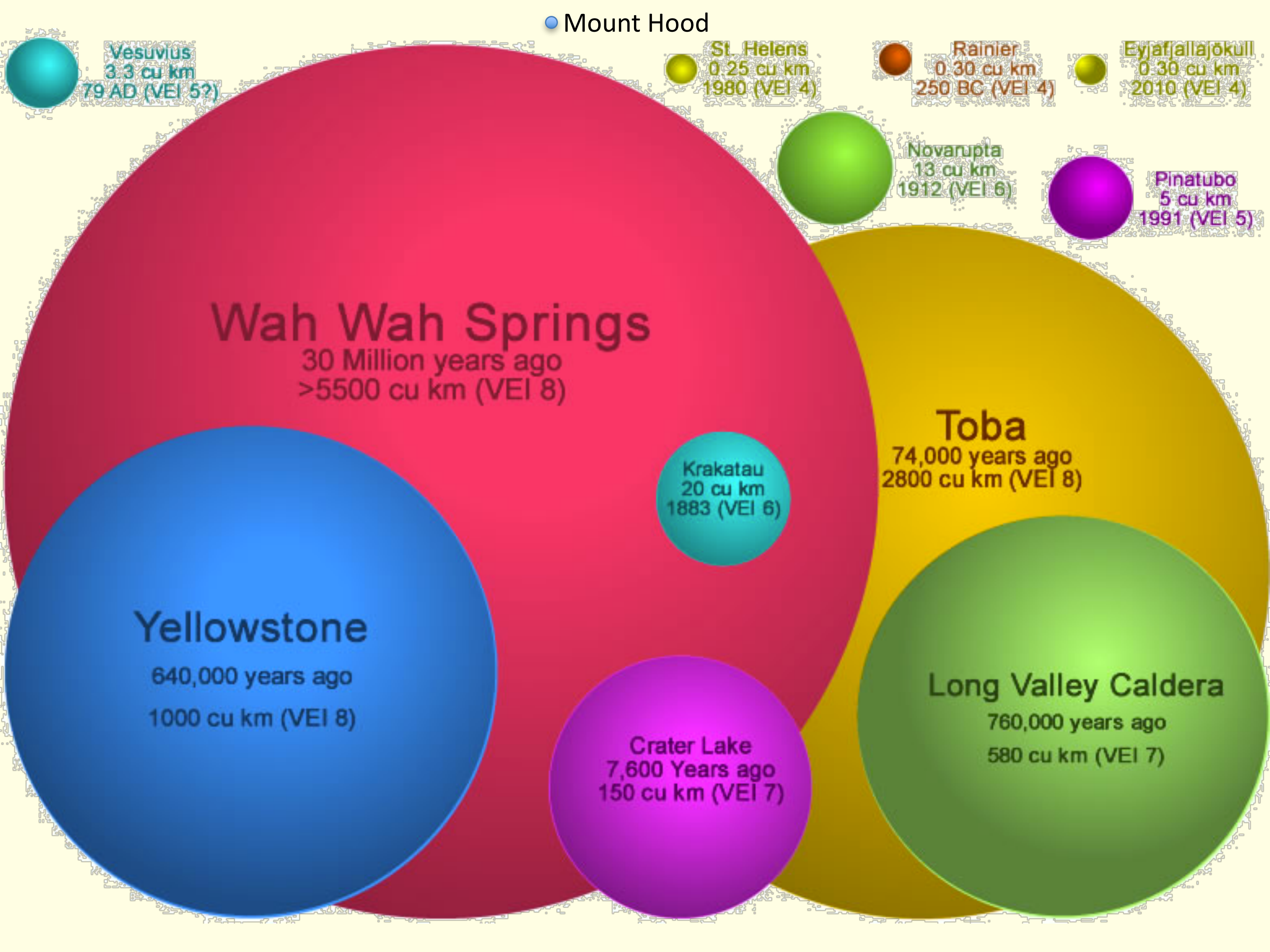
Zircon U-Th ages from Mount St Helens

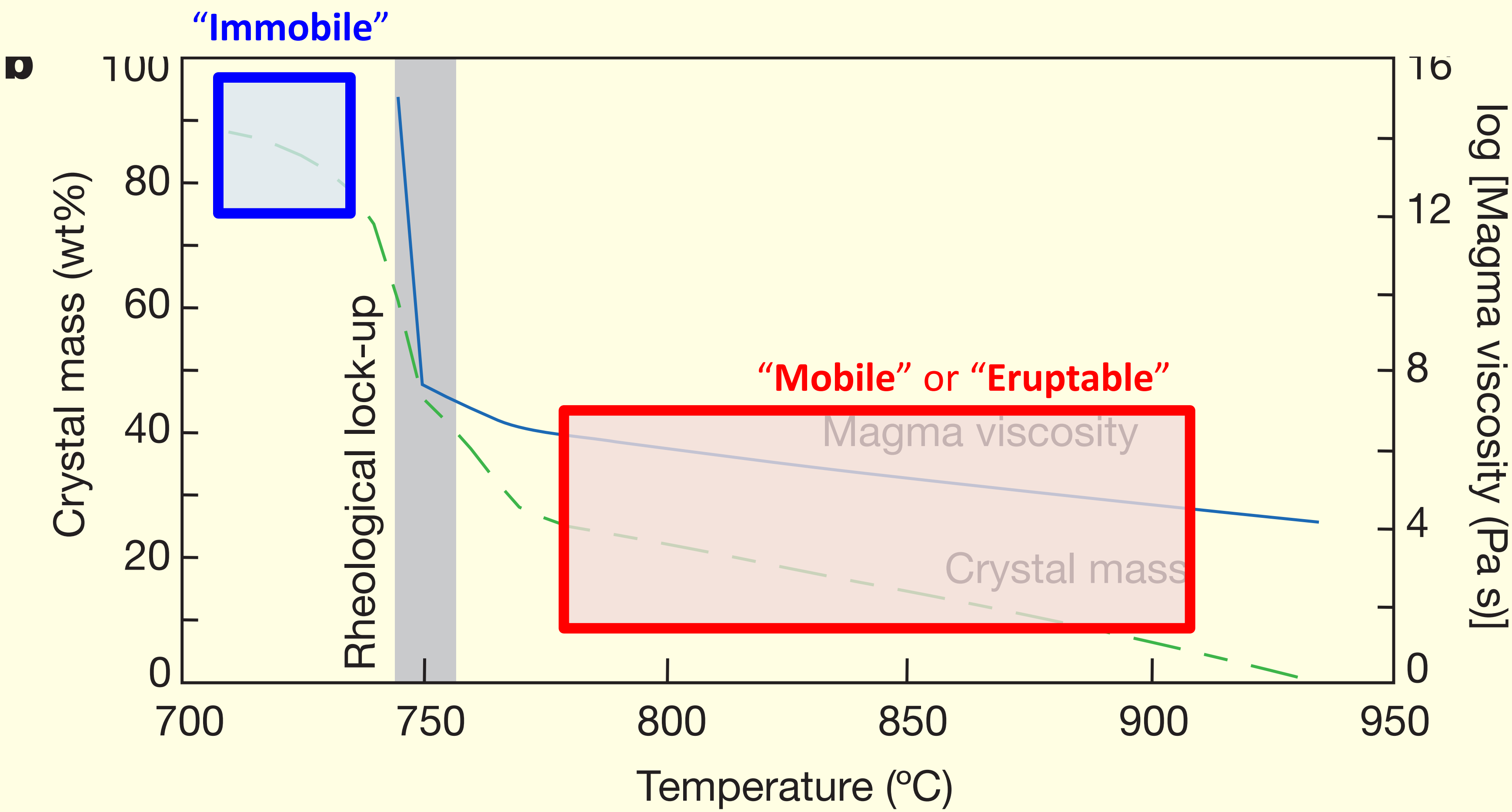
Claiborne et al. 2010

USGS

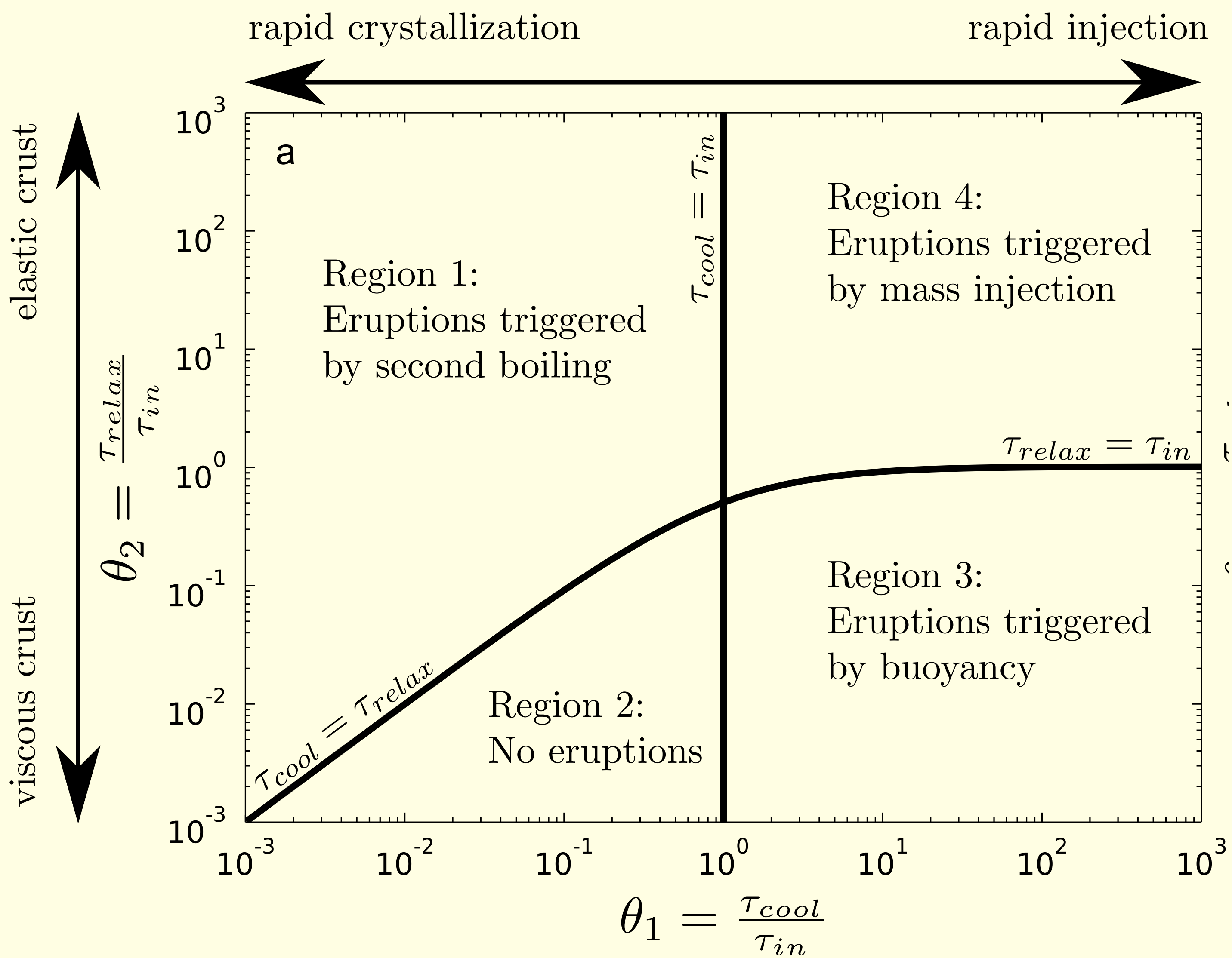
Long lived bodies of ”eruptible magma” are probably quite common n the shallow crust

- True
- False

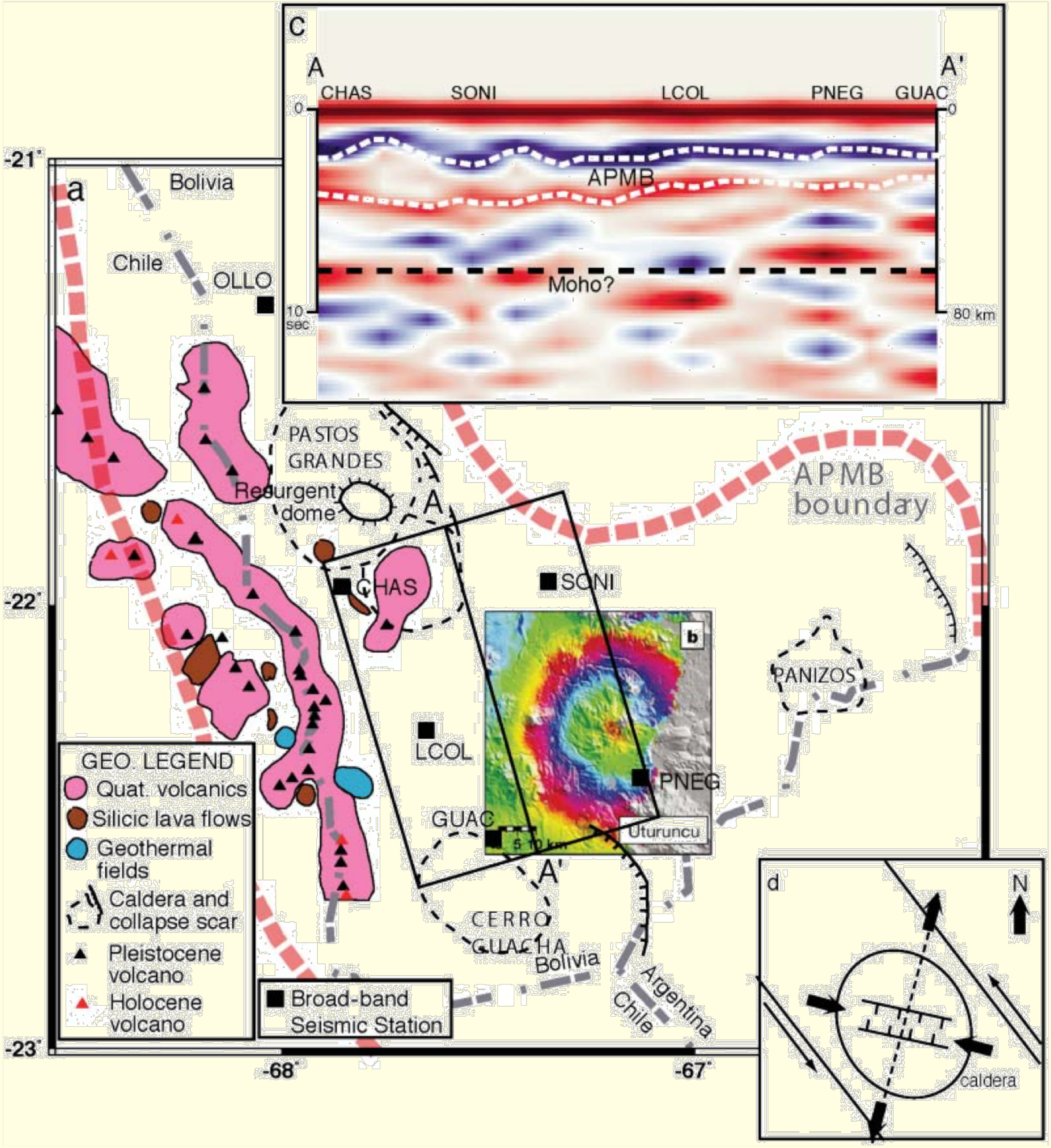

Mount Hood
Vesuvius
3.3 cu km
79 AD (VEI 5?)
St. Helens
0.25 cu km
1980 (VEI 4)
Rainier
0.30 cu km
250 BC (VEI 4)
Eyjafjallajökull
0.30 cu km
2010 (VEI 4)
Novarupta
13 cu km
1912 (VEI 6)
Pinatubo
5 cu km
1991 (VEI 5)
Wah Wah Springs
30 Million years ago
>5500 cu km (VEI 8)
Toba
74,000 years ago
2800 cu km (VEI 8)
Krakatau
20 cu km
1883 (VEI 6)
Yellowstone
640,000 years ago
1000 cu km (VEI 8)
Crater Lake
7,600 Years ago
150 cu km (VEI 7)
Long Valley Caldera
760,000 years ago
580 cu km (VEI 7)



"Immobile"
b
Crystal mass (wt%)
100
80
60
40
20
0
Rheological lock-up
"Mobile" or "Eruptable"
Magma viscosity
Crystal mass
700
750
800
850
900
950
Temperature (°C)
16
12
8
4
0
log [Magma viscosity (Pa s)]



Degruyter and Huber, 2014

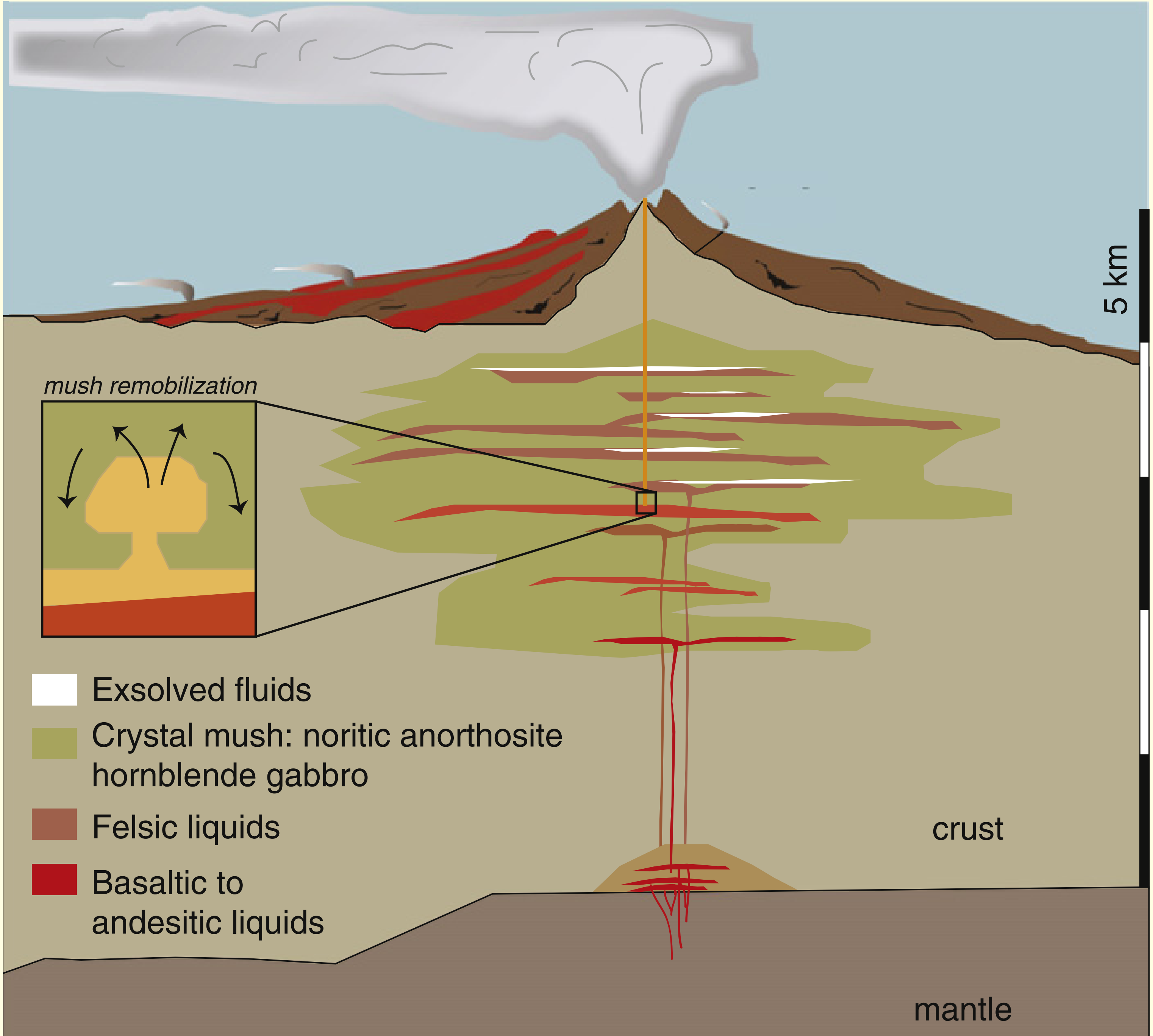


Altiplano-Puna Volcanic Complex (APVC)

Geophysical studies rarely find evidence for large volumes of liquid magma beneath active volcanoes

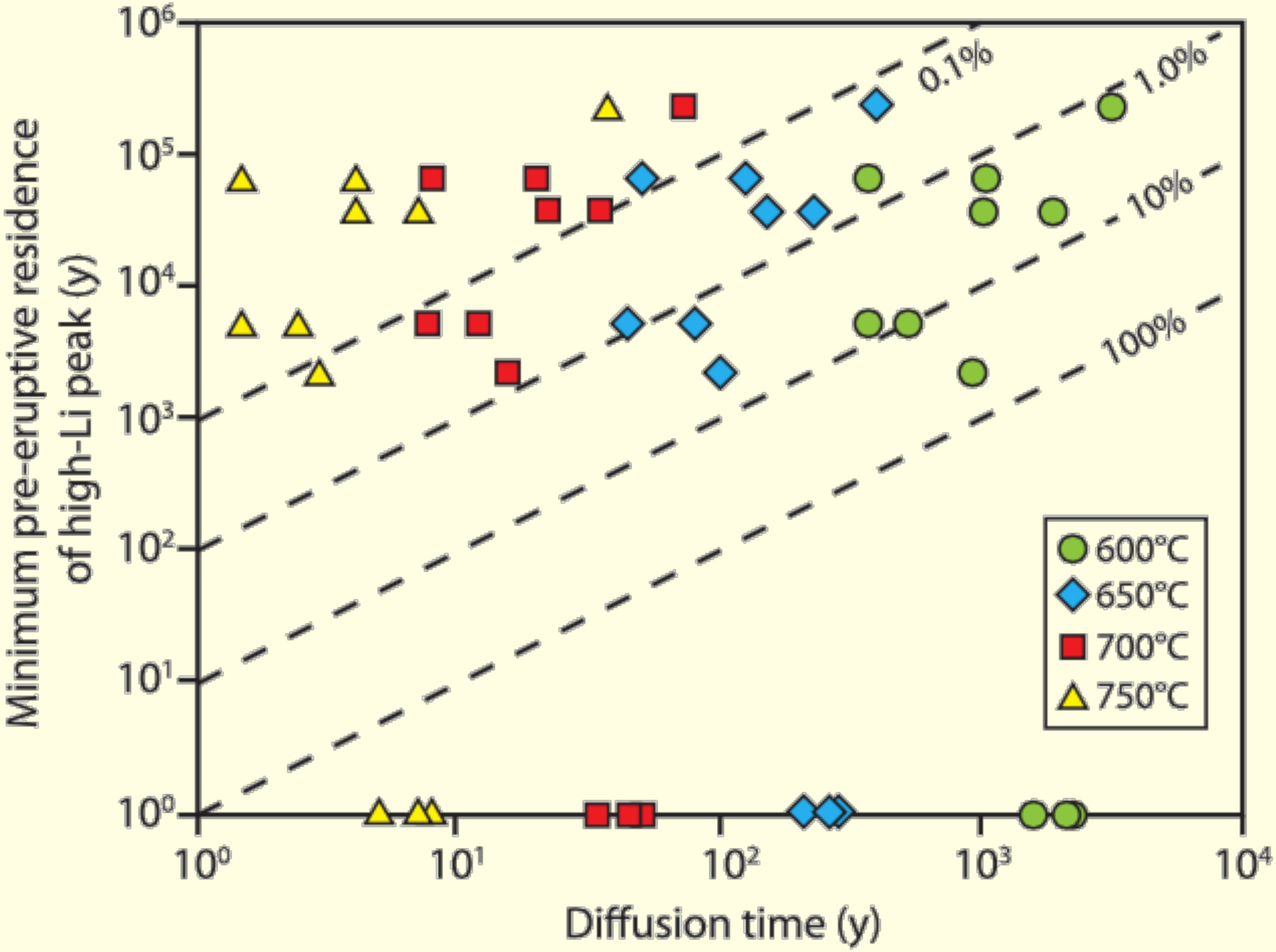
APMB < 20%
Yellowstone < 10%
St Helens < 10%

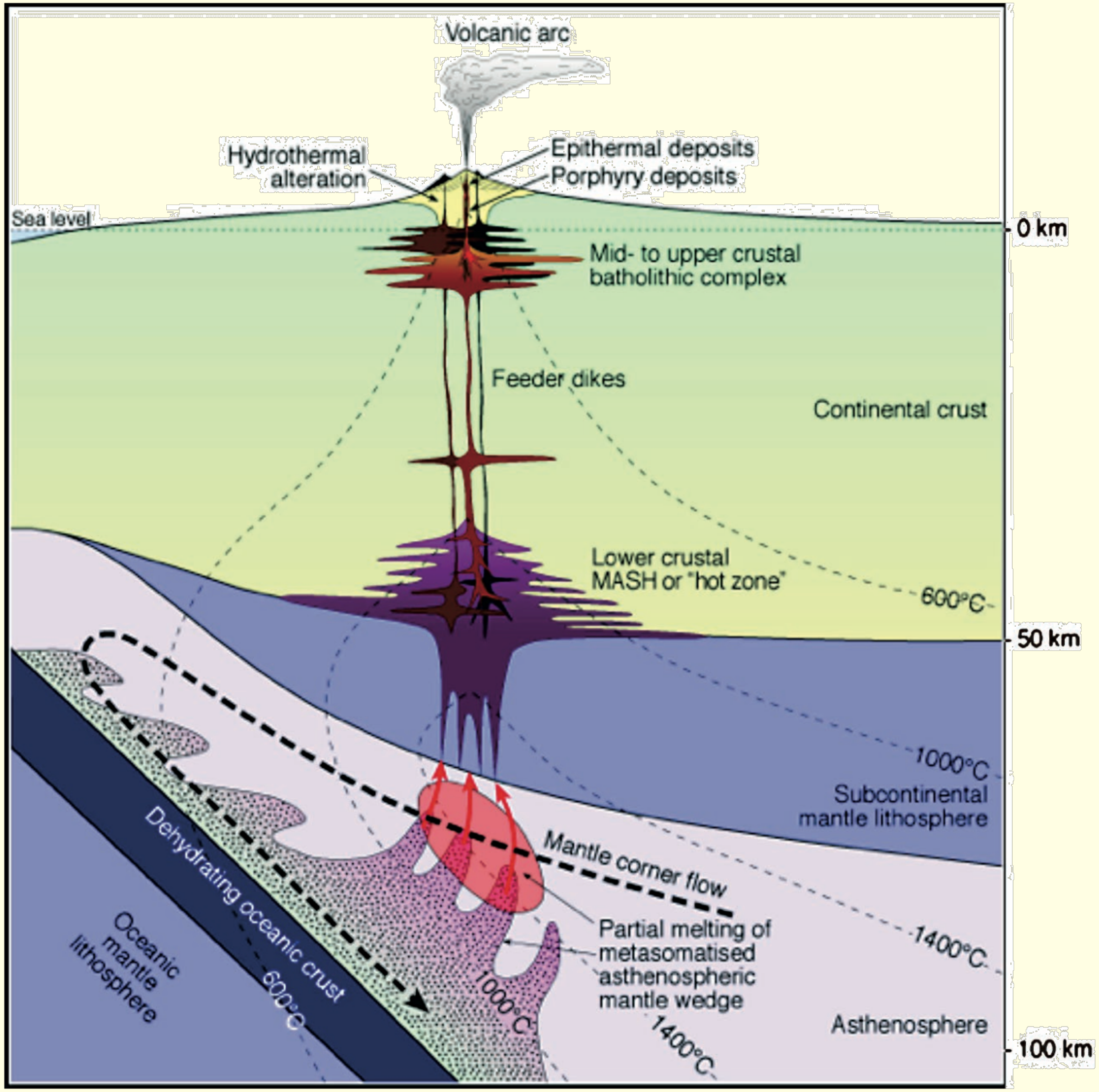
De Silva et al. 2006



Soufriére Hills, Edmonds et al. 2015

Thermal History from zircon (Rubin et al. 2017)




Volcanic arc
Hydrothermal alteration
Epithermal deposits
Porphyry deposits
Sea level
0 km
Mid- to upper crustal batholithic complex
Feeder dikes
Continental crust
Lower crustal MASH or "hot zone"
600°C
50 km
1000°C
Subcontinental mantle lithosphere
Mantle corner flow
Dehydrating oceanic crust
Oceanic mantle lithosphere
600°C
1000°C
1400°C
Partial melting of metasomatised asthenospheric mantle wedge
1400°C
Asthenosphere
100 km

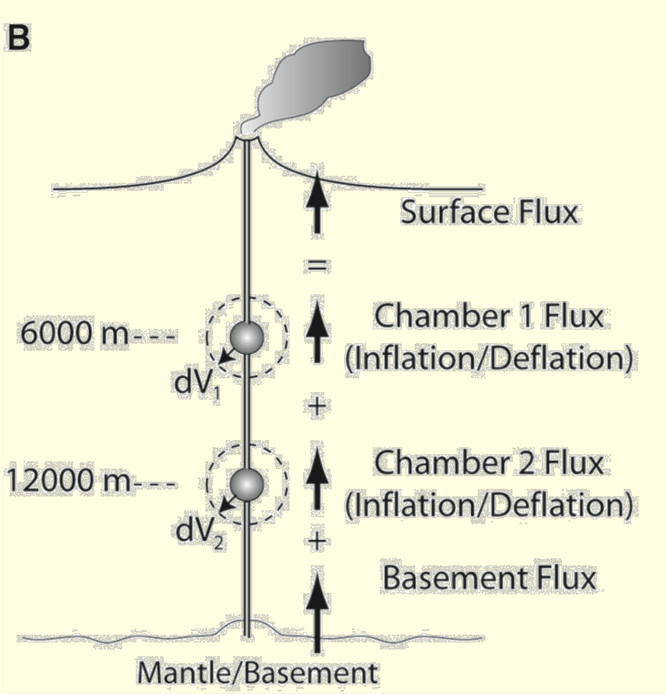
Grand Challenge. Systematic slab to surface understanding of arc magmatic systems

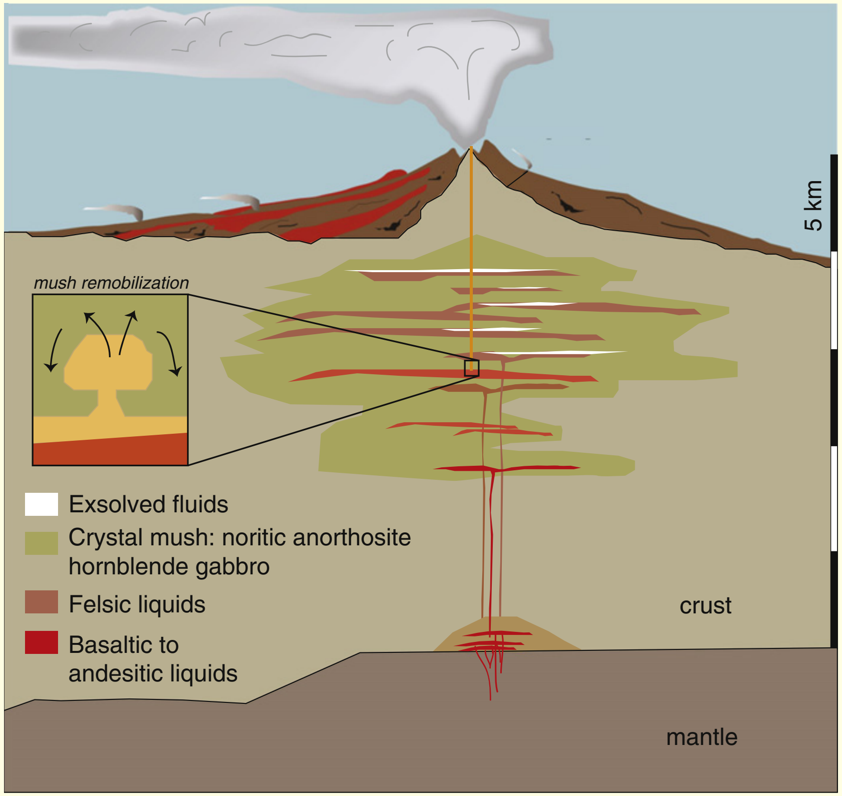
- Cohesive models to understand the dominant controls on:
    - When and where arc volcanoes erupt
    - Style of volcanism
    - Erupted compositions
    - Locations, size and lifetimes of individual volcanoes
    - Pathways taken by ascending magmas (physically & geochemically)
    - Mantle controls

SZO workshop report, 2016; C. Till SZO White Paper, 2016

Interactions within the factory

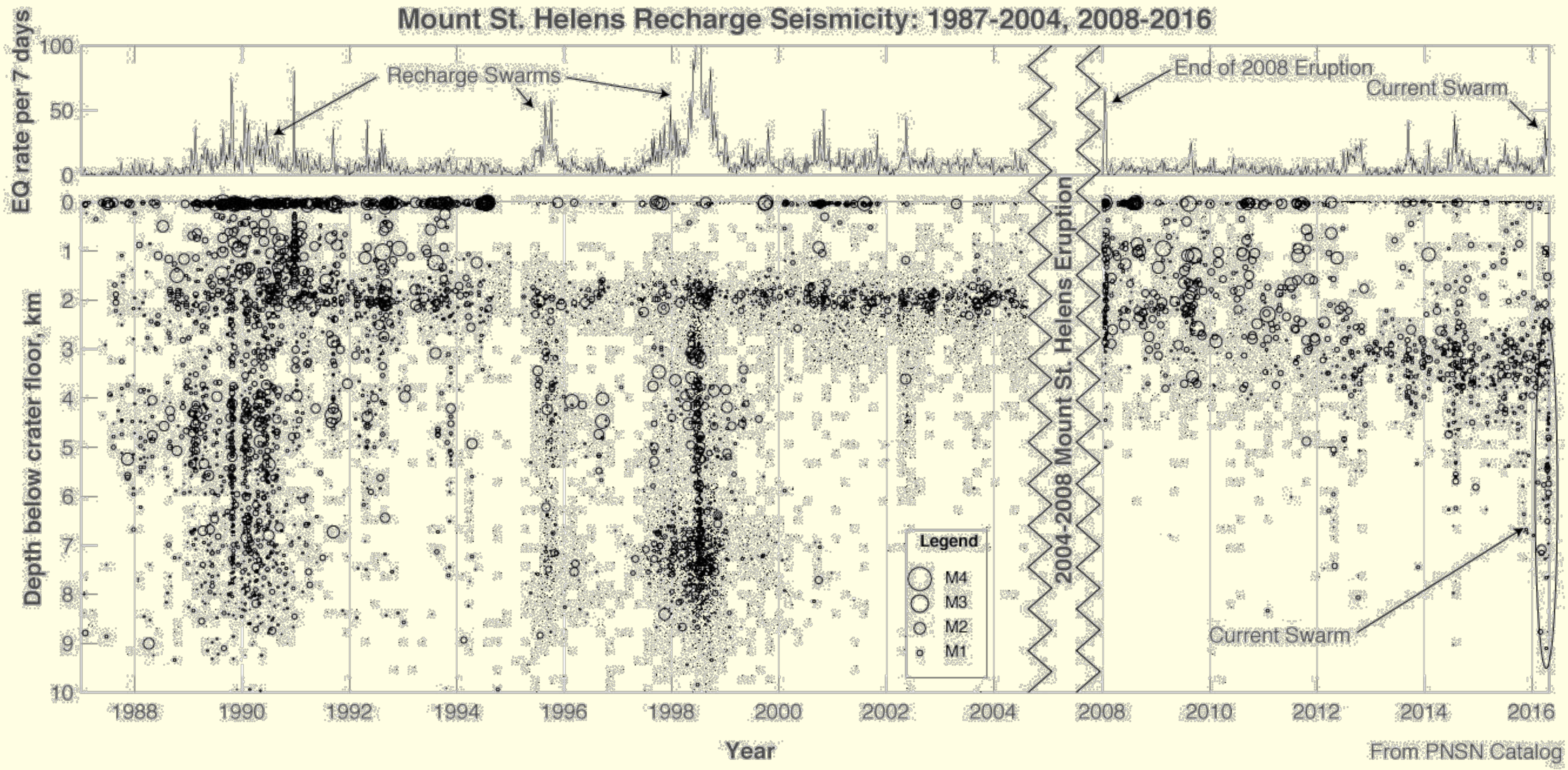
- How do the mantle wedge, lower crust and shallow crust interact?





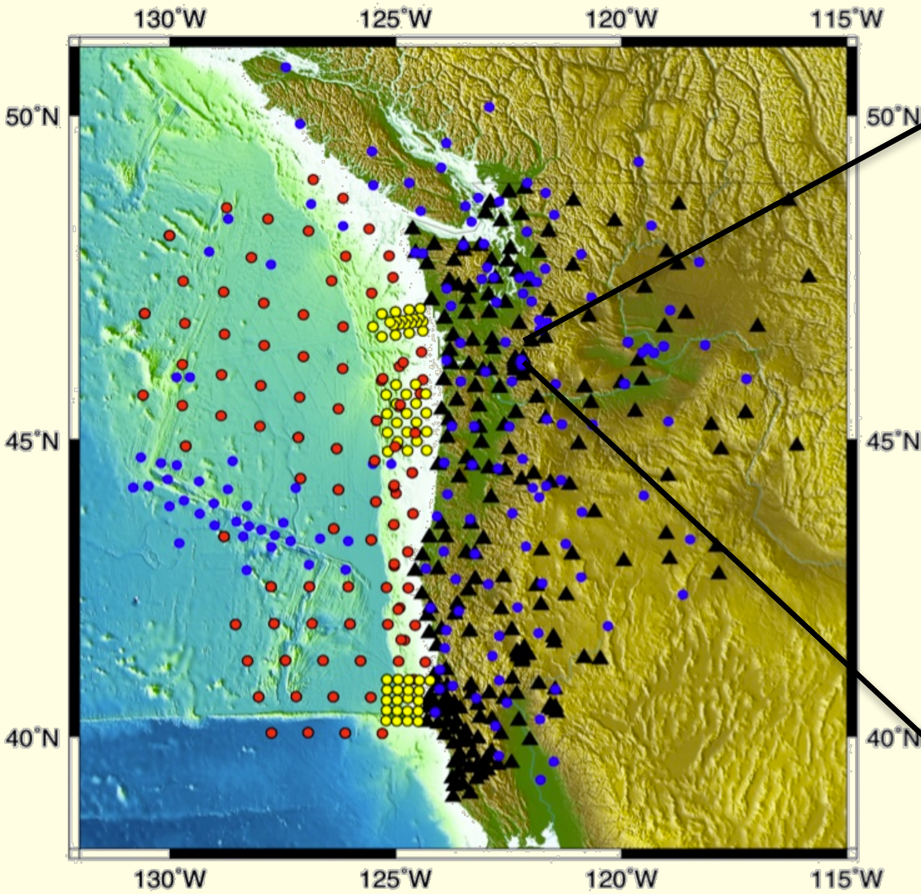
Soufriére Hills Volcano; Ellsworth 2011

Edmonds et al. 2016

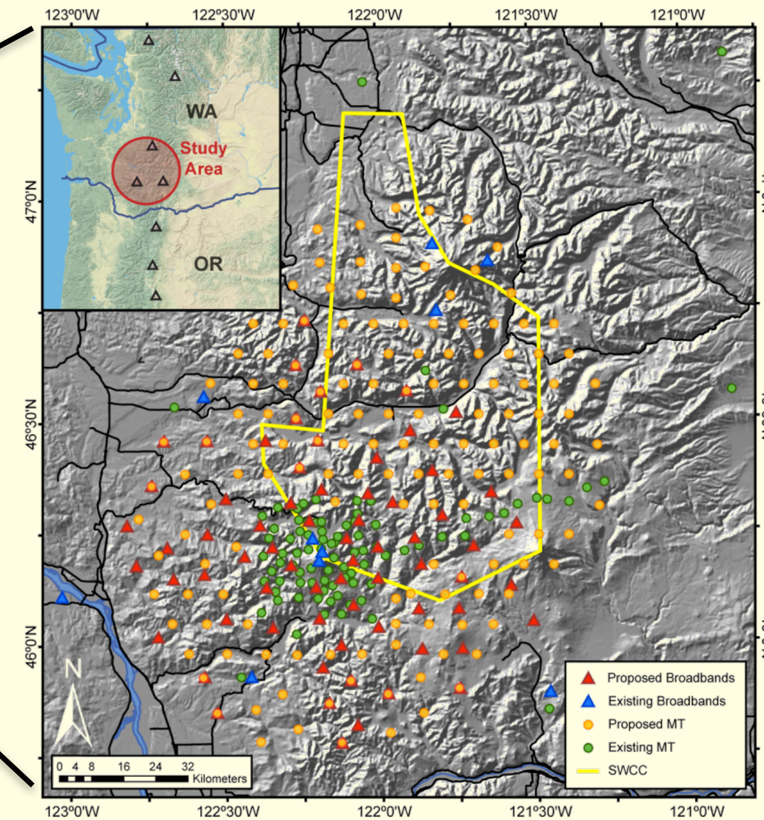


Mount St. Helens Recharge Seismicity: 1987-2004, 2008-2016
EQ rate per 7 days
Recharge Swarms
End of 2008 Eruption
Current Swarm
Depth below crater floor, km
2004-2008 Mount St. Helens Eruption
Legend
M4
M3
M2
M1
Current Swarm
Year
From PNSN Catalog

Inversion/integration of petrology/ geochemistry with regional data sets

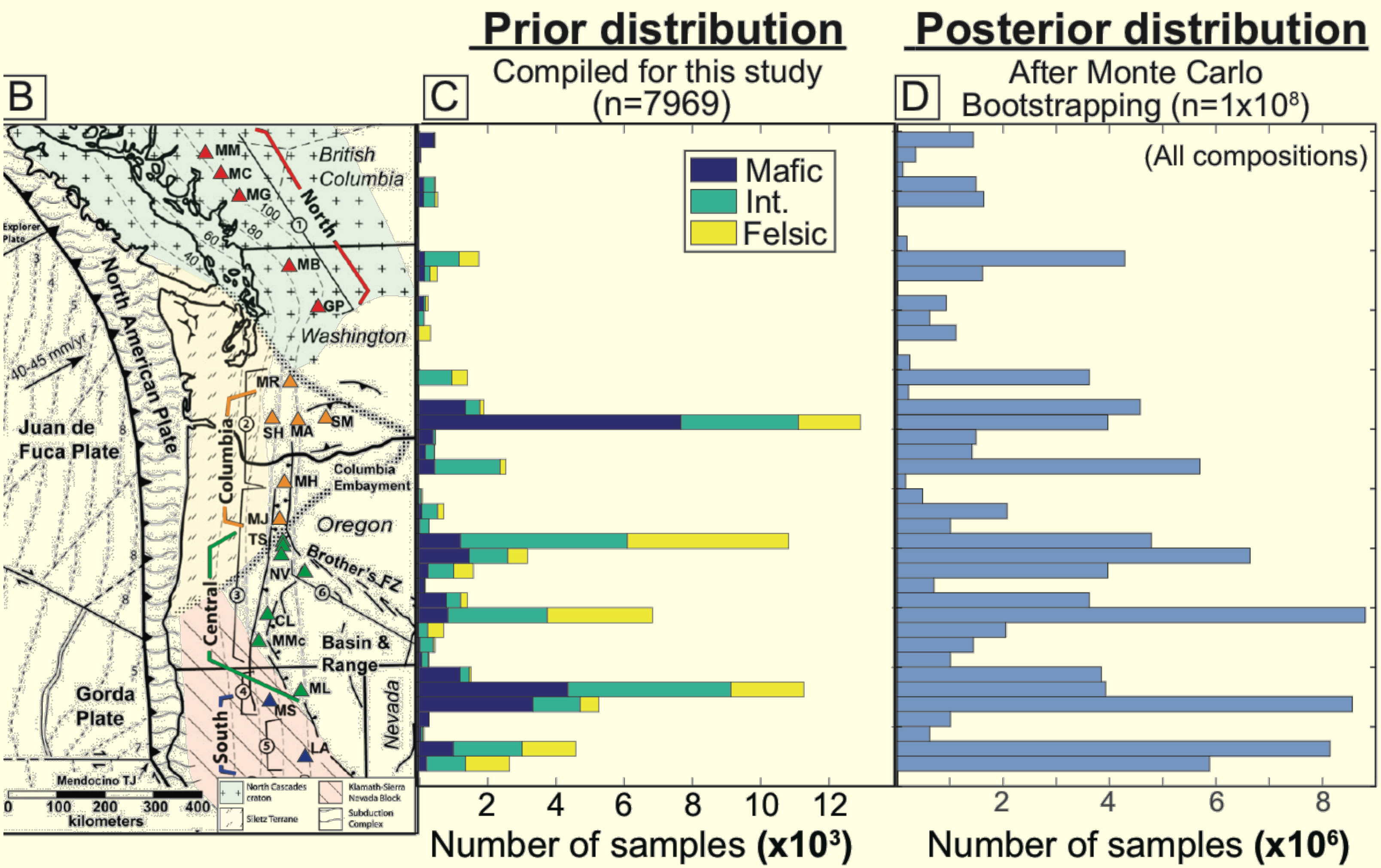


Cascadia PBO and Earthscope Stations



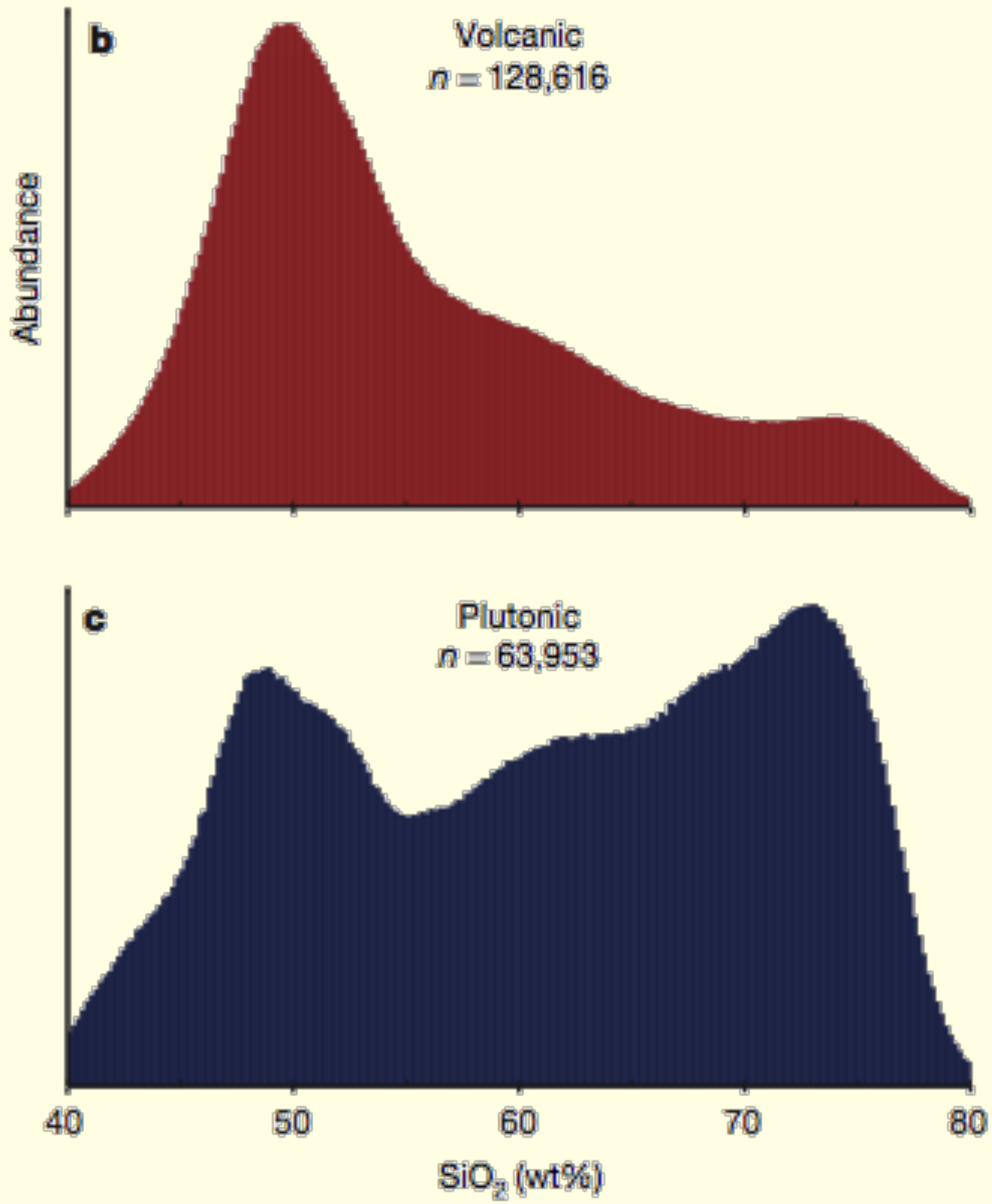
iMUSH stations

Ergodicity and Bulk Properties



Pitcher et al. 2016

Thank You!

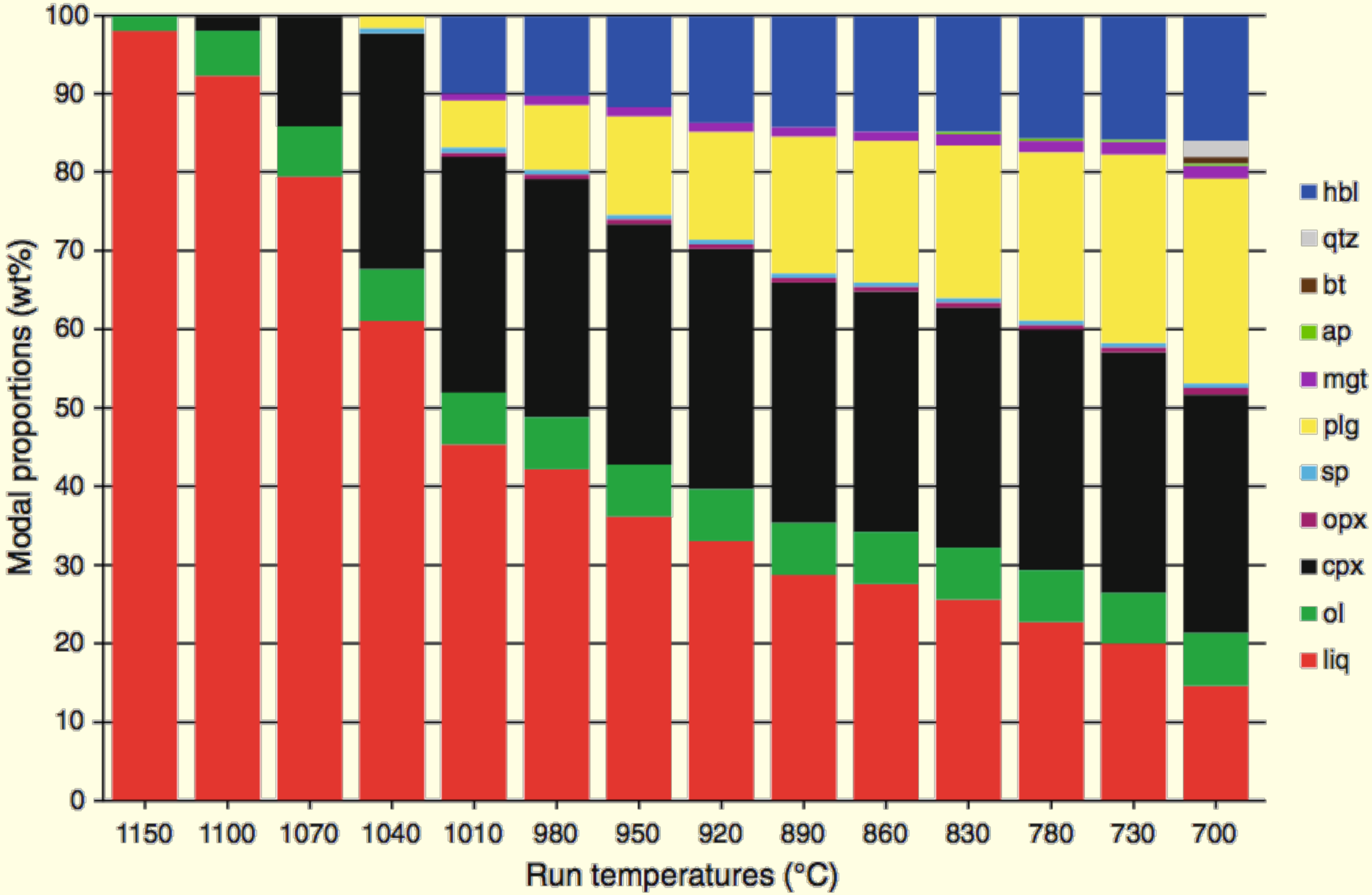


Keller et al., 2015

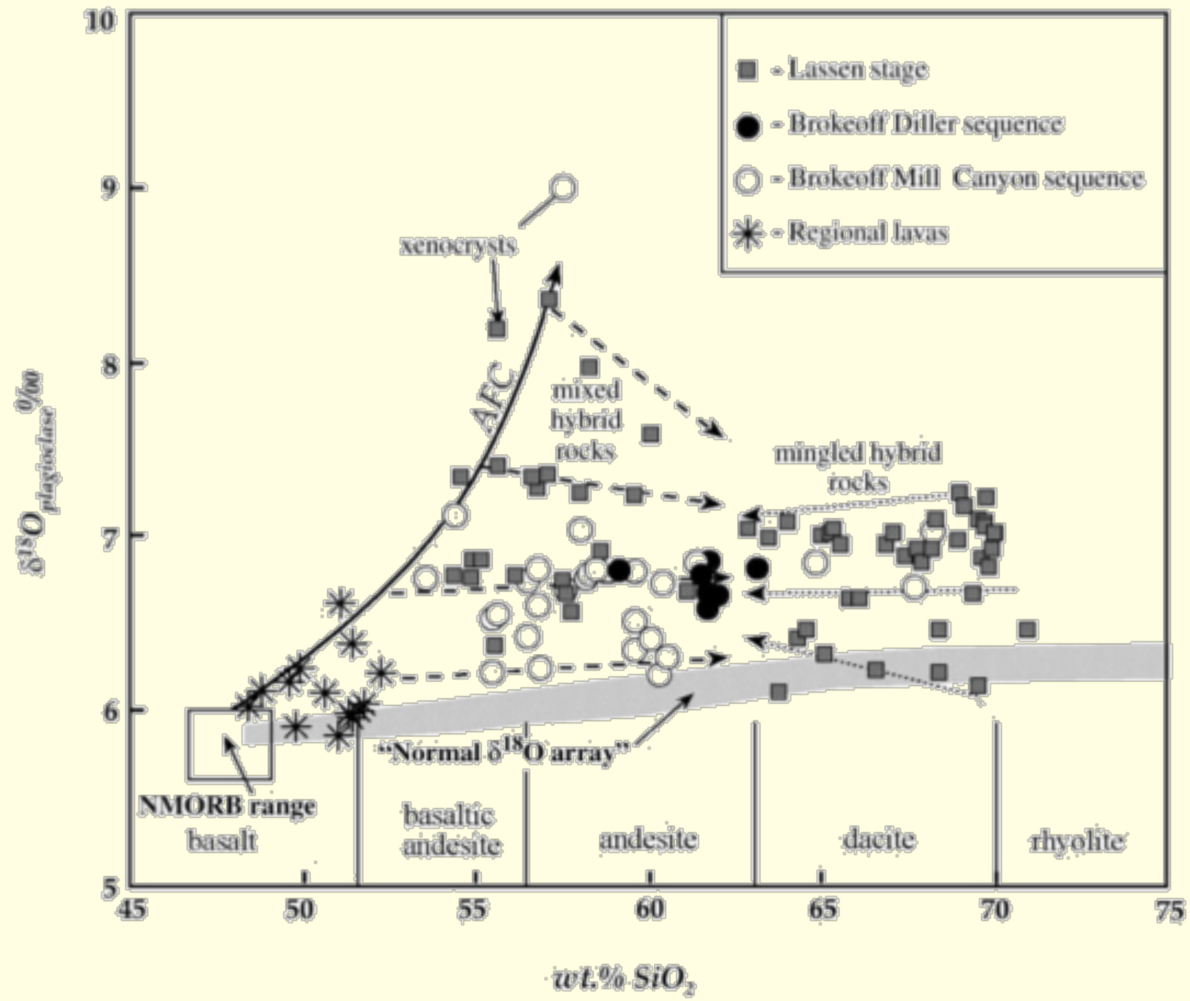
Wt.%	Average Modern Andesite[1]	Bulk Continental Crust[2]
SiO_2	56.3	59.1
TiO_2	0.9	0.7
Al_2O_3	16.4	15.8
FeO	7.7	6.6
MgO	4.8	4.4
CaO	7.9	6.4
Na_2O	3.2	3.2
K_2O	1.3	1.9

[1]Geokem.com [2]Rudnick and Fountain, 1995

Modern Subduction Flux = Basaltic



100
90
80
70
60
50
40
30
20
10
0
Modal proportions (wt%)
1150
1100
1070
1040
1010
980
950
920
890
860
830
780
730
700
Run temperatures (°C)
hbl
qtz
bt
ap
mgt
plg
sp
opx
cpx
ol
liq



Oxygen isotope compositions at Mount Lassen

Feeley et al., 2008