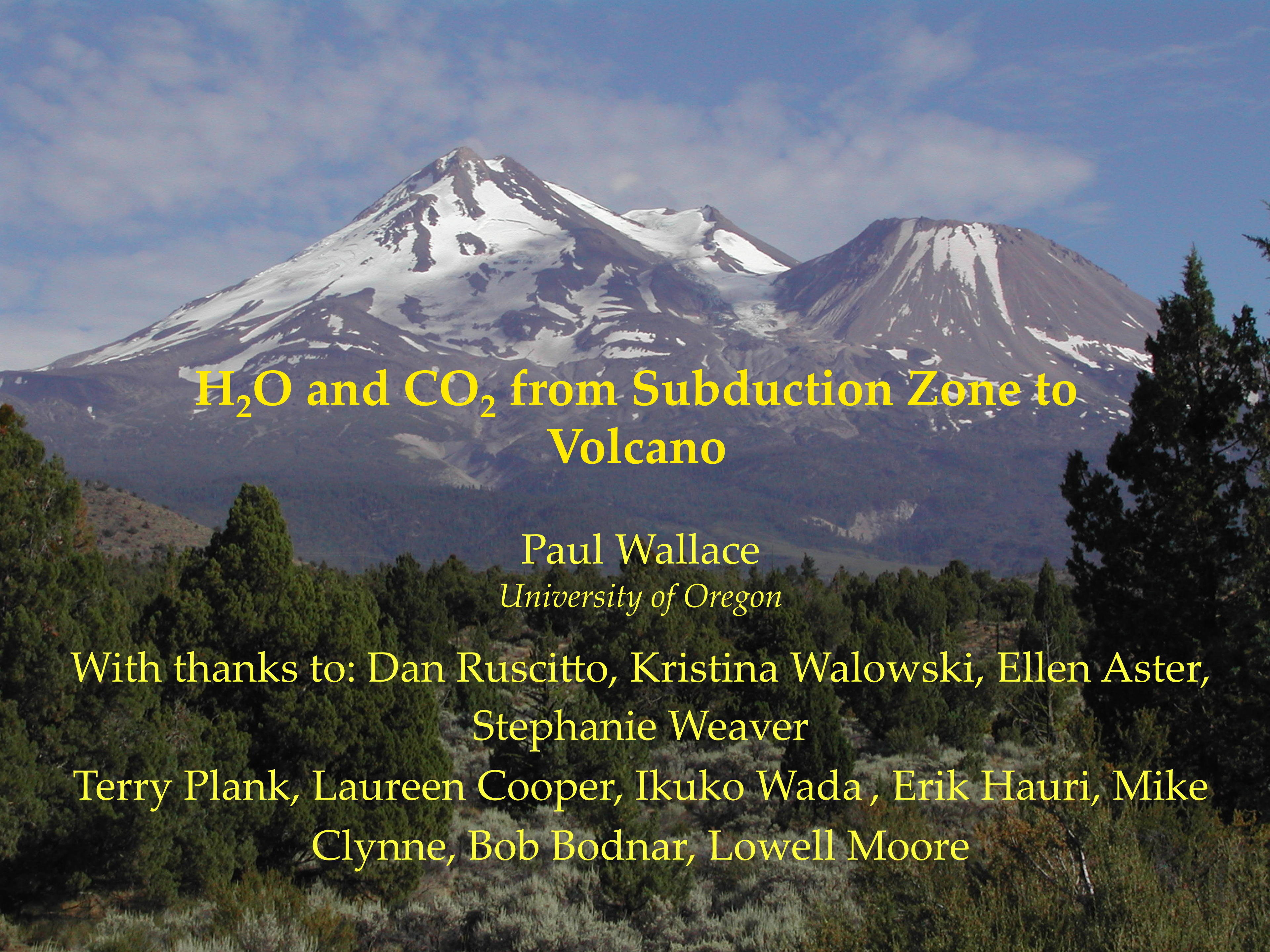


H_2O and CO_2 from Subduction Zone to Volcano

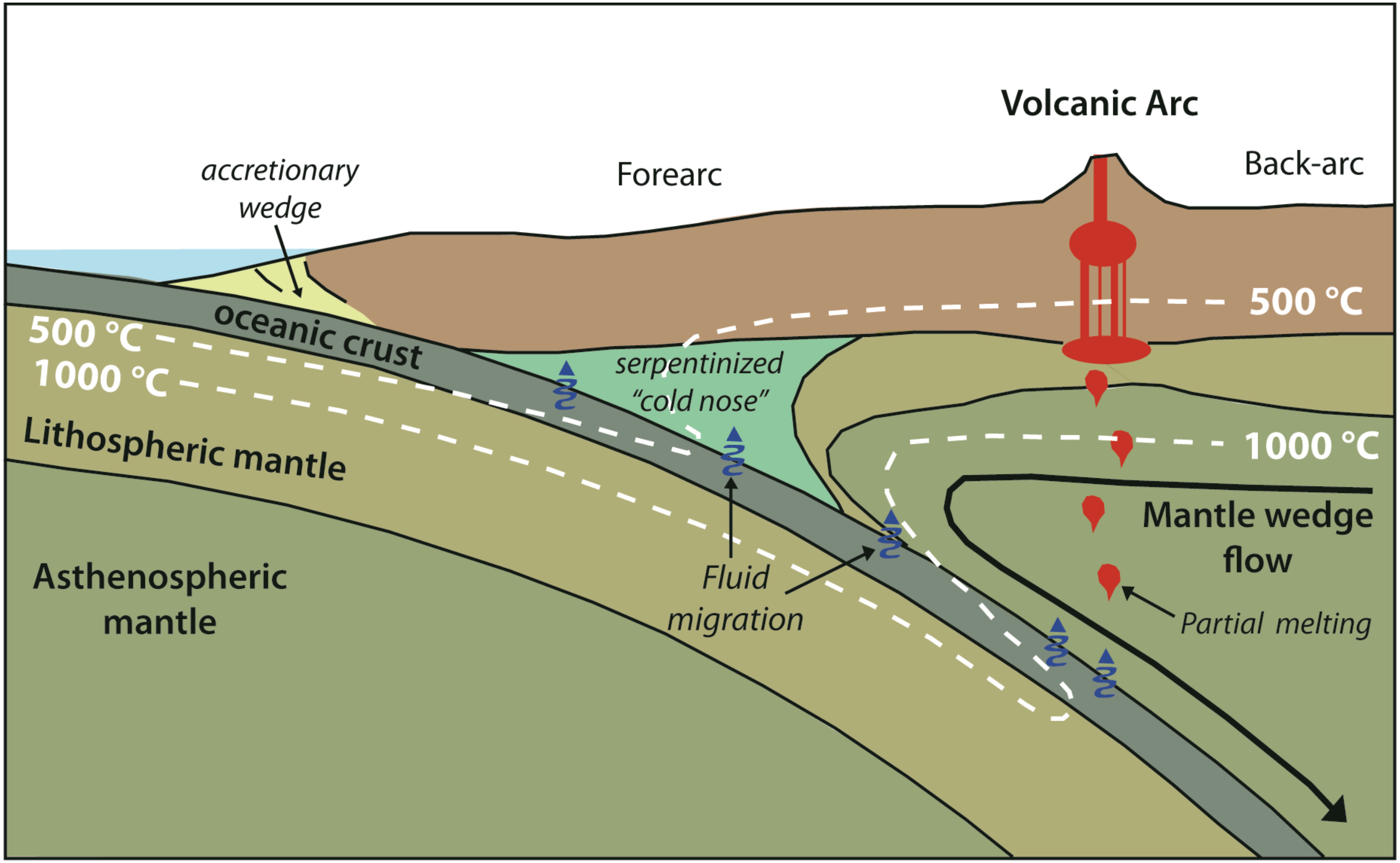
Paul Wallace

University of Oregon

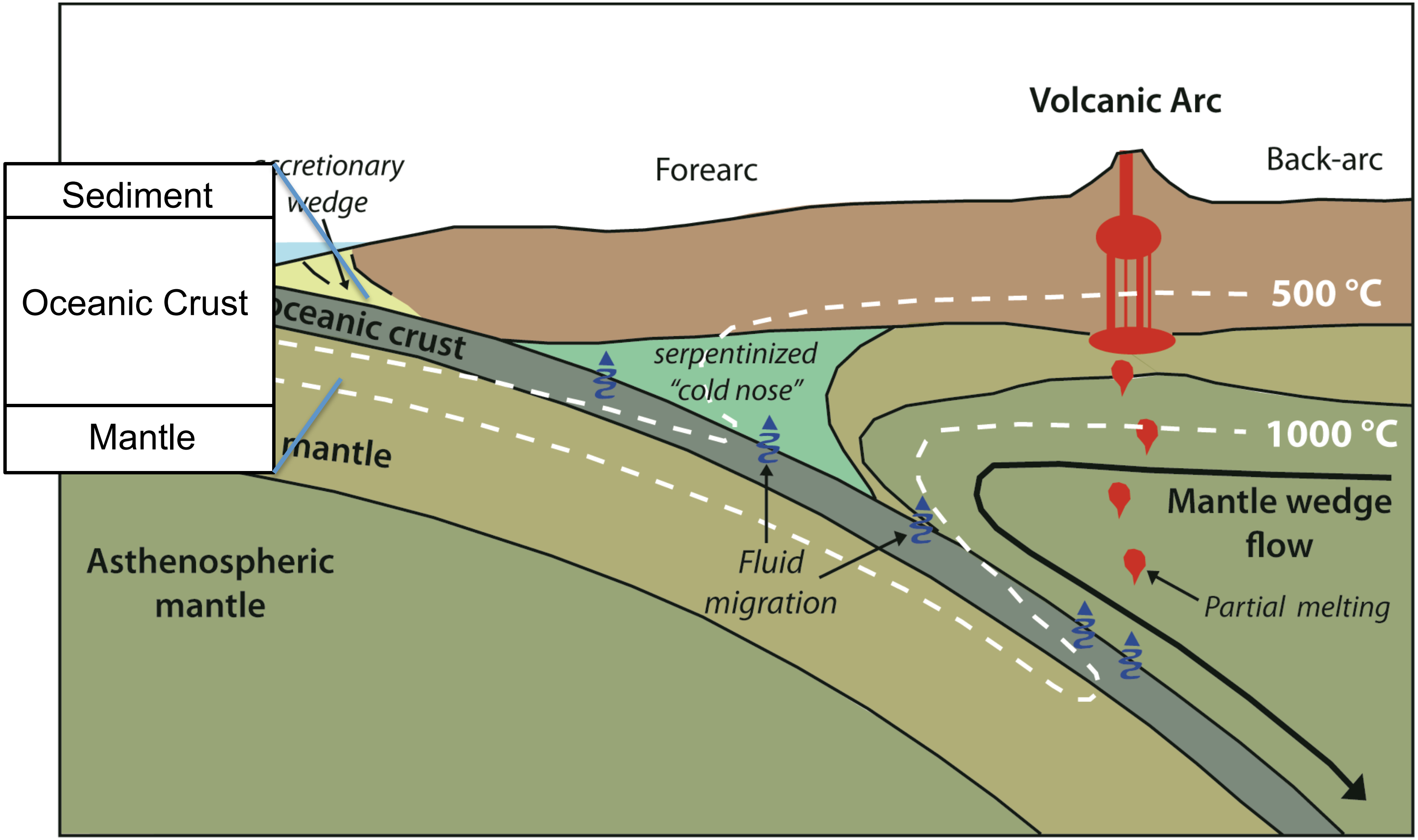
With thanks to: Dan Ruscitto, Kristina Walowski, Ellen Aster, Stephanie Weaver

Terry Plank, Laureen Cooper, Ikuko Wada , Erik Hauri, Mike Clynne, Bob Bodnar, Lowell Moore

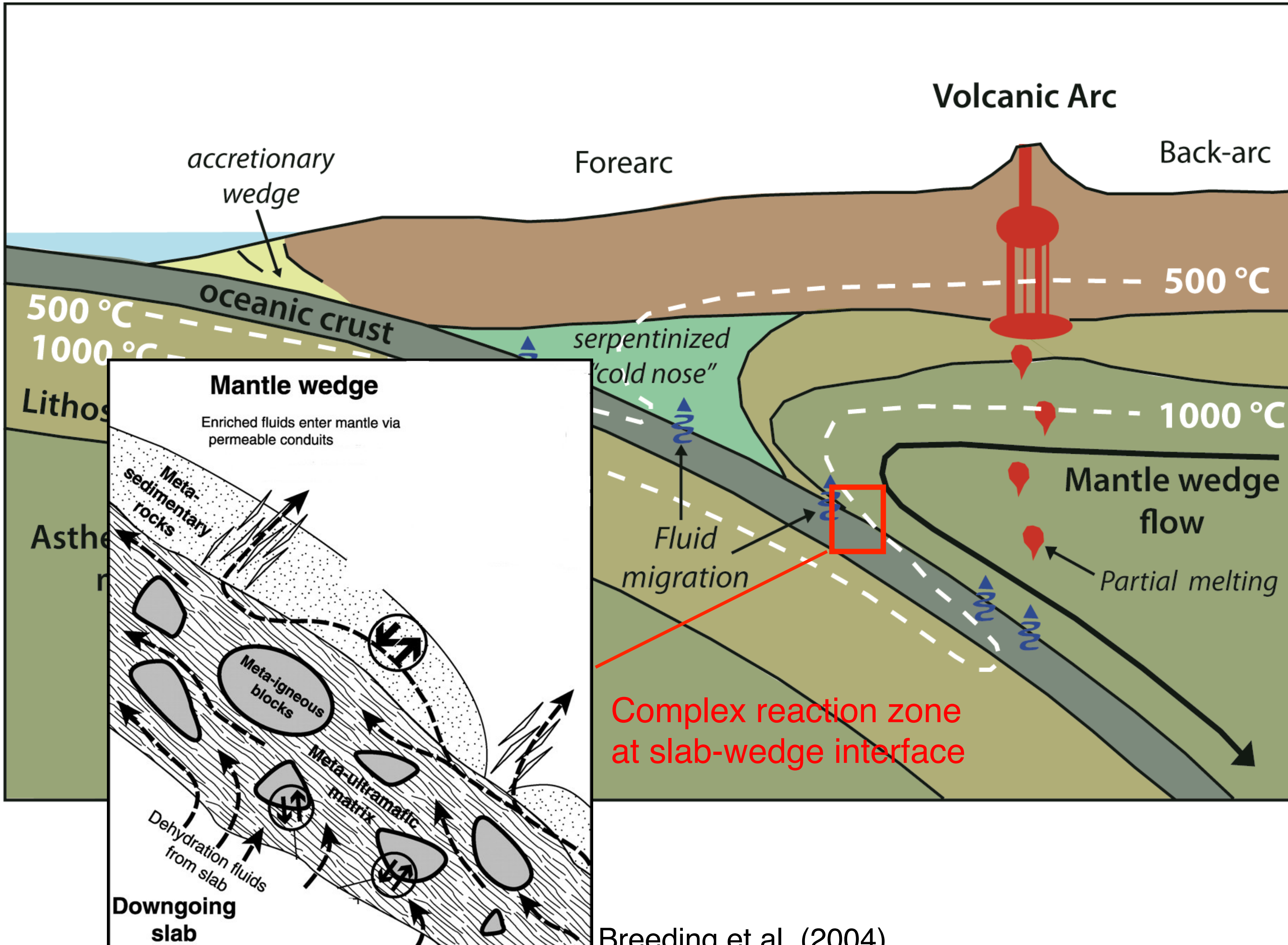
Volatile Recycling & Magma Generation in Arcs



Volatile Recycling & Magma Generation in Arcs



Volatile Recycling & Magma Generation in Arcs



Breeding et al. (2004)

Outline

- H_2O and CO_2 inputs to arcs
- Age and temperature of oceanic crust
- Modeling of slab P-T paths and dehydration
- Complications and known unknowns
- Volatile contents of arc magmas – what controls H_2O?
- H_2O/Ce & slab temperature variations
- Serpentinite, chlorite & fluid flux melting of the slab top
- CO_2 fluxes from arc volcanoes
- Why are arc magma CO_2 concentrations so poorly known?

H_2O & CO_2 in Sediment & Altered Oceanic Crust

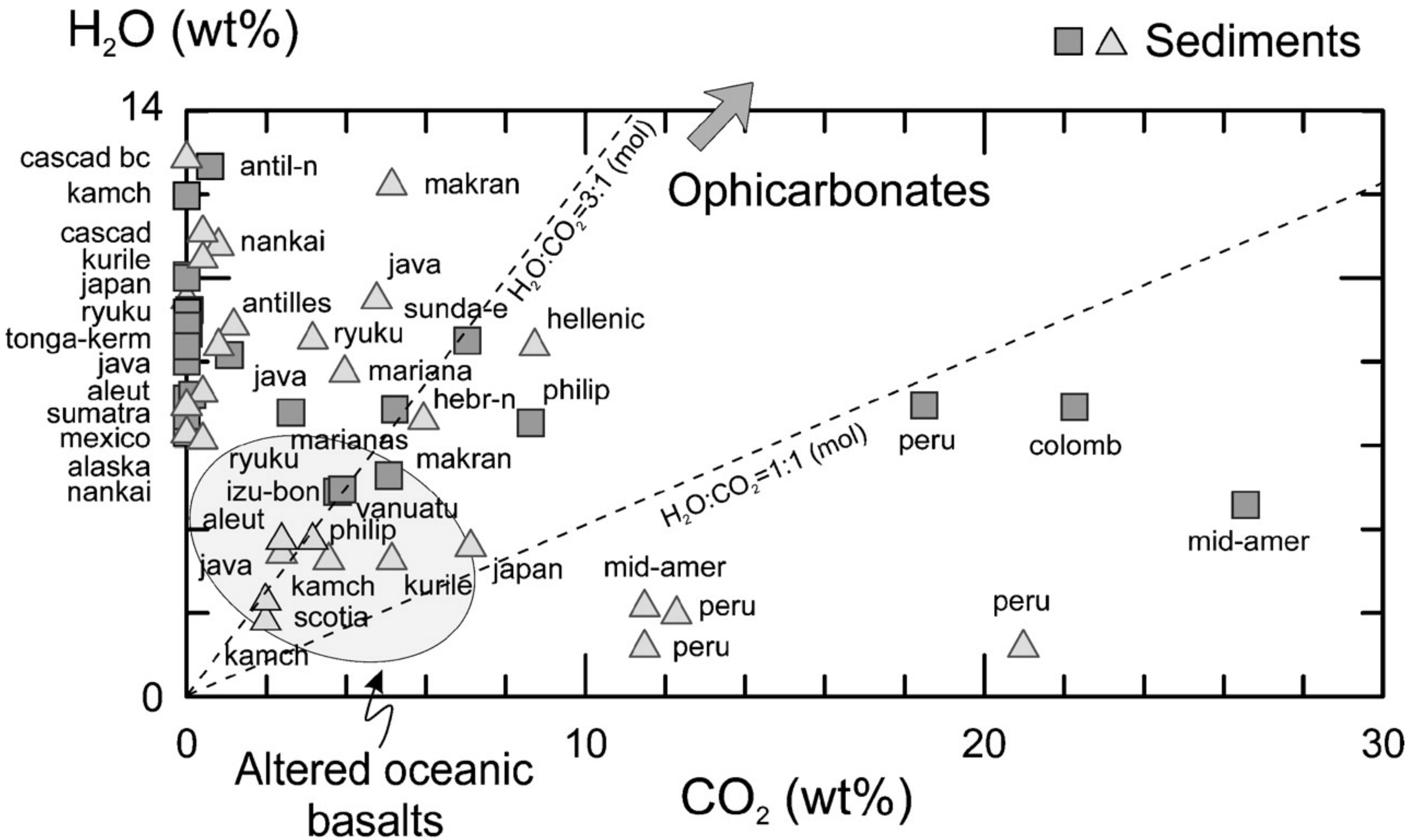
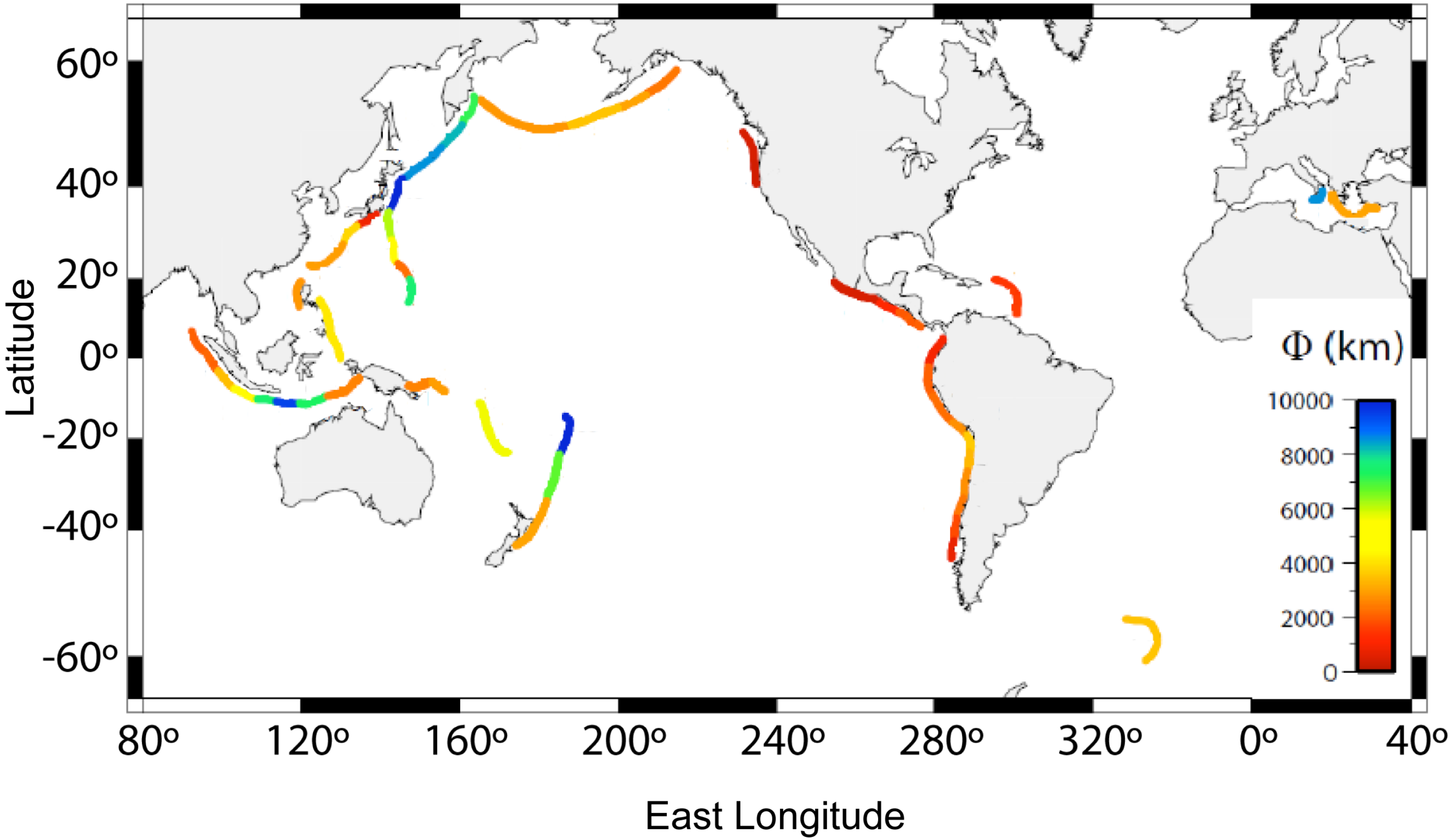


Figure 2 Estimates of the amount of H_2O in hydrates and CO_2 in carbonates in crustal columns being subducted. From Plank & Langmuir (1998) (*squares*) and Rea & Ruff (1996) (*triangles*). The shaded field represents altered MORB (Staudigel et al. 1996). Ophicarbonates after the data in Sciuto & Ottonello (1995) and Bonatti et al. (1974).

Poli & Schmidt (2002)

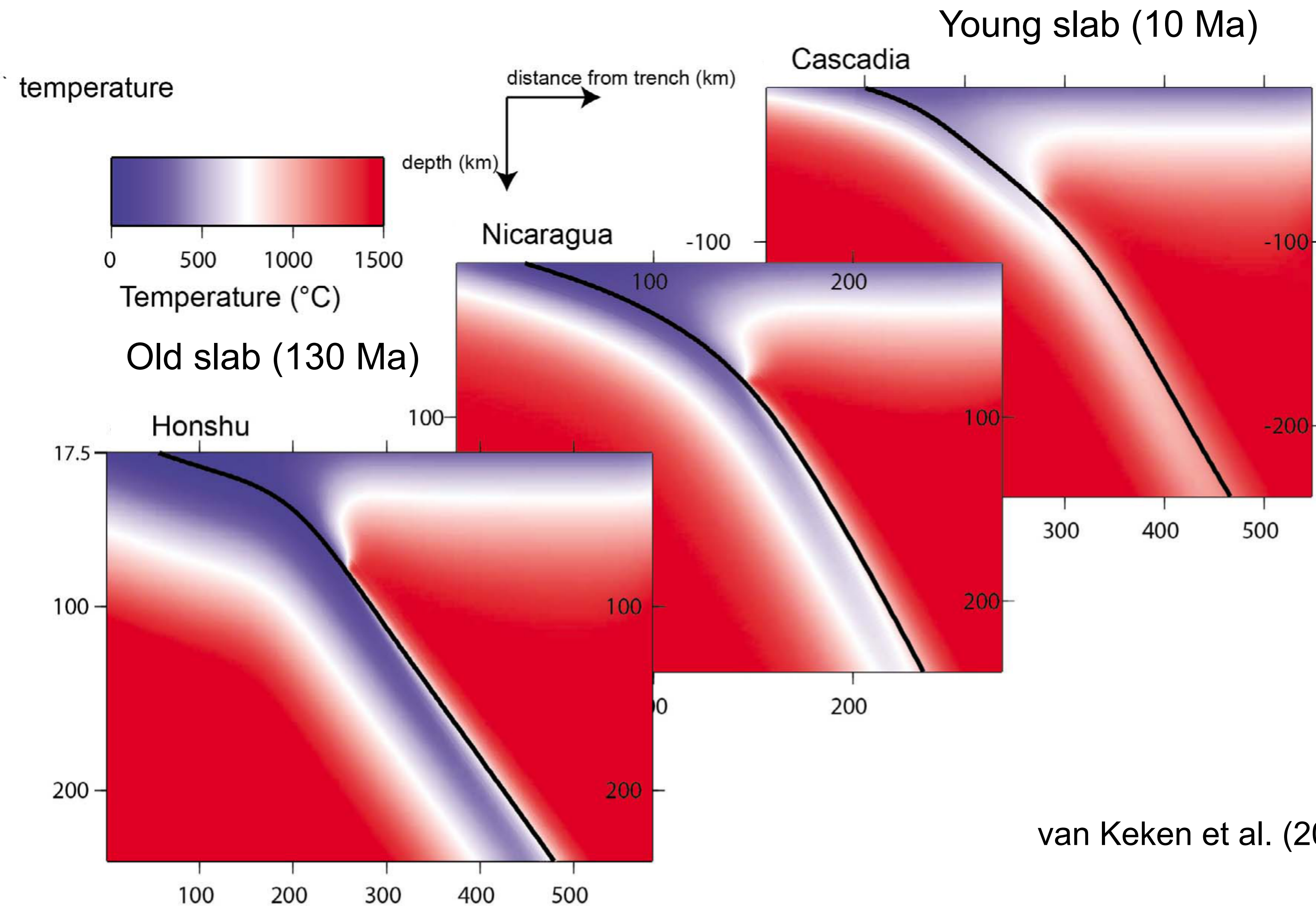
Variations in Thermal State of Subducted Lithosphere



Slab Thermal Parameter: $\Phi = V_c * \text{Age} * \sin \delta$

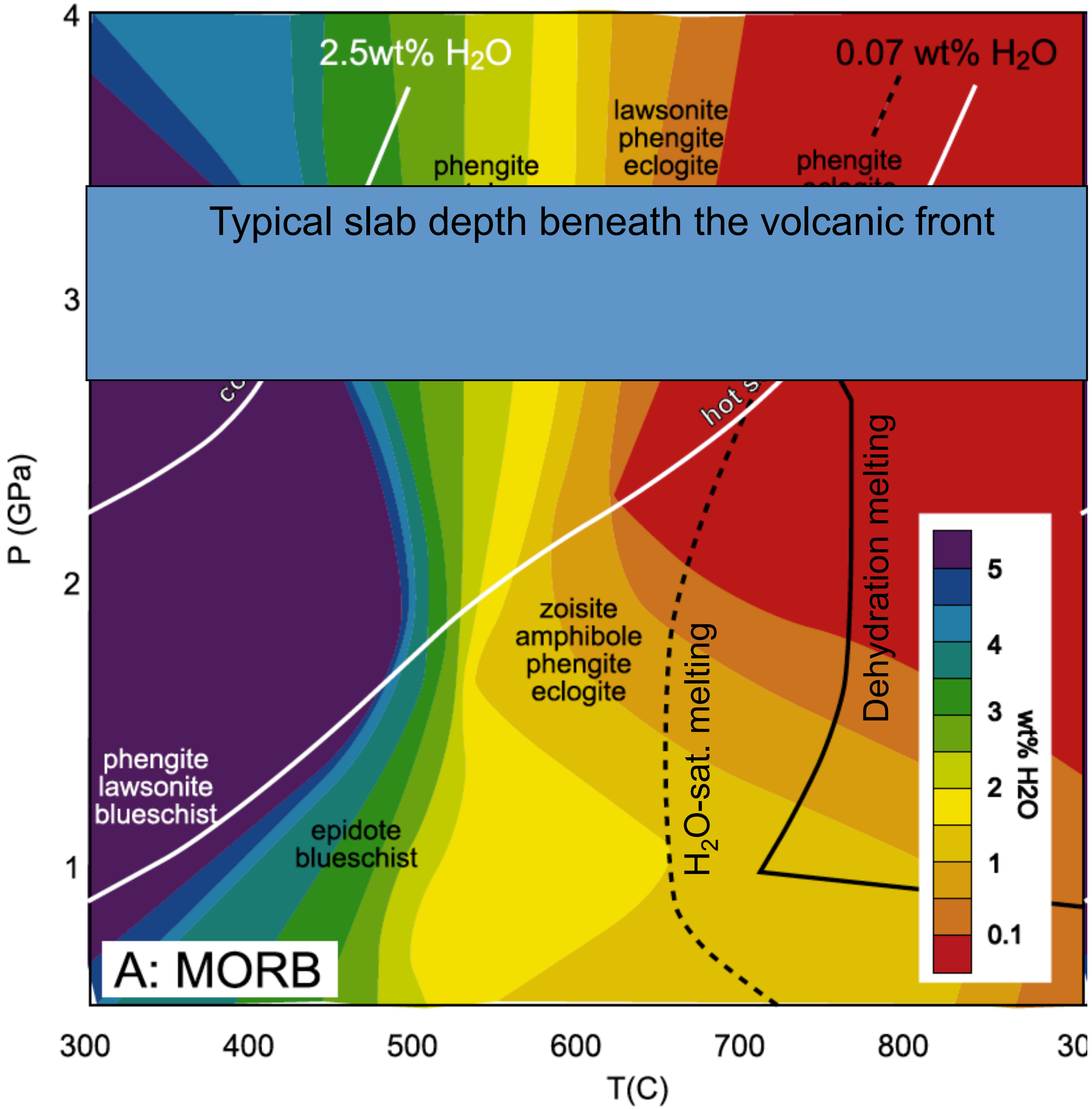
van Keken et al. (2011)

Geodynamic Modeling & the Effect of Slab Age



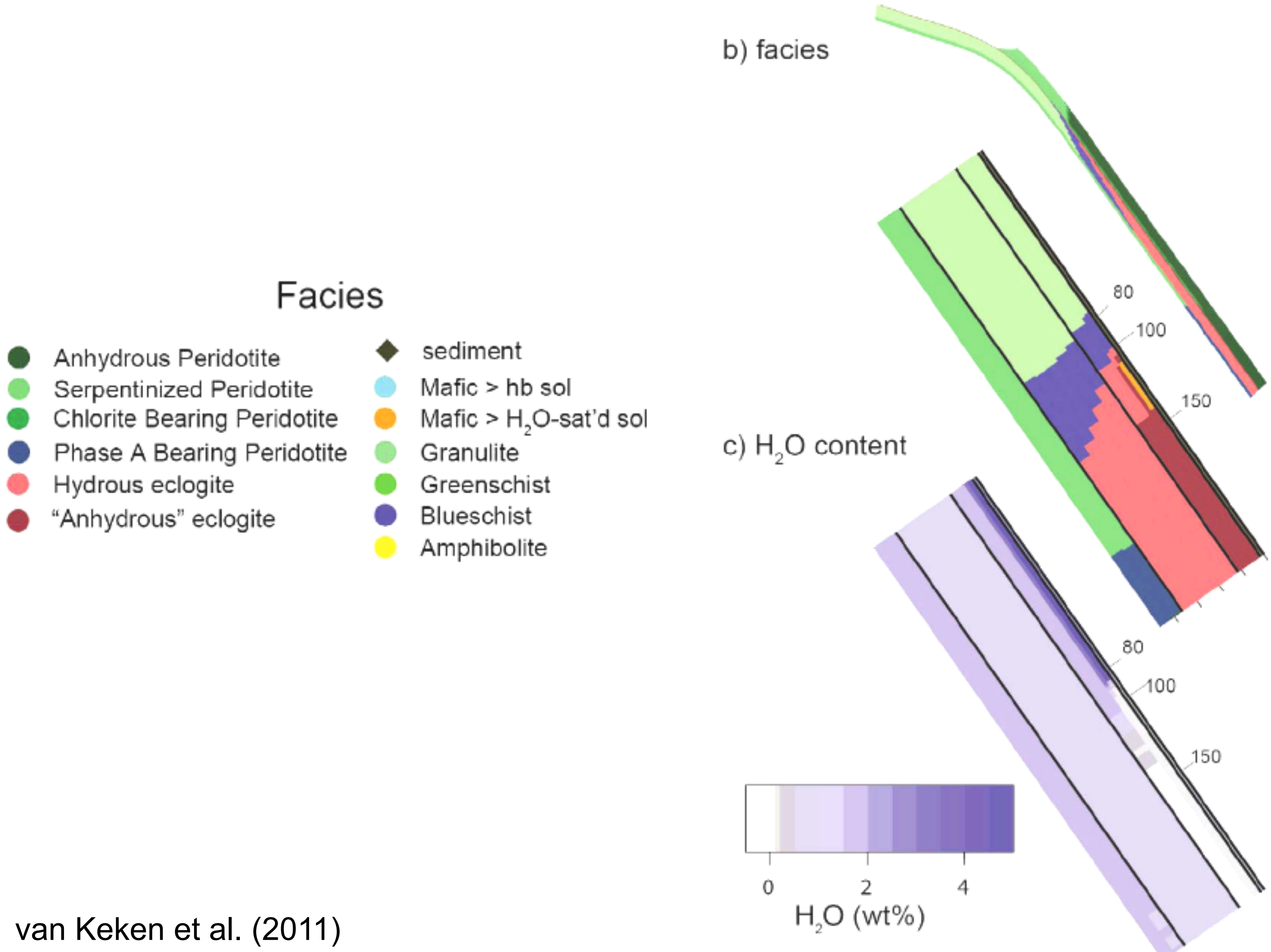
van Keken et al. (2011)

H_2O Contents of Subducted Oceanic Crust



Hacker (2008)

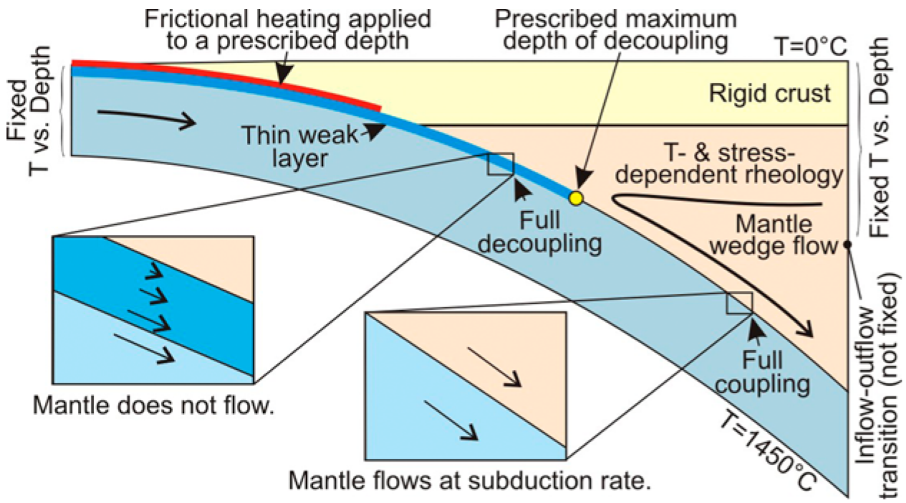
Lithologies and H_2O Contents in Slabs during Subduction Dehydration



van Keken et al. (2011)

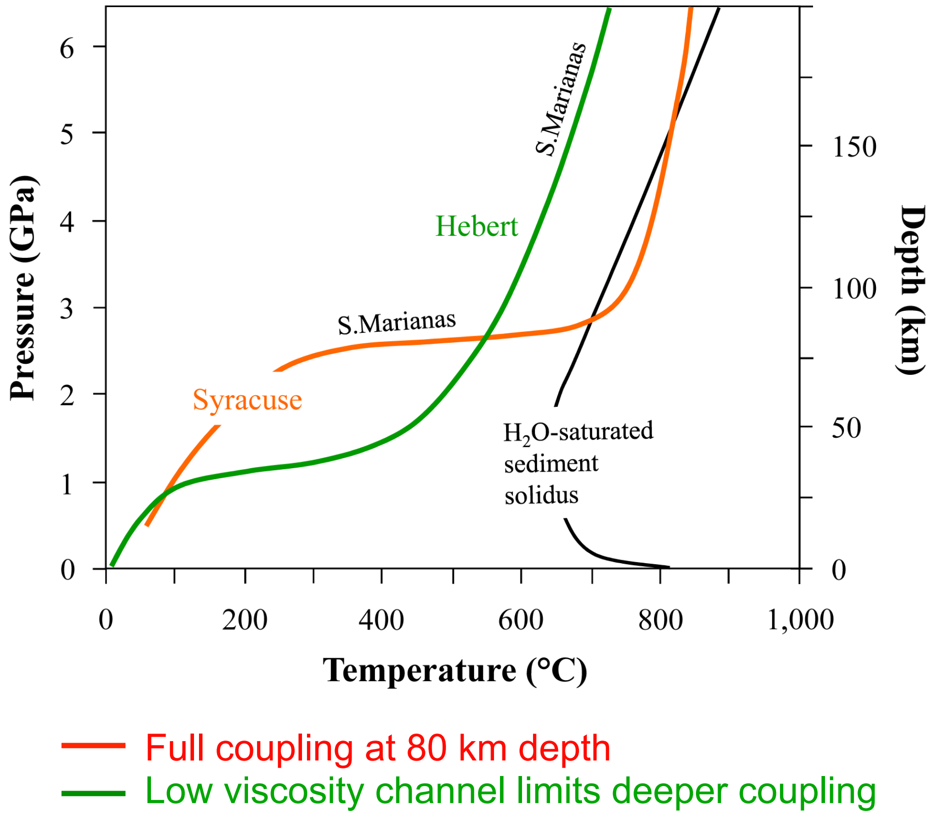
Temperatures from 2D Thermal Models

Boundary & Interface Conditions for Thermal Models



Wada & Wang (2009)

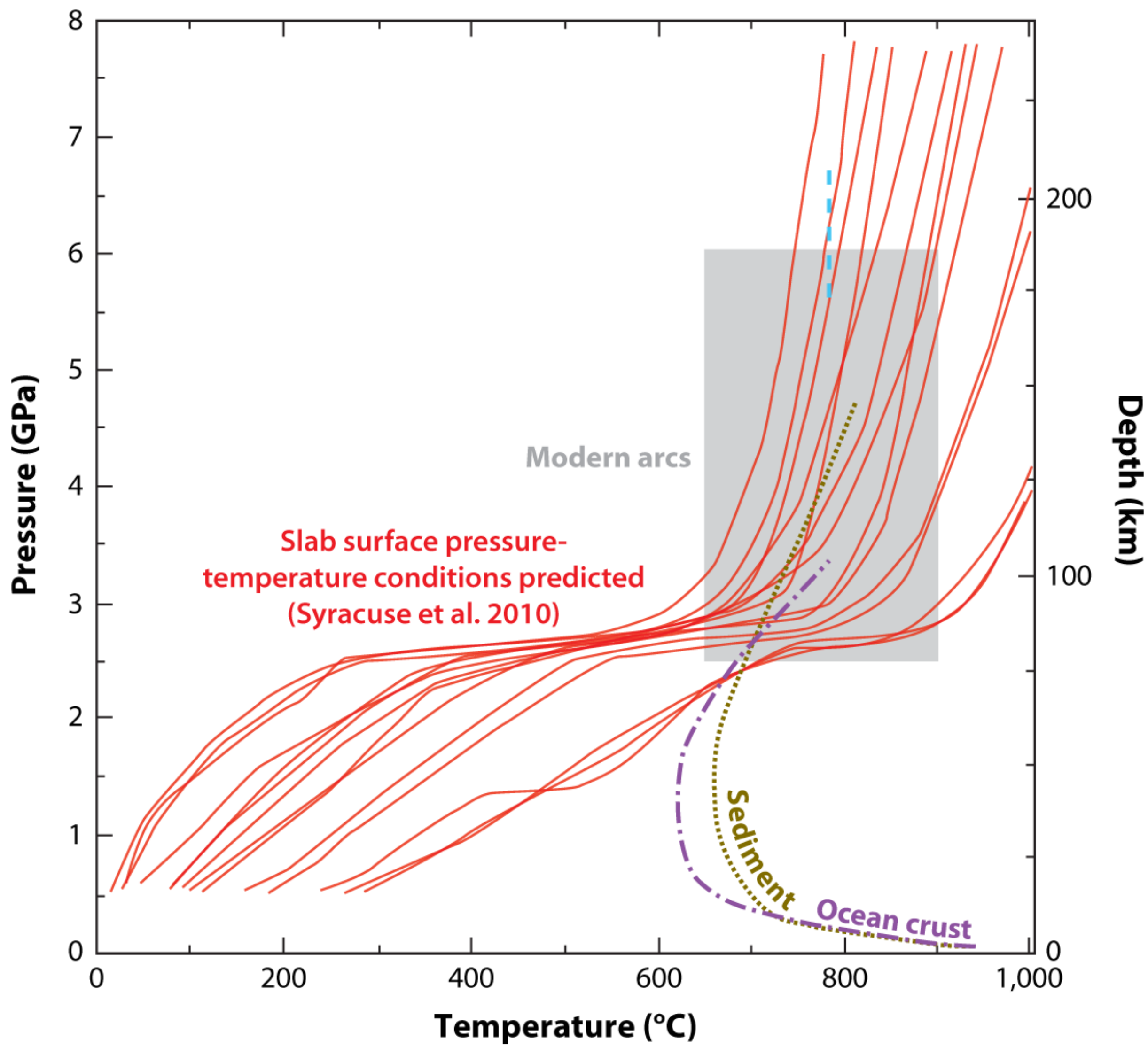
Comparison of Models



Cooper et al. (2012)
Hebert et al. (2009)

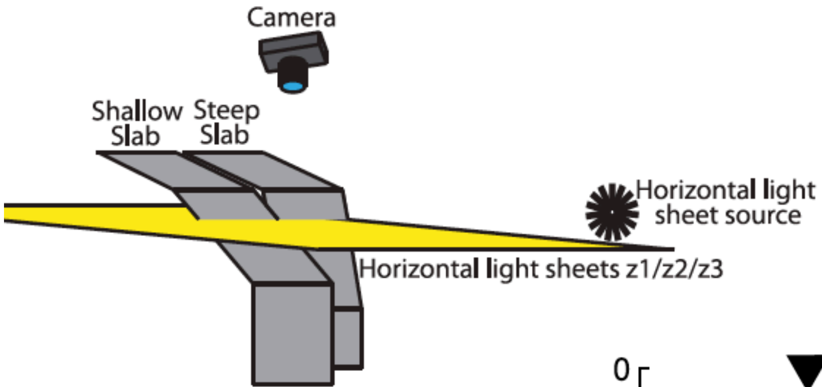
• Models with low-viscosity channels extending to depth predict cooler slab temperatures

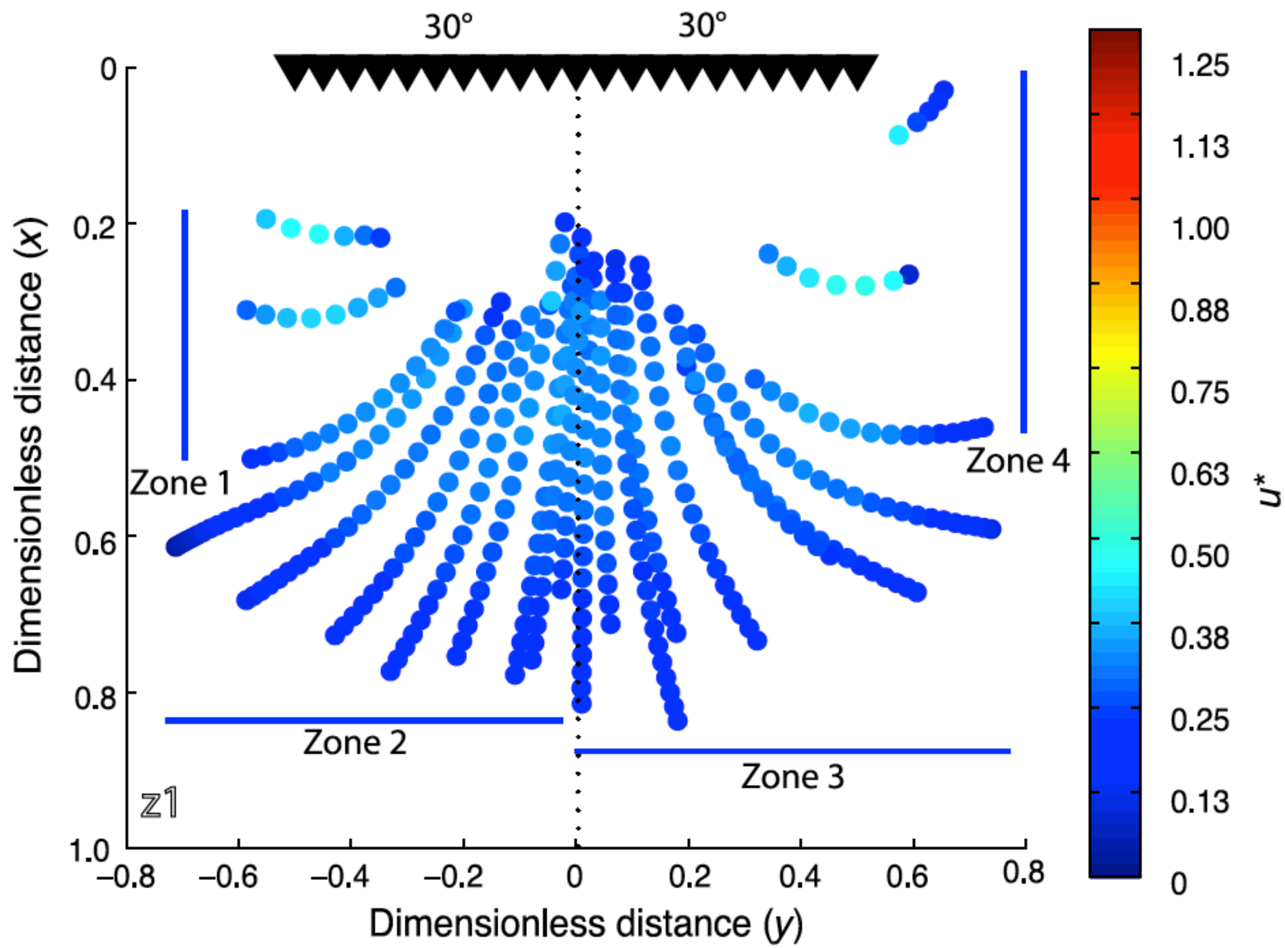
Modeled Slab Top P-T Paths



Grove et al. (2012)

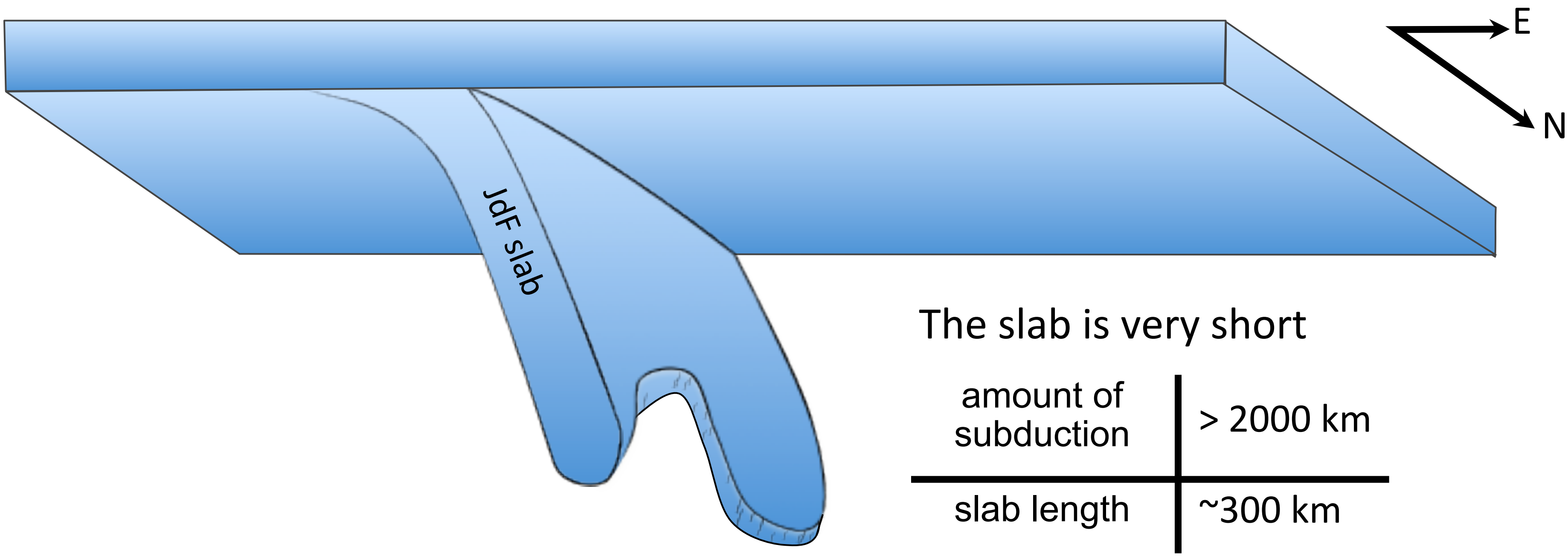
Analog Experiments Simulating Mantle Wedge Flow





MacDougall et al. (2014)

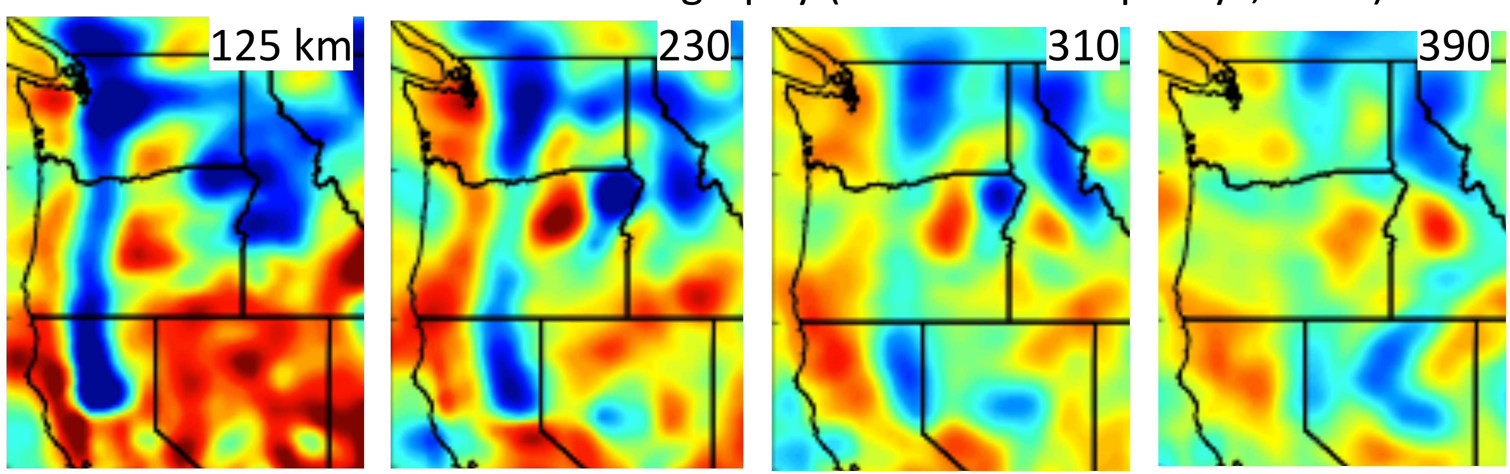
Complications in Slab Geometry – Cascadia



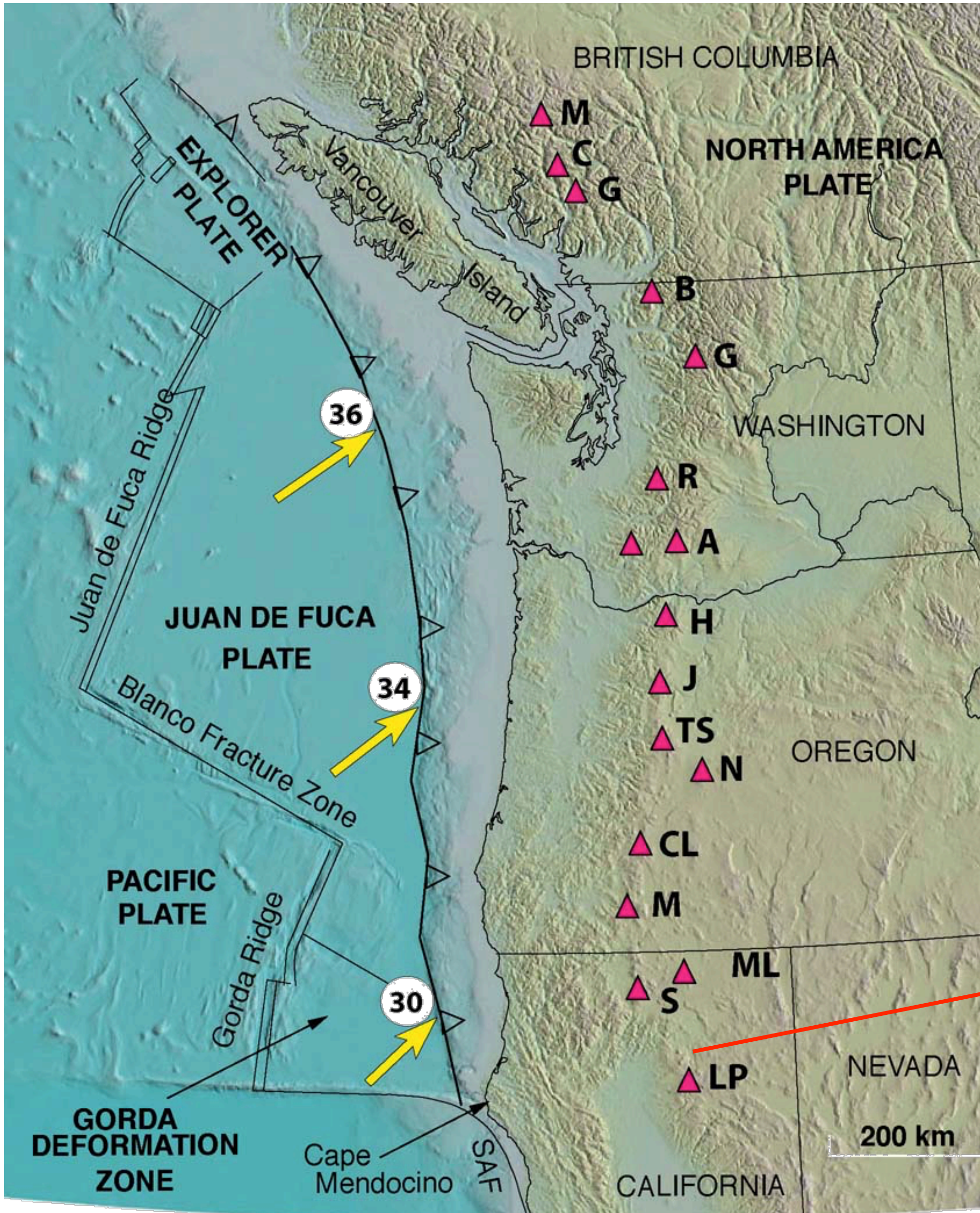
The slab is very short

amount of subduction	> 2000 km
slab length	~300 km

P-wave tomography (Darold & Humphreys, 2012)



Cascadia Subduction Zone & Volcanic Arc



- Oblique subduction
- Modest convergence rate
- Global endmember for hot slabs because of young oceanic crust

Abundant mafic cinder cones in the Lassen region

Key Conclusions About H_2O Fluxes Beneath Arcs

The top of the slab is sufficiently hot in all subduction zones that the upper crust, Including sediments and volcanic rocks, is predicted to dehydrate significantly.

The degree and depth of dehydration in the deeper crust and uppermost mantle are highly diverse and depend strongly on composition (gabbro versus peridotite) and local pressure and temperature conditions.

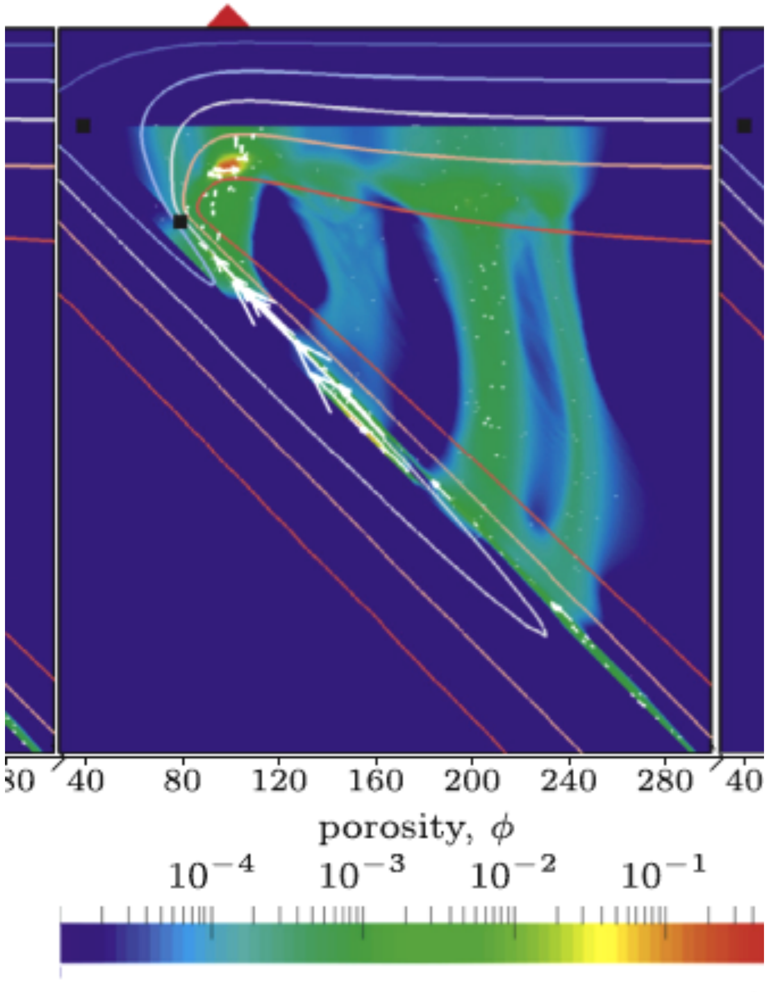
The upper mantle dehydrates at intermediate depths in all but the coldest subduction zones.

On average, ~30% of the bound H_2O subducted globally in slabs reaches 240 km depth, carried principally … in the gabbro and peridotite sections.

The predicted global flux of H_2O to the deep mantle is smaller than previous estimates but still amounts to about one ocean mass over the age of the Earth. At this rate, the overall mantle H_2O content increases by 0.037 wt % (370 ppm) over the age of the Earth.

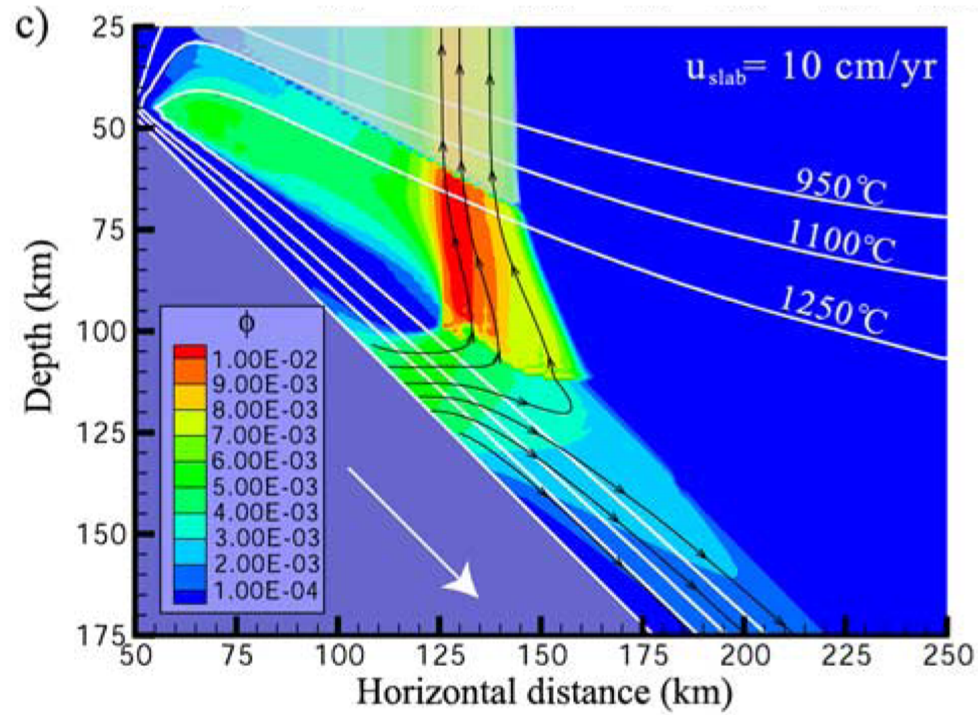
Van Keken, Hacker, Syracuse, Abers (2014) JGR

How Do Fluids & Melts Move Through the Slab & Wedge?



Compaction pressure gradients cause updip flow within the slab

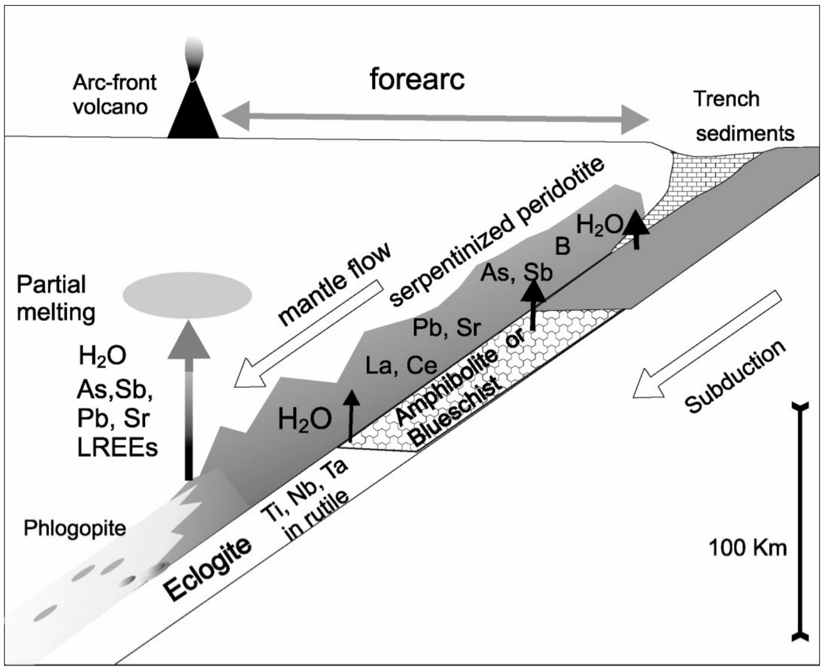
Wilson et al. (2014)



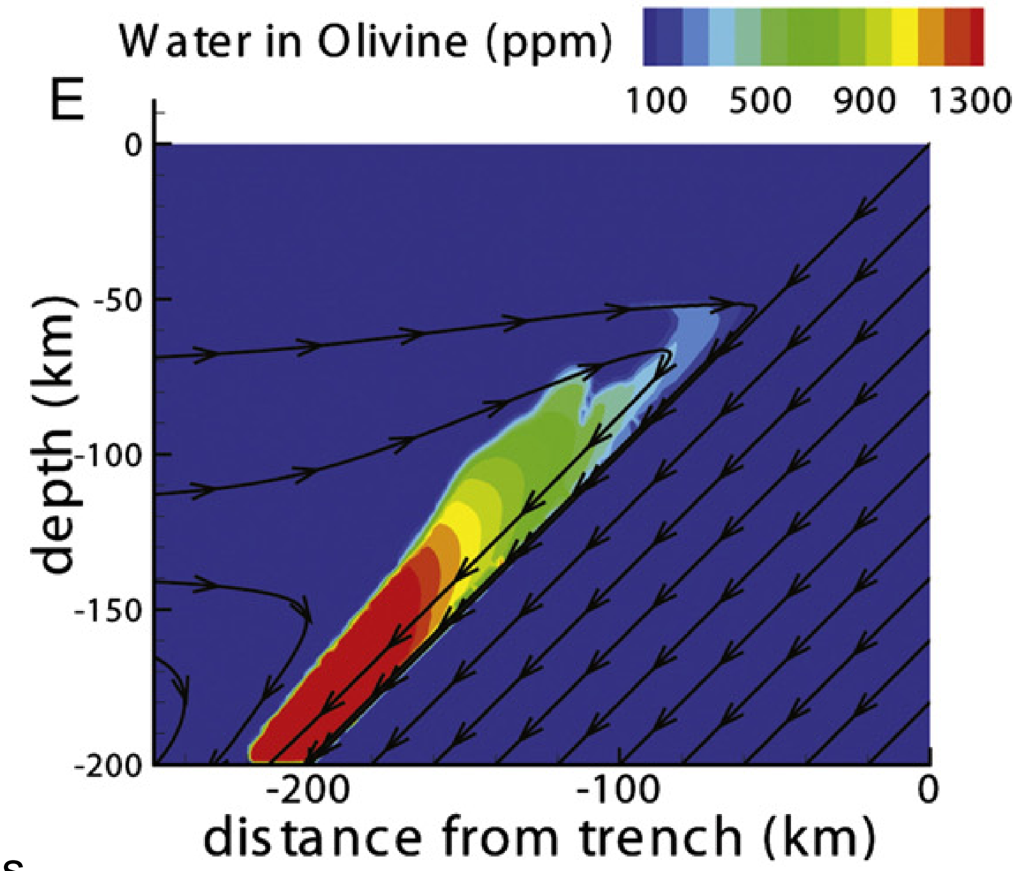
Solid mantle flow deflects rising fluids & melts in the mantle wedge

Cagnioncle et al. (2007)

Reaction of Fluids with the Mantle Wedge



Downdragging of forearc mantle supplies fluid through multistage process

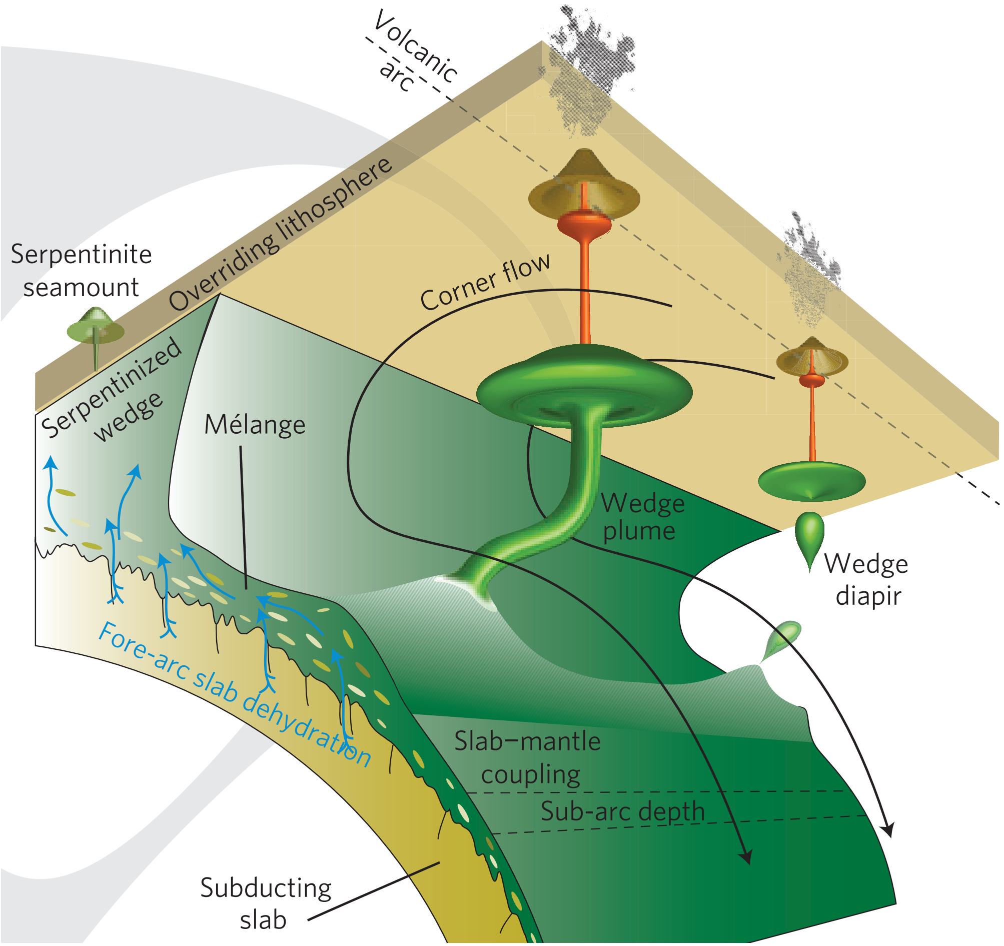


Hydration of olivine forms a low-viscosity channel

Hattori & Guillot (2004)

Hebert et al. (2009)

Diapiric Rise of Sediments or Melange from the Slab Top



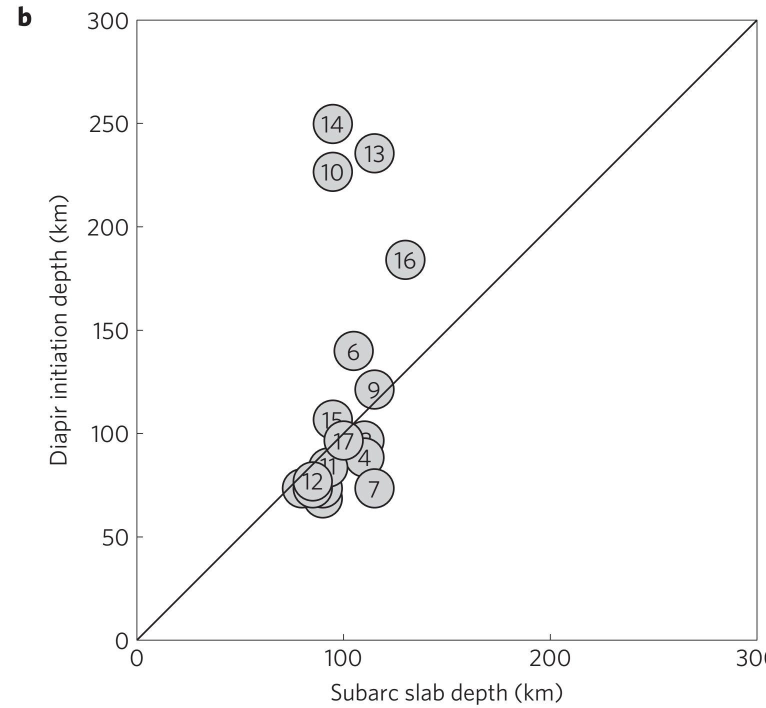
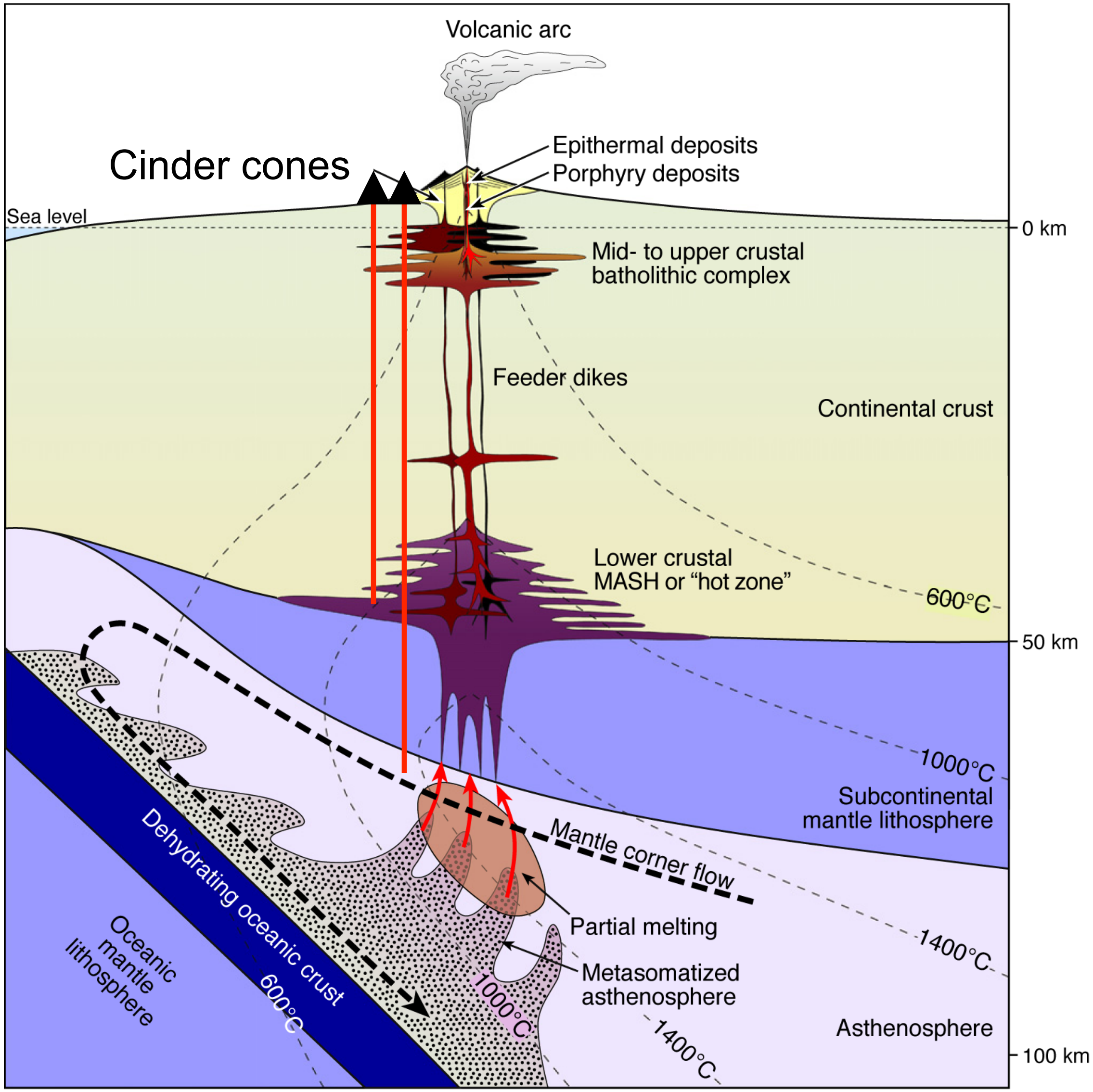


Figure 5 | Summary of conditions for sediment diapir formation in global subduction zones. a, Diapir initiation temperature versus sediment layer thickness[30], and **b**, diapir initiation depth versus subarc slab depth (as compiled in ref. 8) calculated for 17 slab-top geotherms[8]. Subducting sediment layer thicknesses are corrected for compaction to a density of 2,800 kg m^{-3}. Numbers (in order of increasing slab thermal parameter) correspond to subduction zones: 1—Cascadia, 2—Nankai, 3—Mexico, 4—Colombia-Ecuador, 5—SC Chile, 6—Kyushu, 7—N. Sumatra, 8—Alaska, 9—N. Chile, 10—N. Costa Rica, 11—Aleutians, 12—N. Hikurangi, 13—Mariana, 14—Tonga-Kermadec, 15—Kamchatka, 16—Izu, and 17—NE Japan.

Marschall & Schumacher (2012)

Behn et al. (2011)

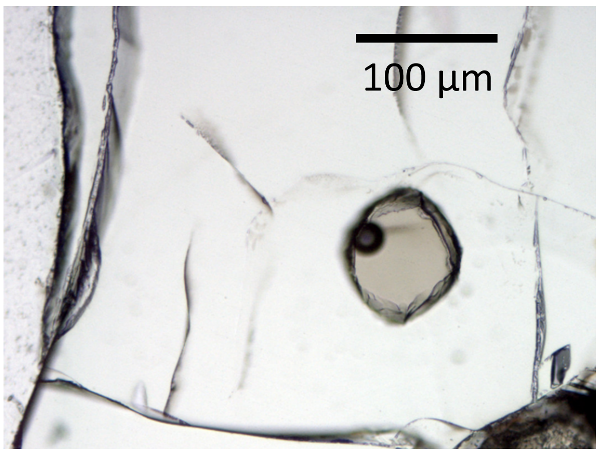
Magmatic Volatile Contents – The View from Above

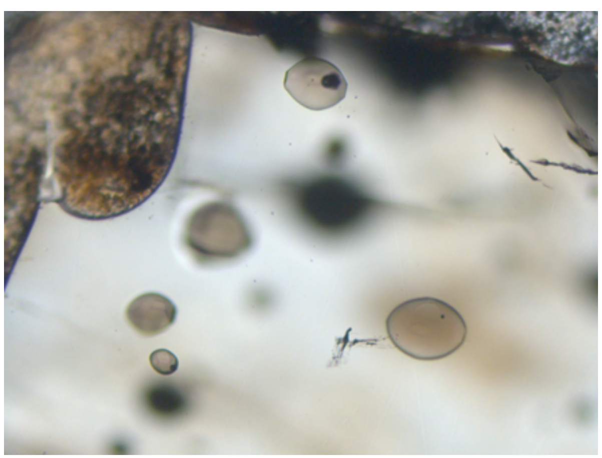


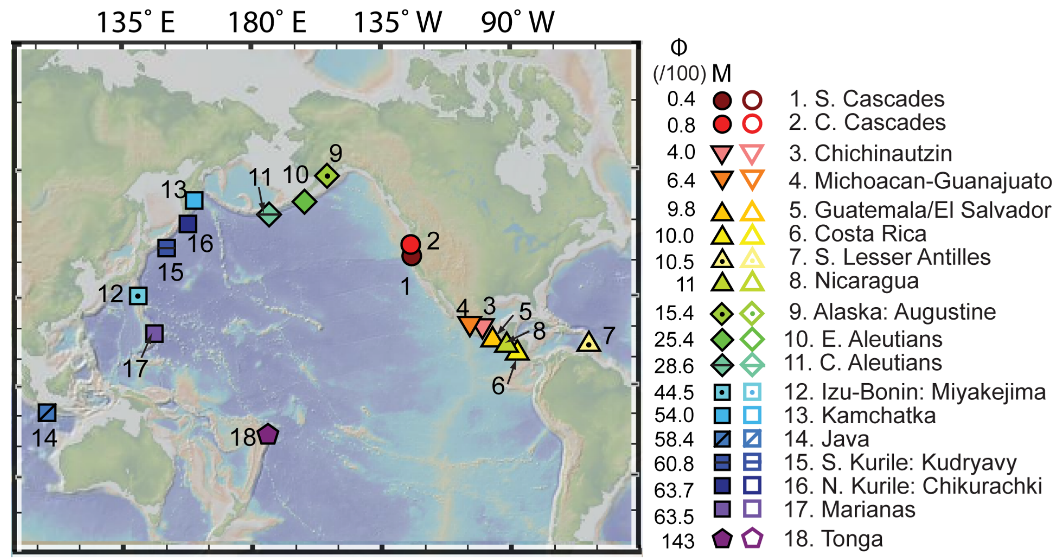
Modified from Richards (2011)

Data & Methods

- Melt inclusions trapped in olivine phenocrysts provide a record of volatiles & trace elements.
- Published data for 100 volcanoes from 18 subduction zone segments.

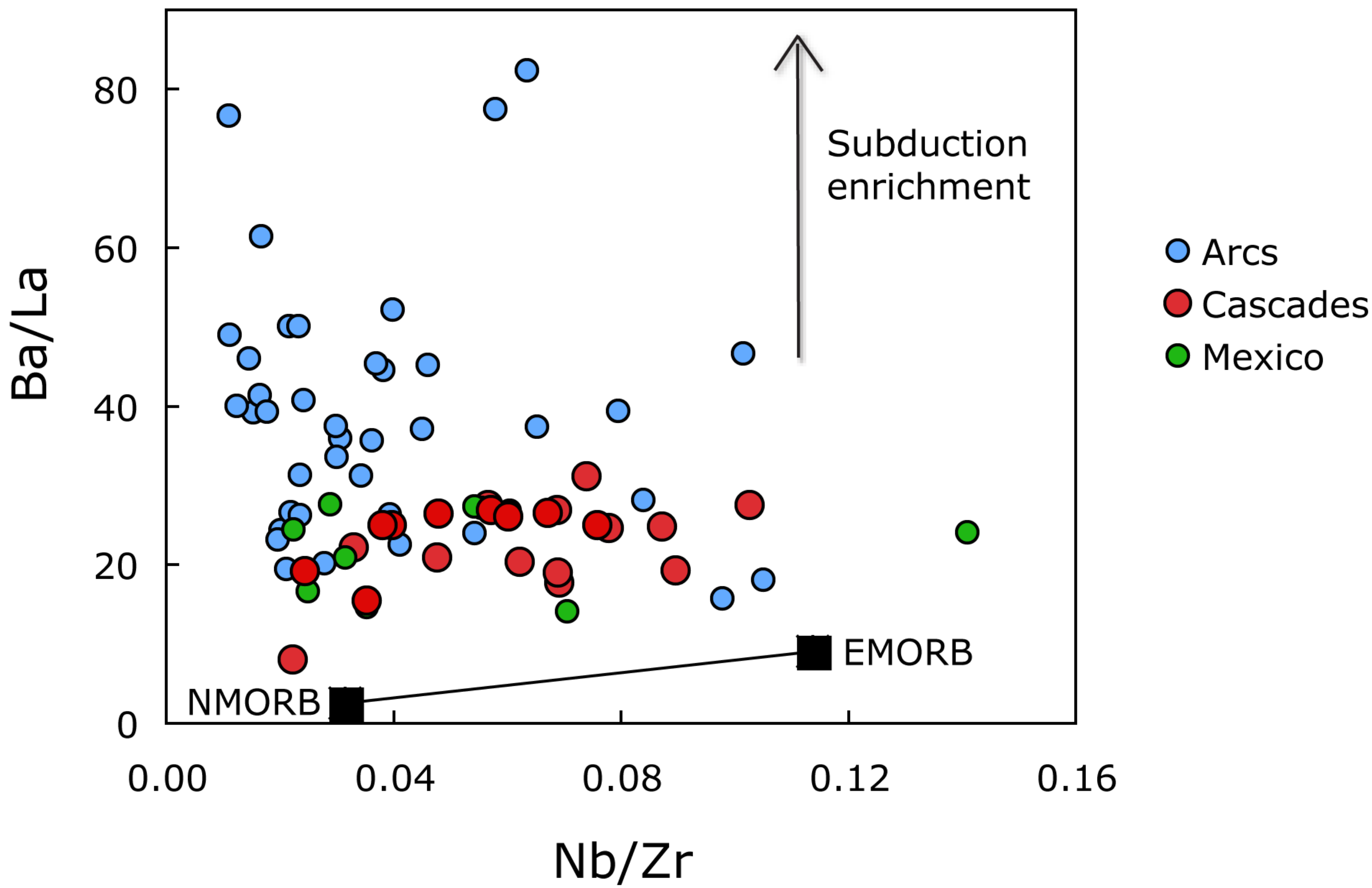






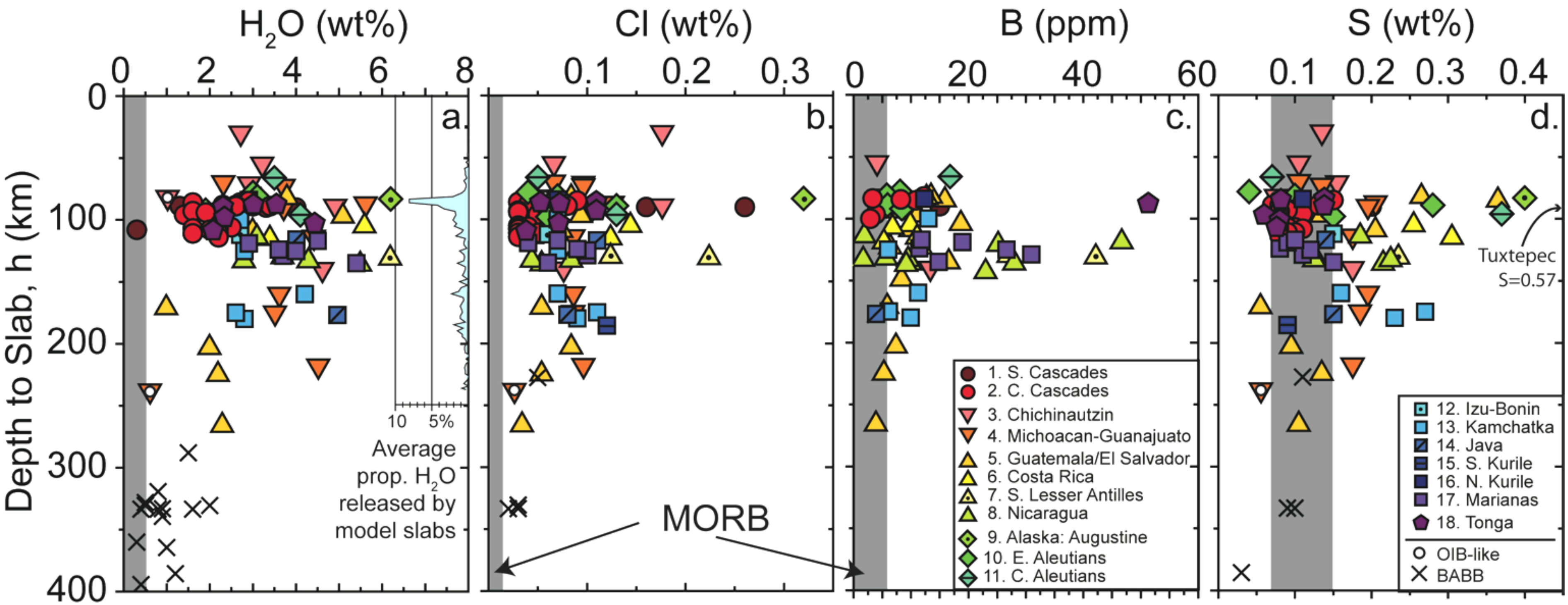
Cooper et al. (2012) G-Cubed
Ruscitto et al. (2012) G-Cubed
Plank et al. (2013) EPSL

Compositional Variations in Arc Melt Inclusions



Global arc database of melt inclusions from Ruscitto et al. (2012)

Volatile Contents of Primitive Arc Magmas

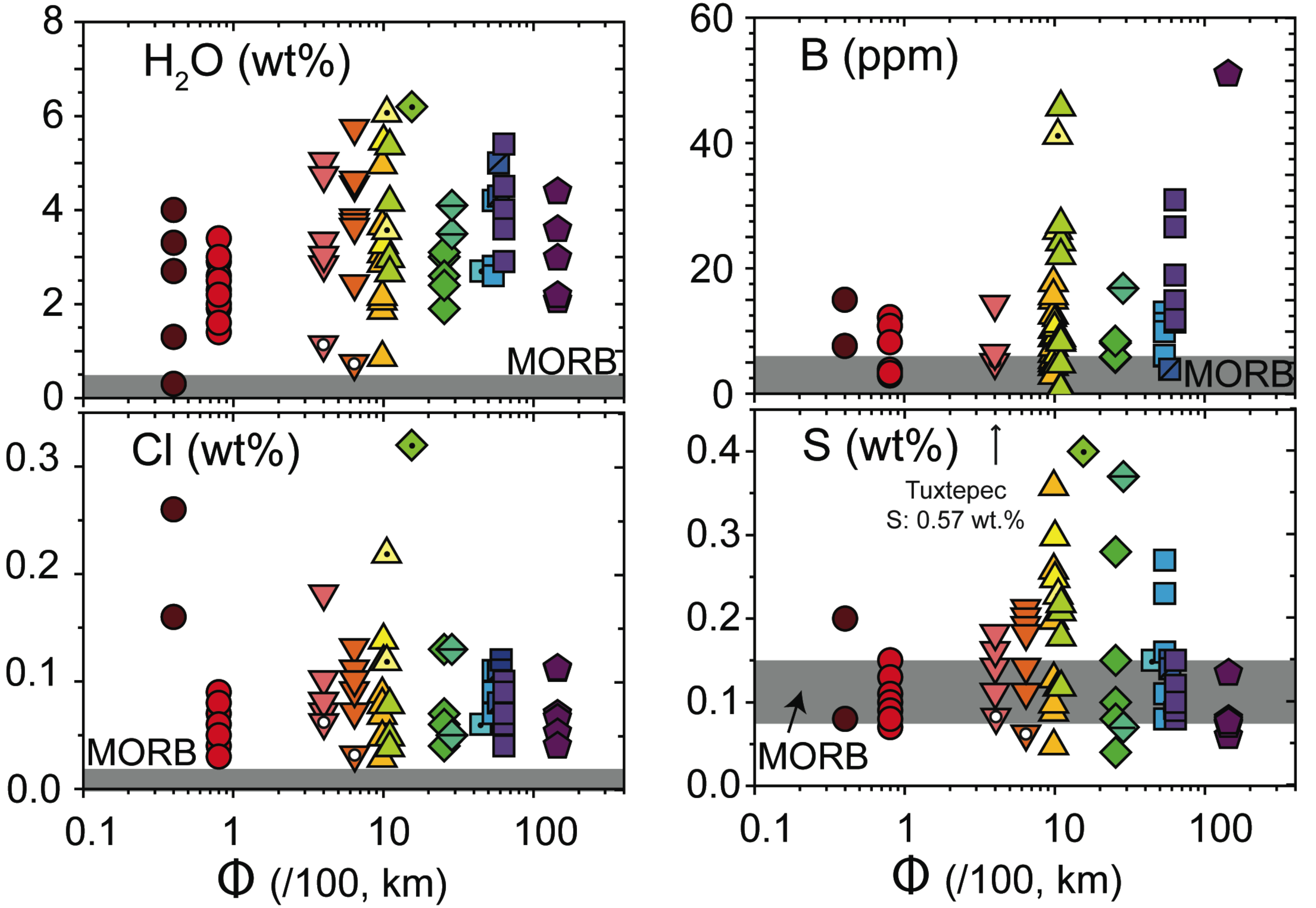


Ruscitto et al. (2012)

- Each data point represents a single volcano based on melt inclusion data
- All compositions have been corrected to equilibrium with Fo_{90} olivine

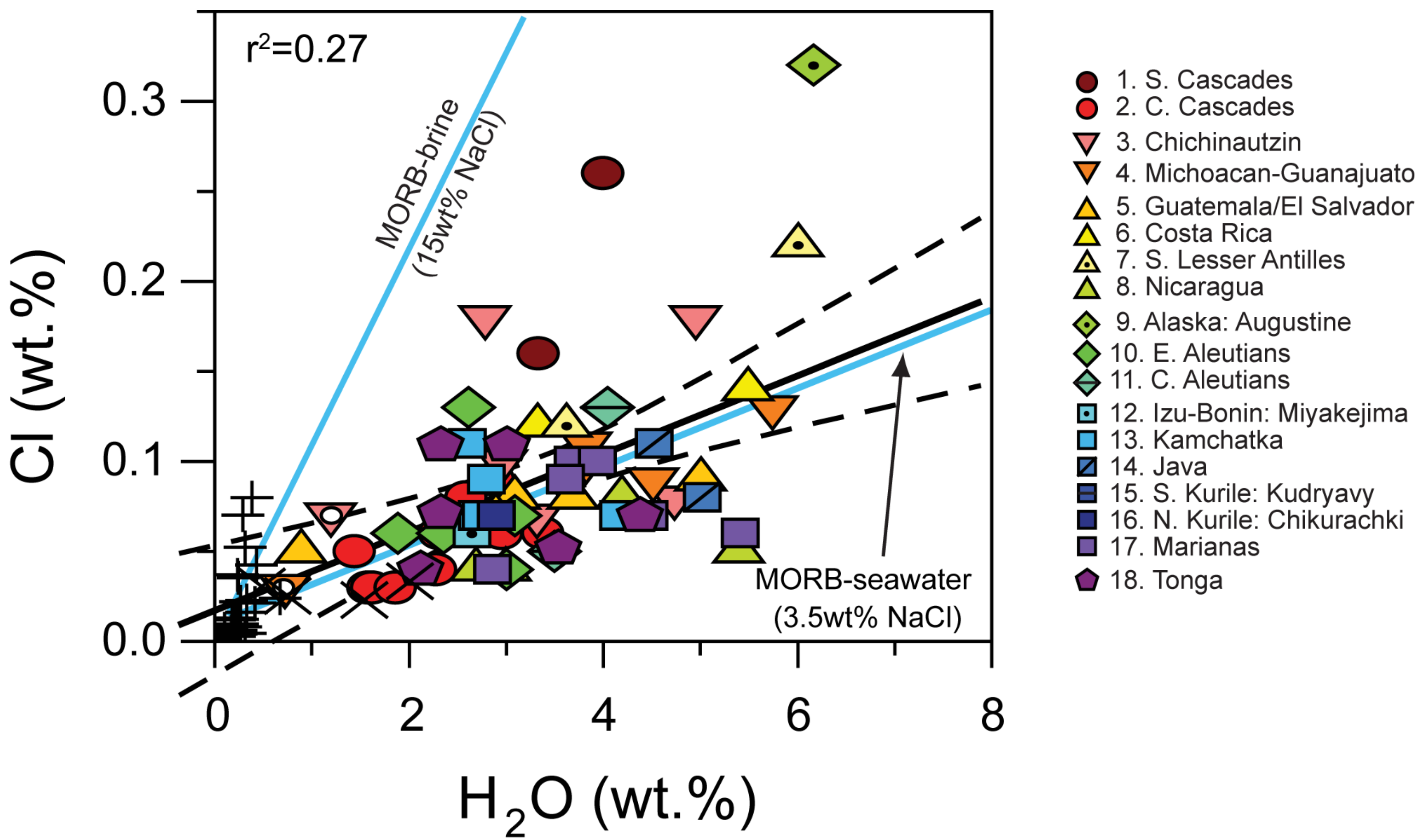
H_2O release in A from van Keken et al. (2011)

Comparison of Volatile Contents & Slab Thermal Parameter



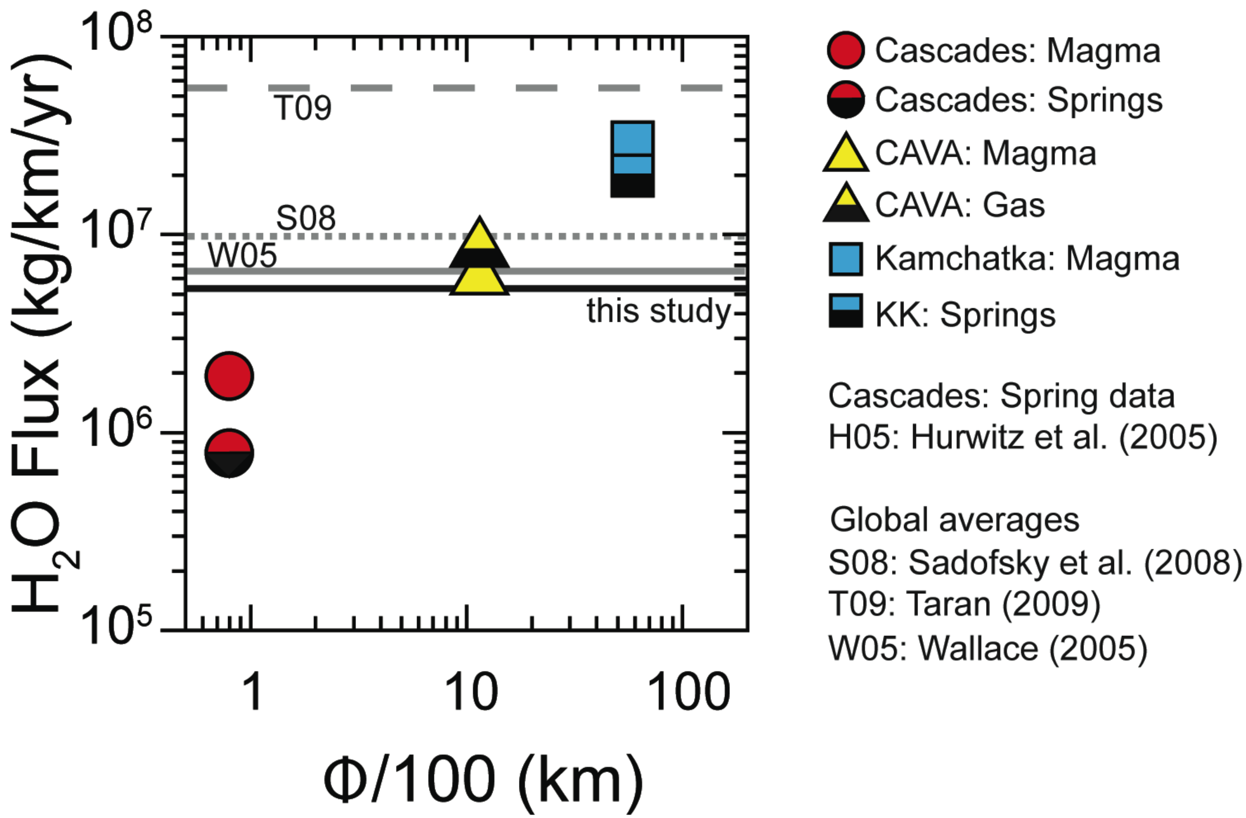
Ruscitto et al. (2012)

Subduction Recycling of Seawater Chlorine



Ruscitto et al. (2012)

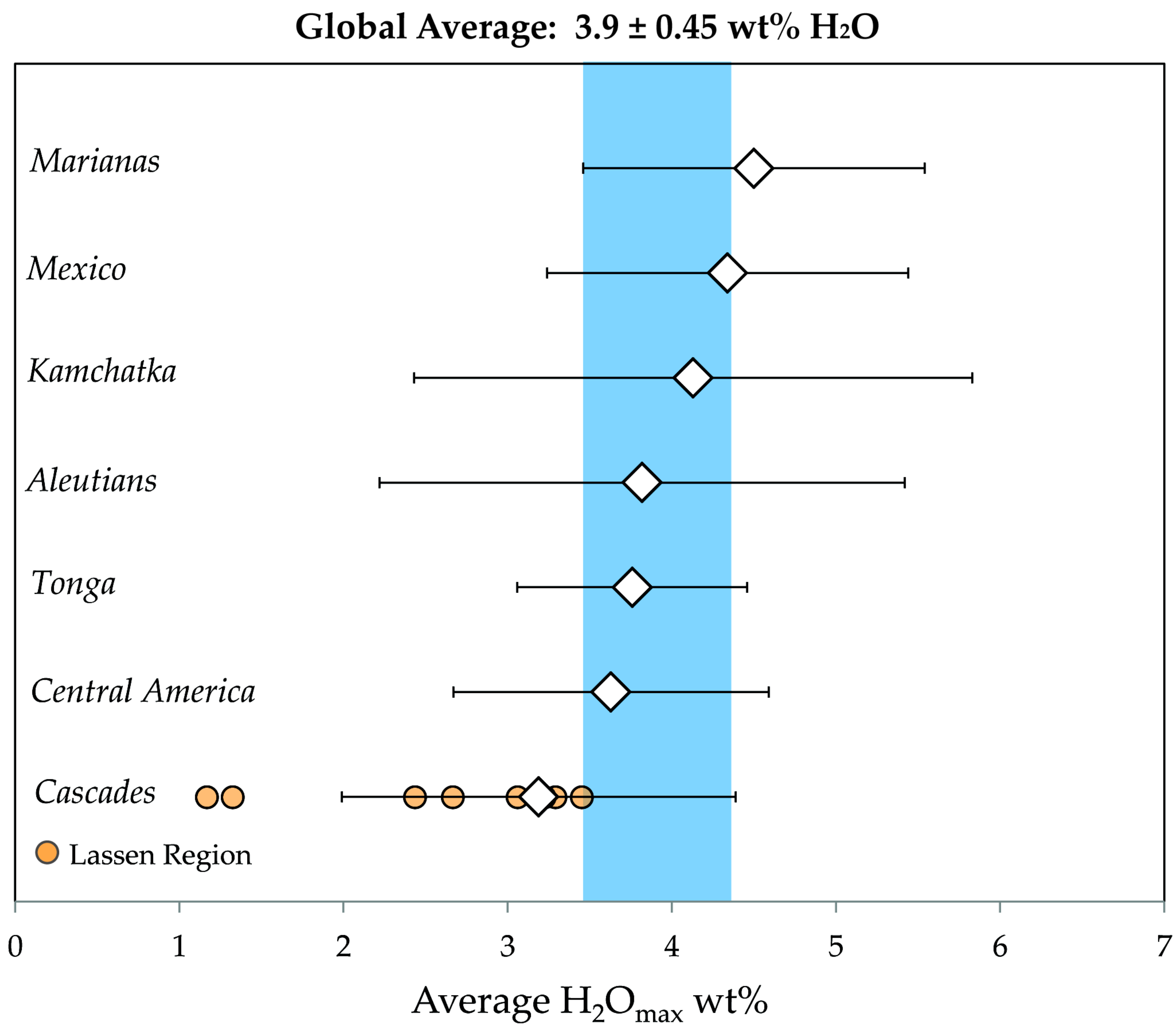
H_2O Fluxes from Subduction Zone Magmatism



- Arcs With Hotter Slabs Have Lower H_2O Outfluxes
- Consistent with prediction that hot slabs strongly dehydrate beneath the forearc

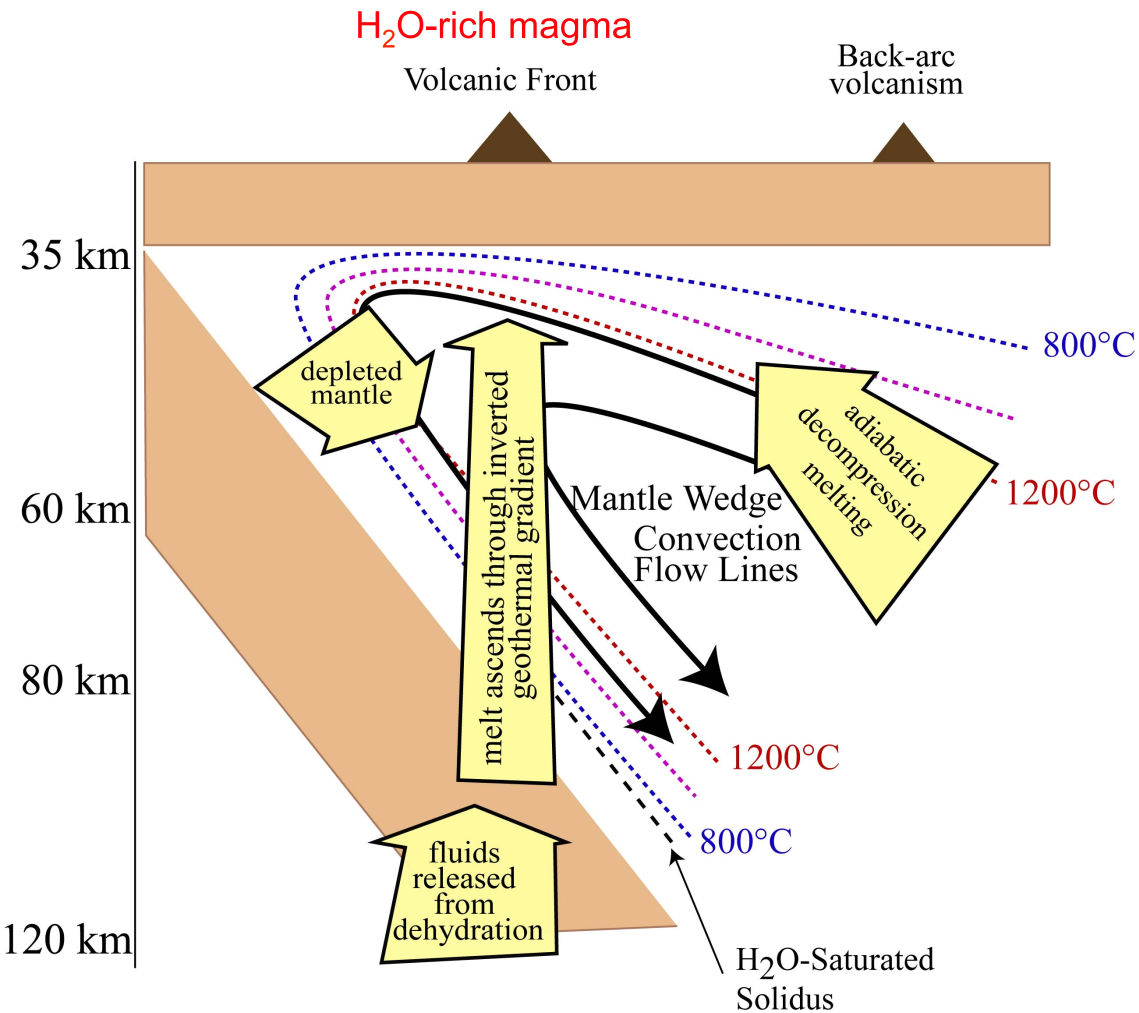
Ruscitto et al. (2012)

H_2O Contents of Arc Magmas



Modified from Plank et al. (2013)

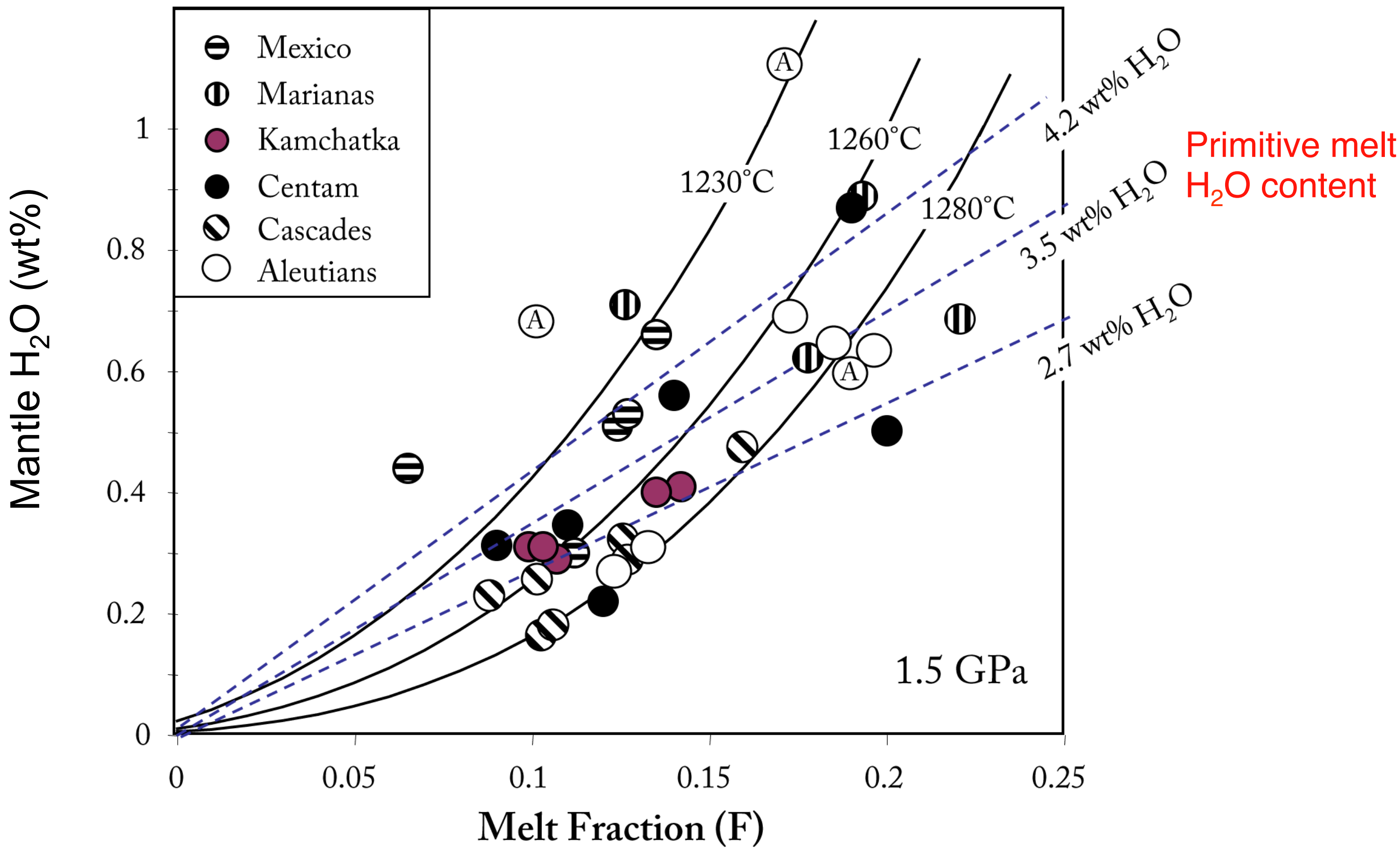
Flux Melting in Subduction Zones



- H_2O-rich magmas form as fluids or hydrous melts percolate upward through the inverted thermal gradient in the mantle wedge

Grove et al. (2006)

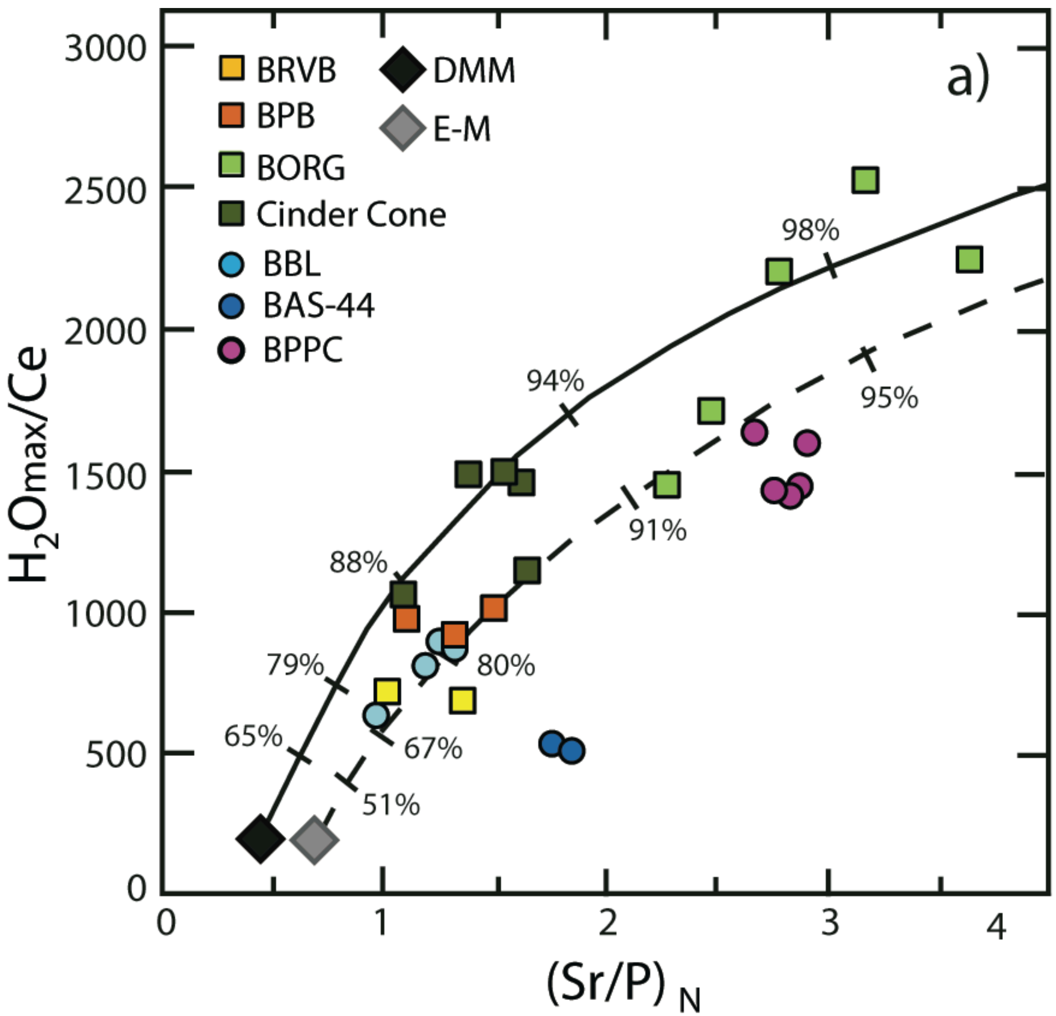
Mantle Melt Fraction vs. Mantle H_2O Concentration



Interpretation 1: Feedback between mantle H_2O & degree of melting limits melt H_2O

Plank et al. (2013); Kelley et al. (2010)

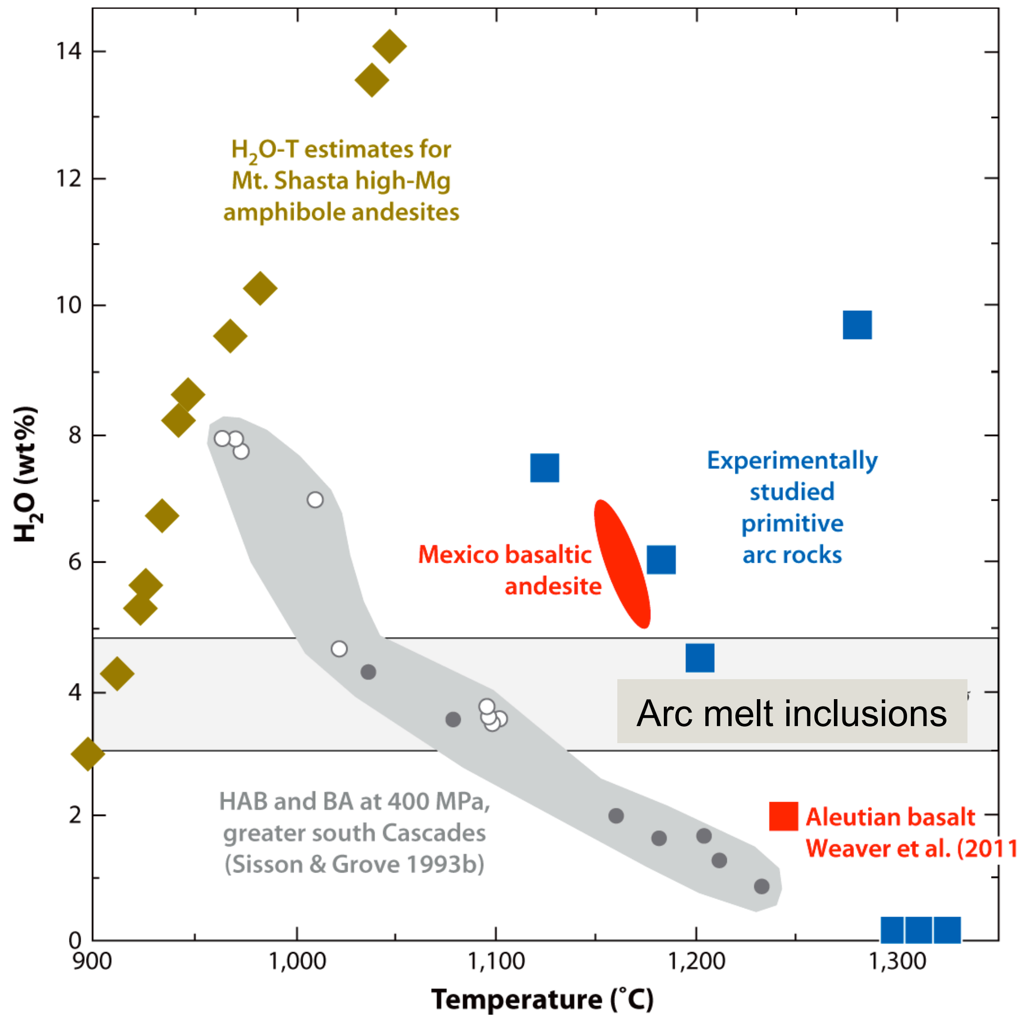
H_2O and Trace Elements in Cascades Melt Inclusions



- Correlation of volatiles and LILEs indicates variable addition of a hydrous subduction component.
- Mixing calculations show that the subduction component accounts for 70-98% of the H_2O dissolved in Lassen region mafic magmas.

Walowski et al. (2015)

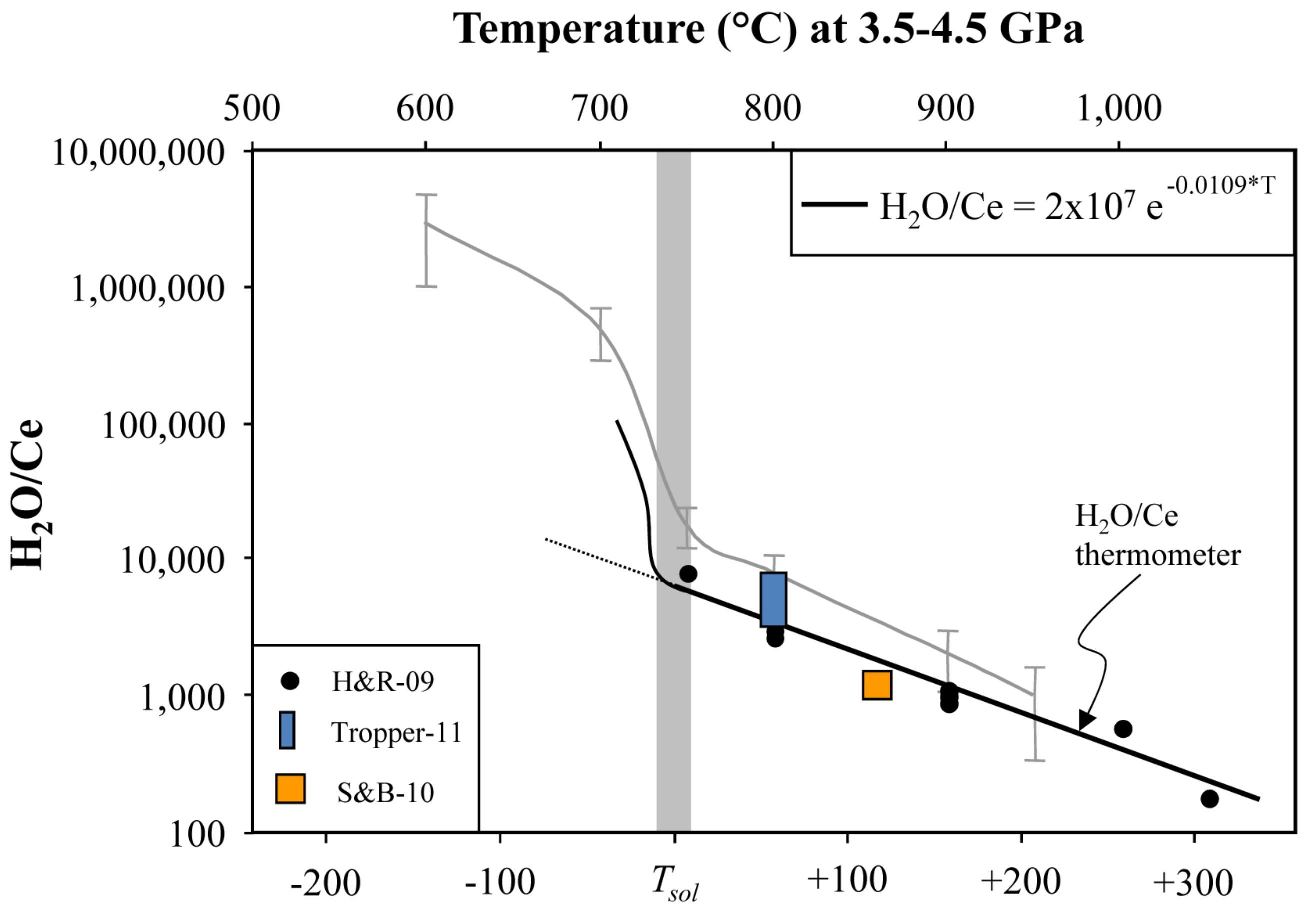
Comparison of Melt Inclusions & Experimental H_2O Estimates



Interpretation 2: Arc magmas start with higher H_2O than is recorded in melt inclusions

Modified from Grove et al. (2012)

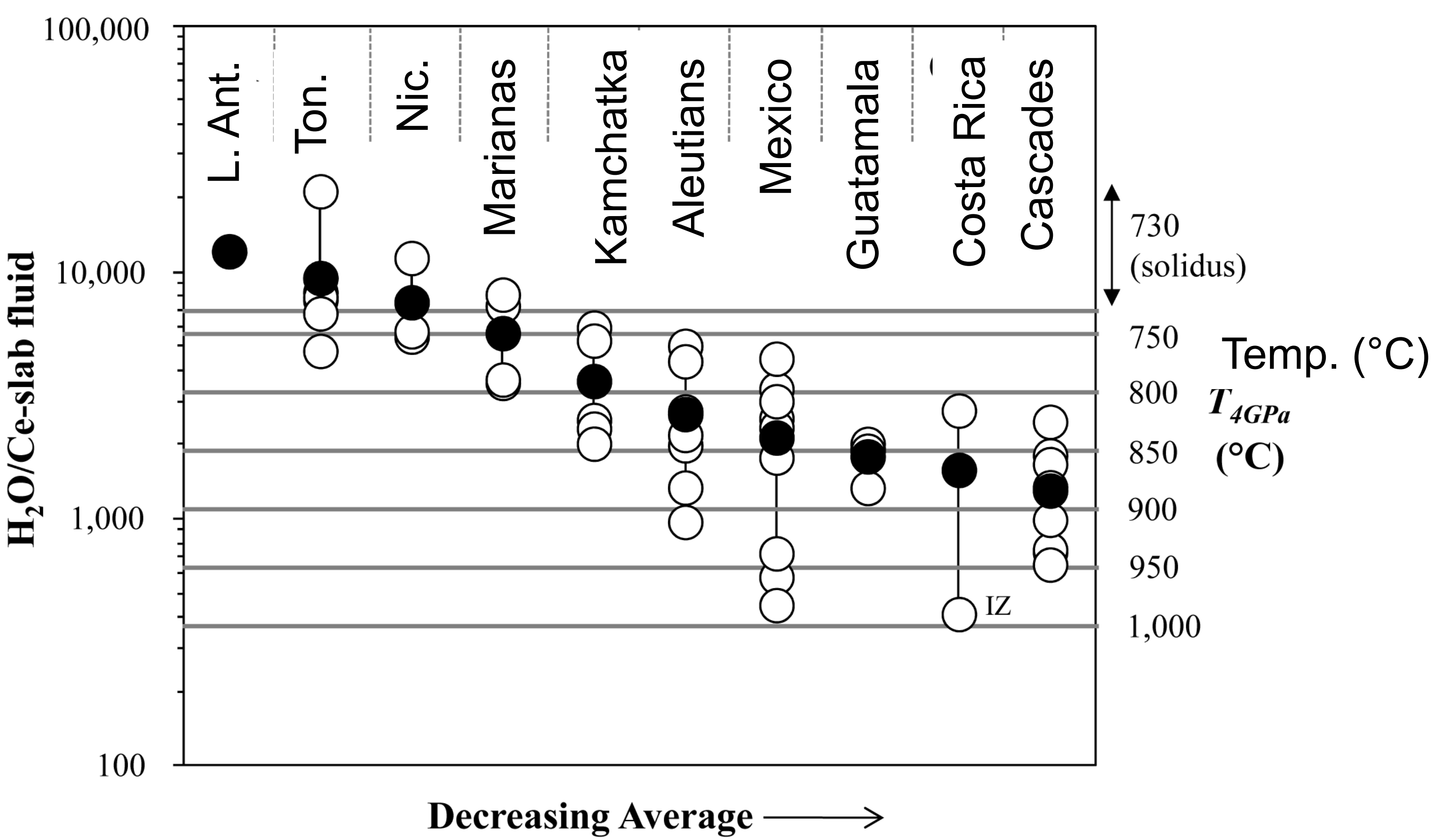
How Hot is the Slab Top? – H_2O/Ce Slab Geothermometer



- Geochemical data for arc magmas can be used to infer slab top temperatures
- Requires allanite and/or monazite to be present in metasediment & metabasalt

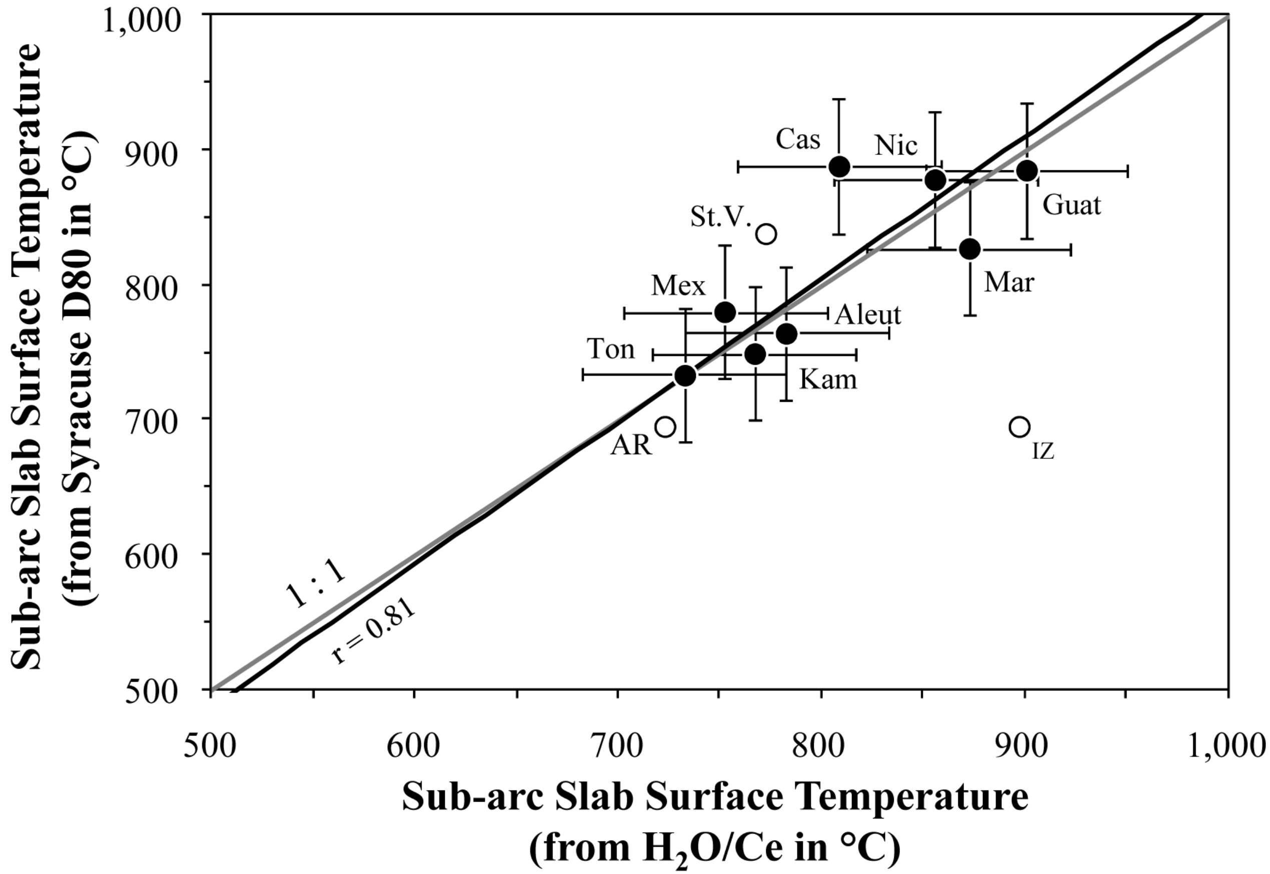
Plank et al. (2009); Cooper et al. (2012)

Slab Temperatures Predicted from H_2O/Ce



Cooper et al. (2012)

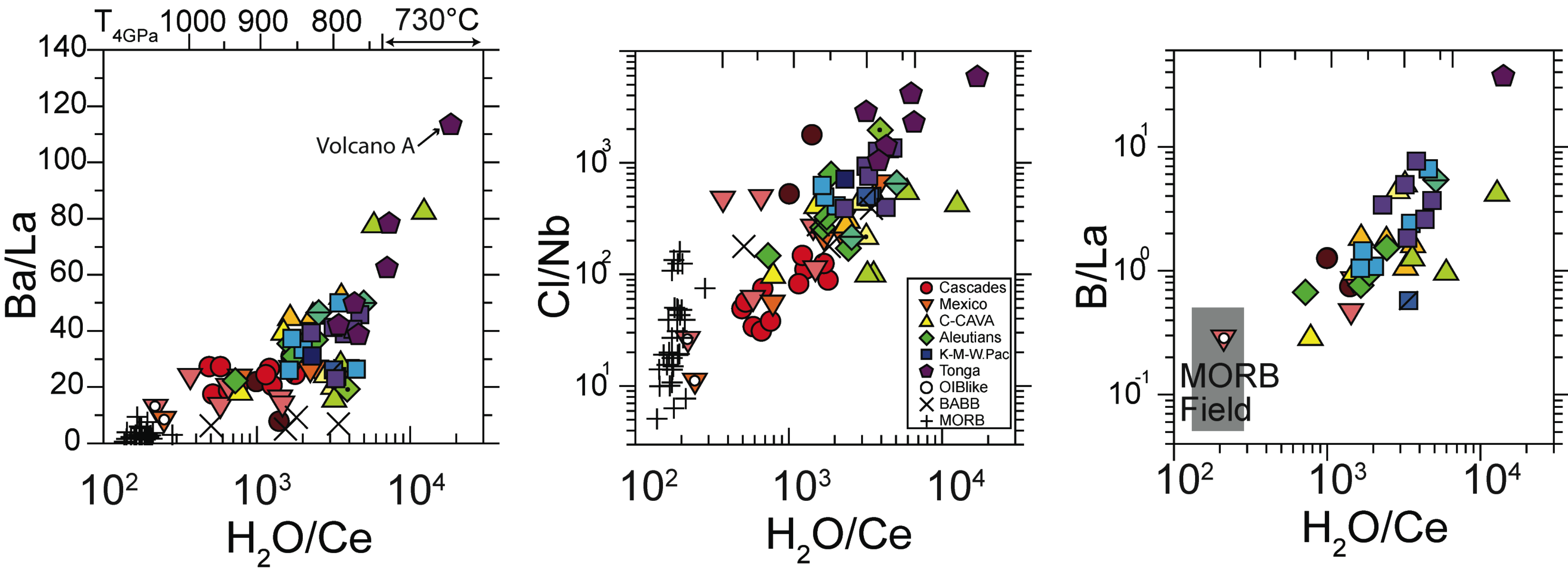
Comparison of Temperatures from H_2O/Ce & Geodynamic Models



- Relatively good agreement between geodynamic models & H_2O/Ce temperatures
- Suggests mainly vertical rise of slab components

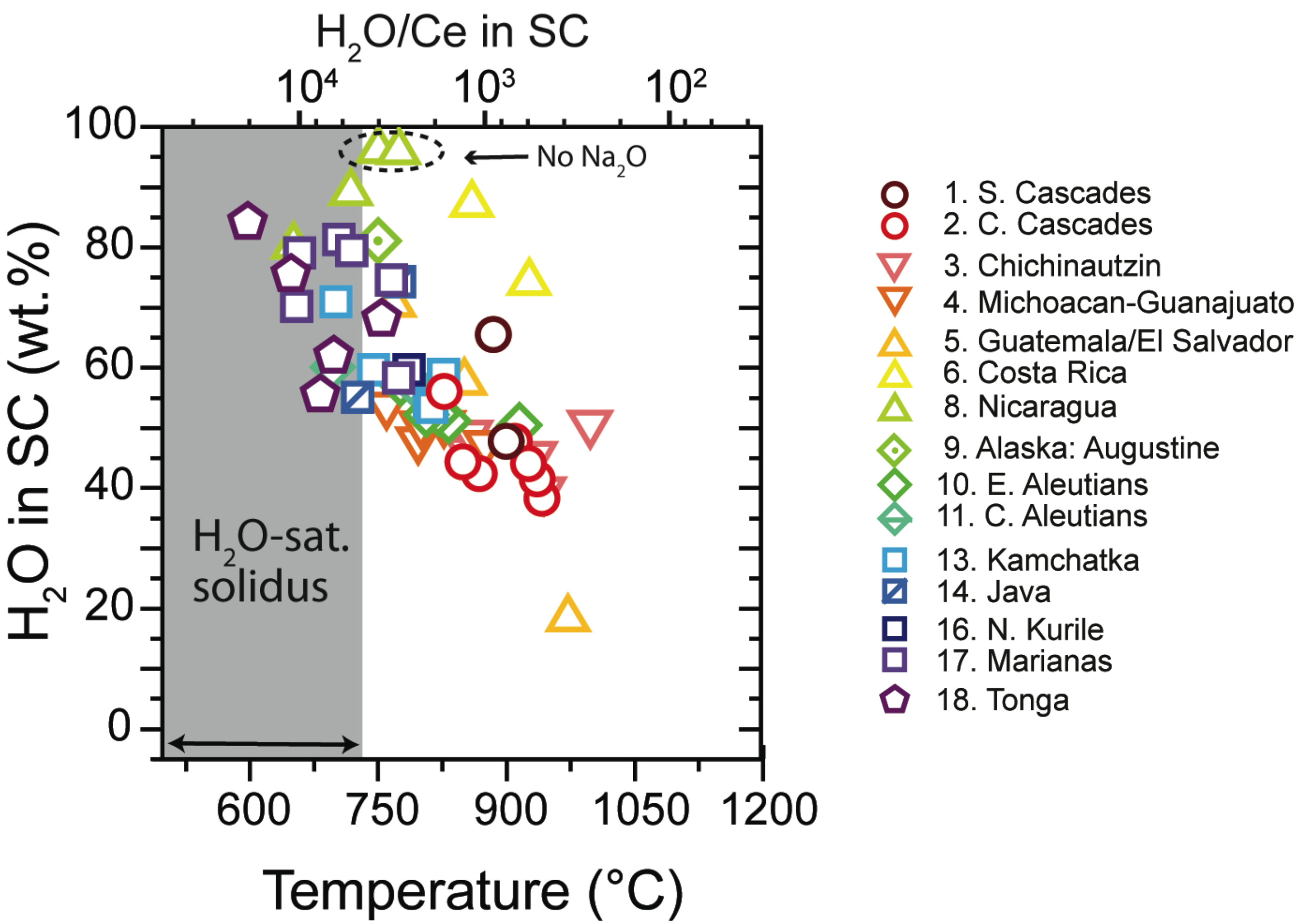
Cooper et al. (2012)

Relationship of H_2O/Ce to Other Slab Tracers



Ruscitto et al. (2012)

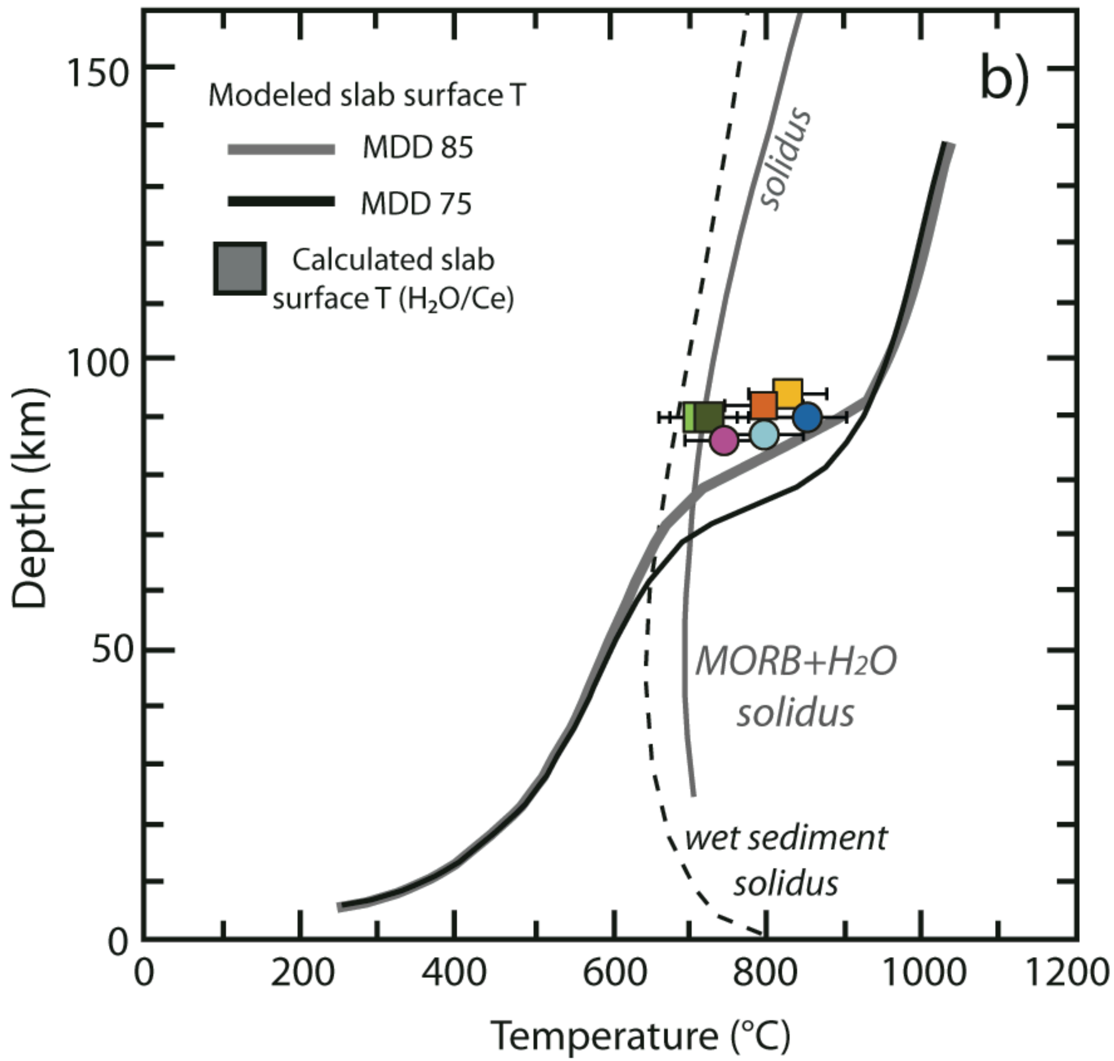
Slab Component (SC) H_2O Contents



- Slab components become more solute-rich (more melt-like) with increasing slab temperature

Ruscitto et al. (2012)

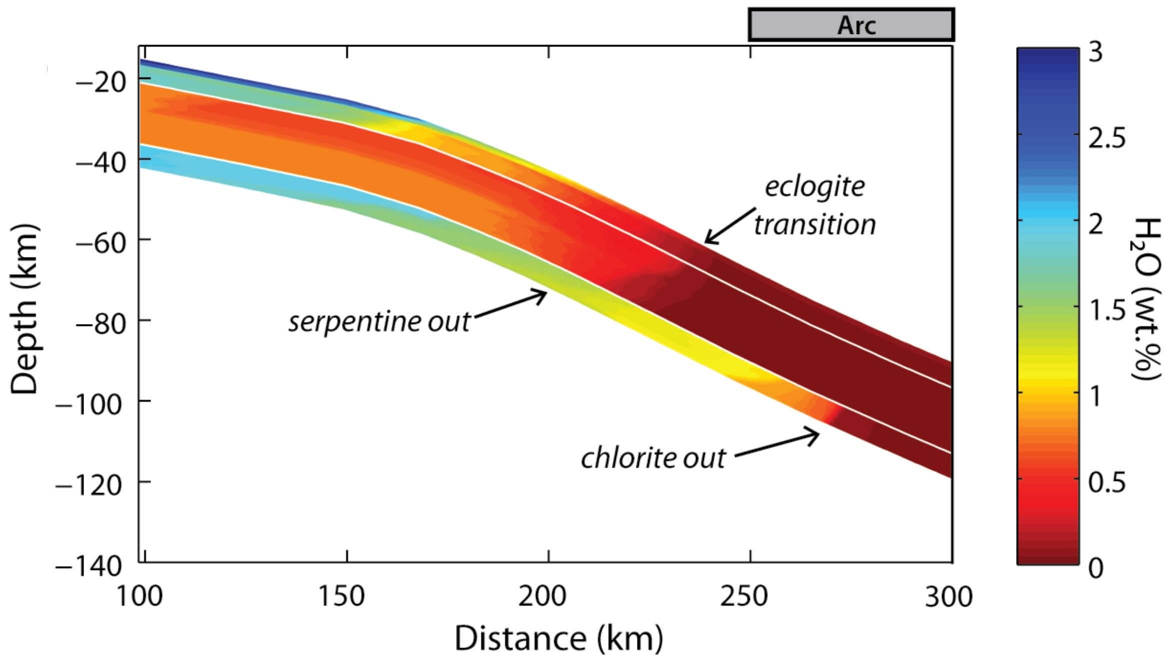
Hot Temperatures Can Cause Melting of the Slab Top Beneath Arcs

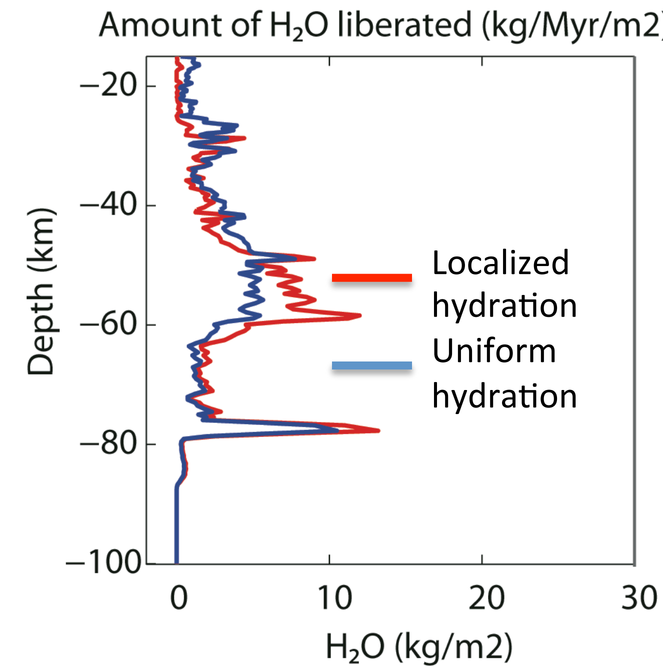


Southern Cascade Arc

Walowski et al. (2015); solidi from Poli & Schmidt (1998), Hermann & Spandler (2008)

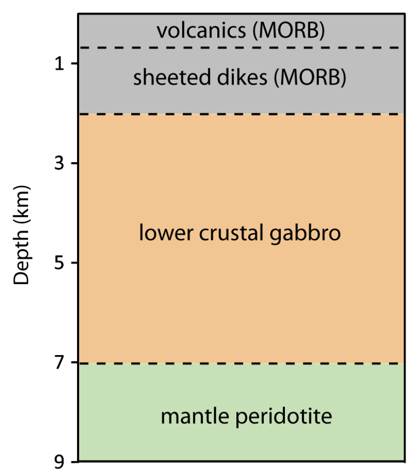
Modeling of H_2O Released from the Downgoing Slab





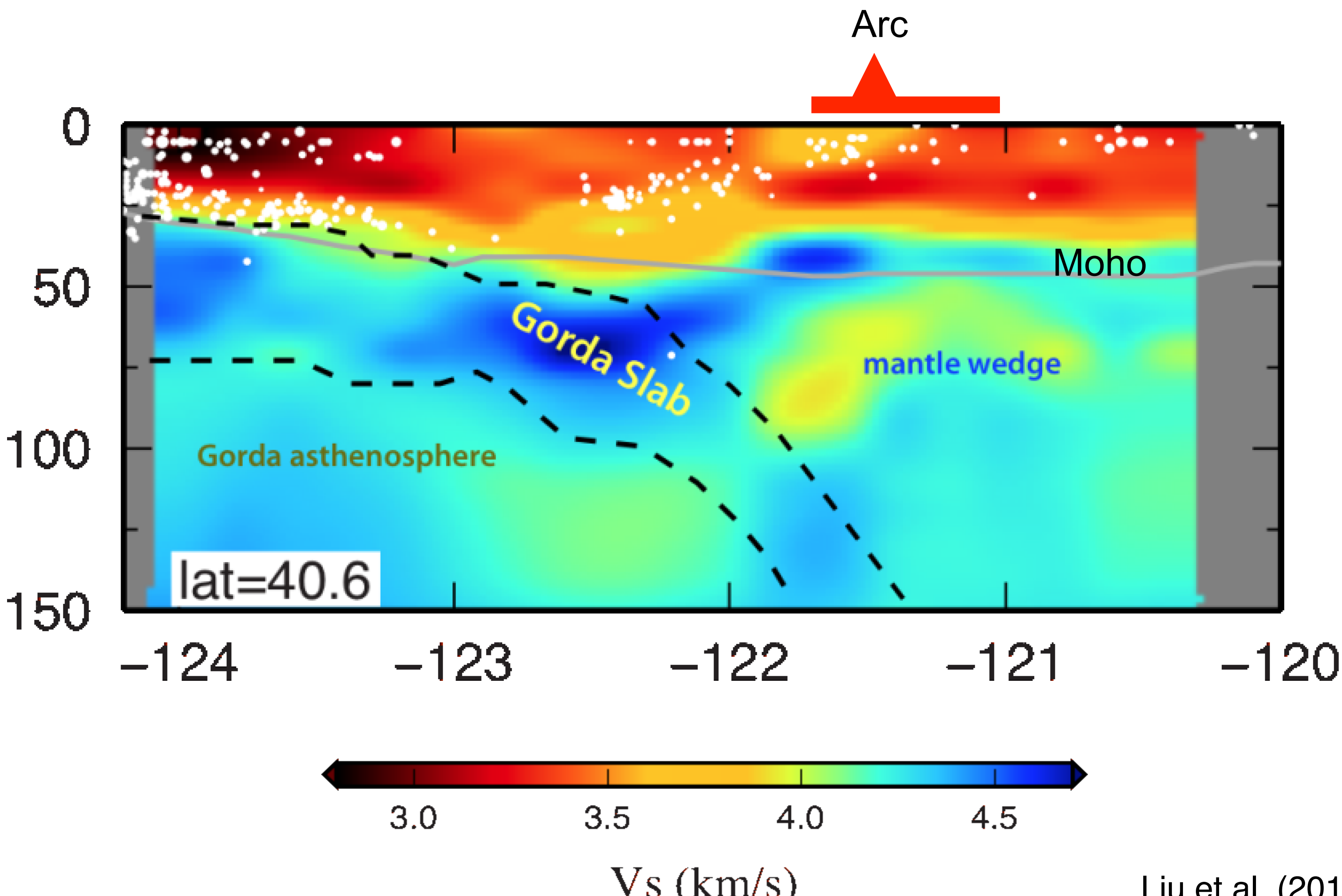
- Model results for the southern Cascades using localized hydration and 2 km of hydrated upper mantle

- Modeling uses methods of Wada et al. (2012) & assumes localized hydration & vertical fluid migration



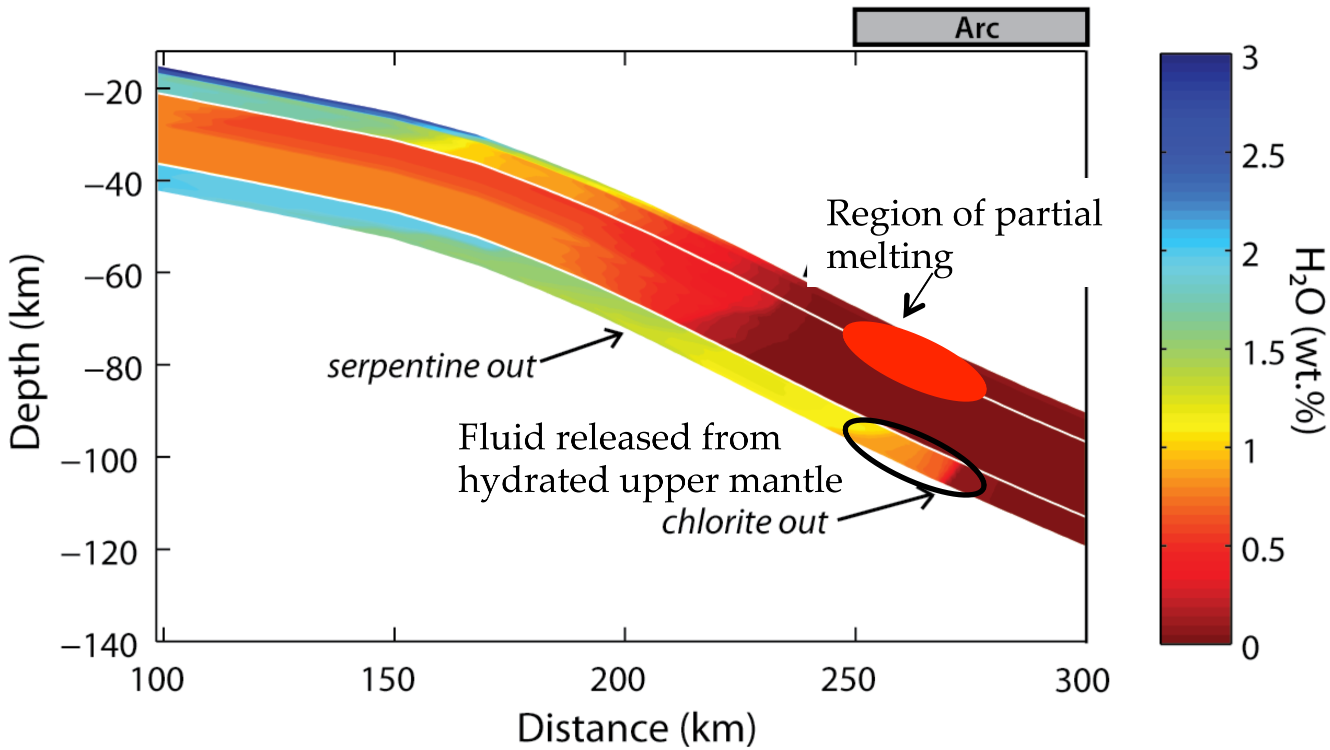
Walowski et al. (2015)

Shear Velocity Model for the Southern Cascades



Liu et al. (2012)

Fluid Release & Slab Melting



- Because slab surface temperatures are at or above the MORB + H_2O solidus, the upper oceanic crust is likely flux-melted by fluids rising from the slab interior

Walowski et al. (2015)

Reevaluating carbon fluxes in subduction zones, what goes down, mostly comes up

Peter B. Kelemen[a,1] and Craig E. Manning[b,1]

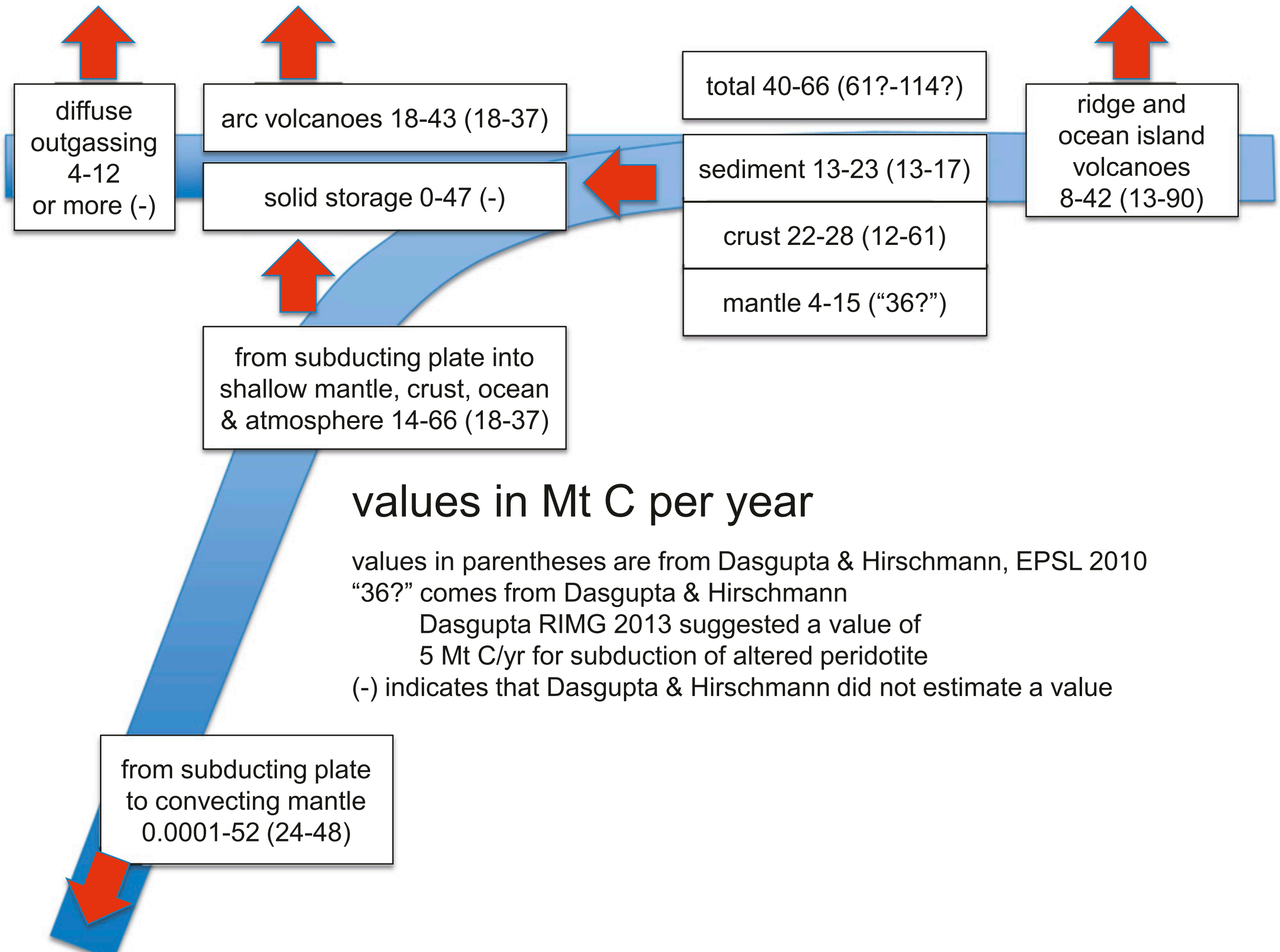
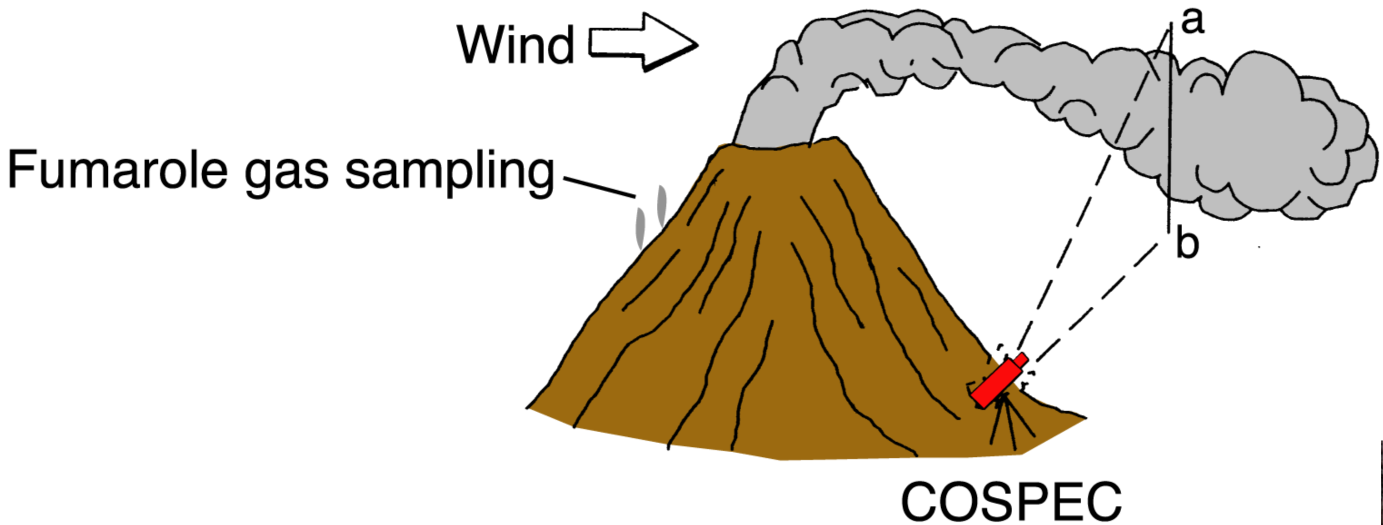


Fig. 5. Major fluxes of carbon estimated in this paper, with values from Dasgupta and Hirschmann (1) for comparison.

Measuring Volatile Fluxes from Volcanoes

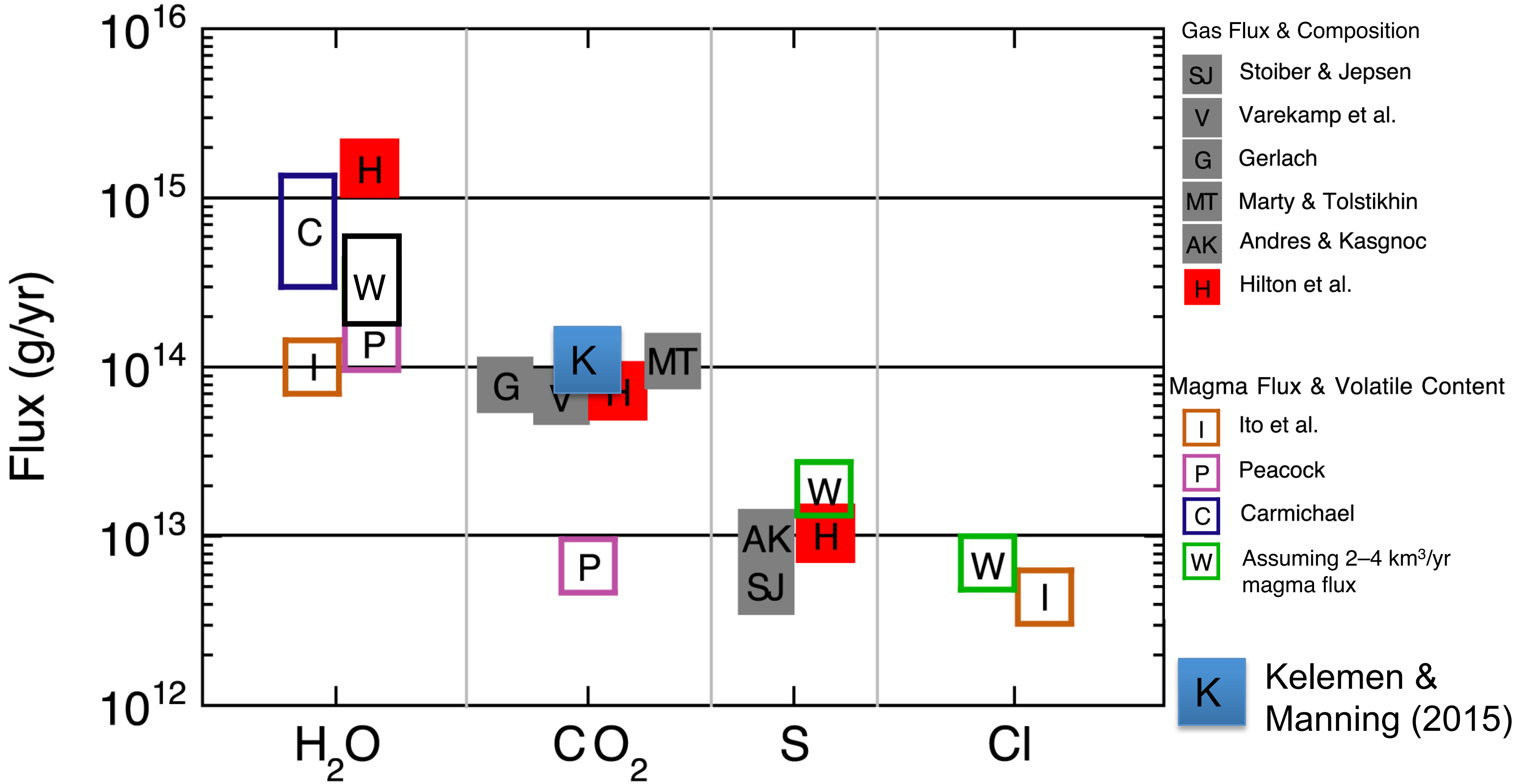


Modified from Fischer et al. (2002)

<u>Volcanic Gases</u>

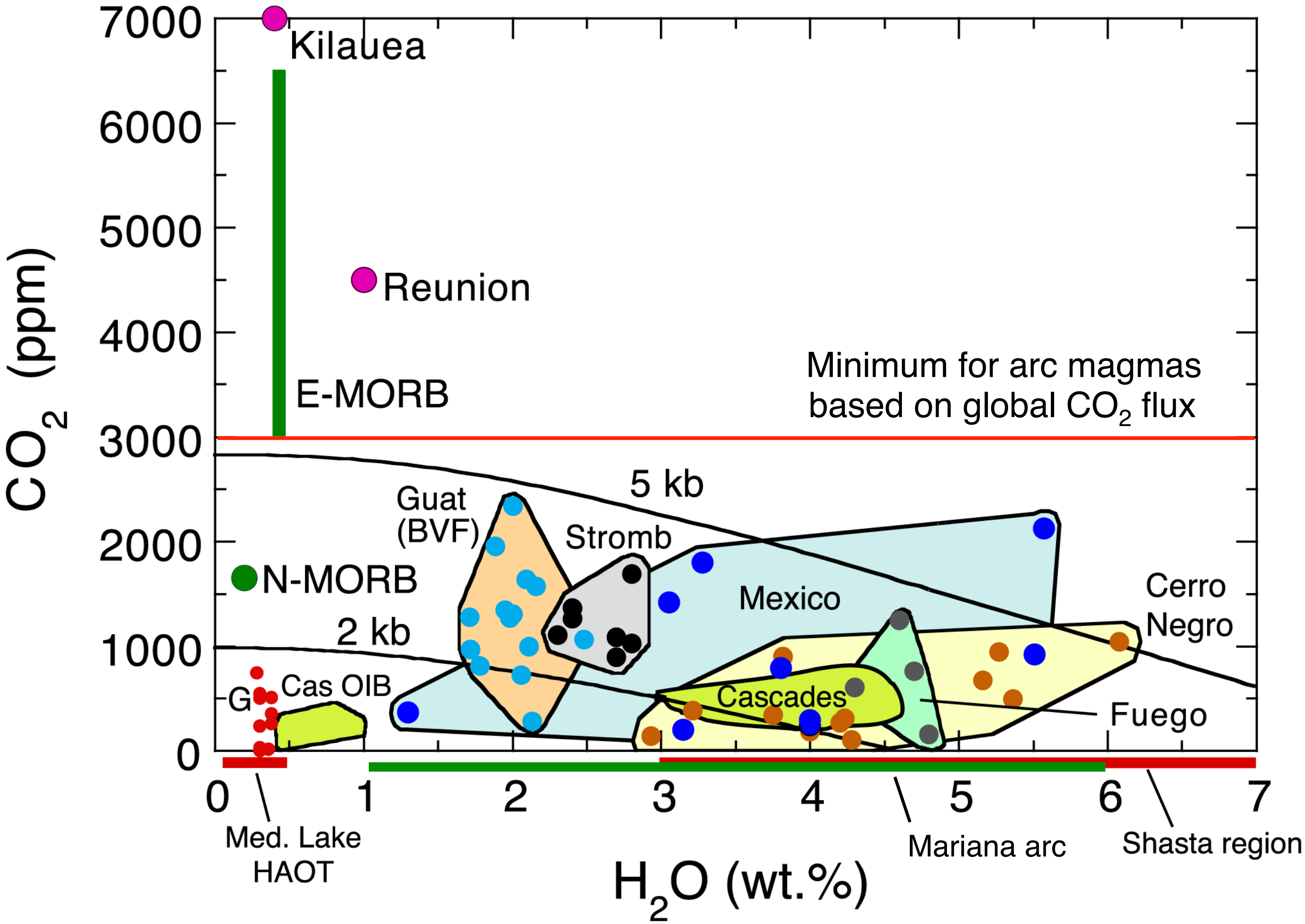
- Measure SO_2 flux by remote sensing
- Collect & analyze fumarole gases
- Use fumarole gas ratios (e.g., CO_2/SO_2) to calculate fluxes of other components

Fluxes of Volatiles from Subduction-related Magmatism



Wallace (2005)

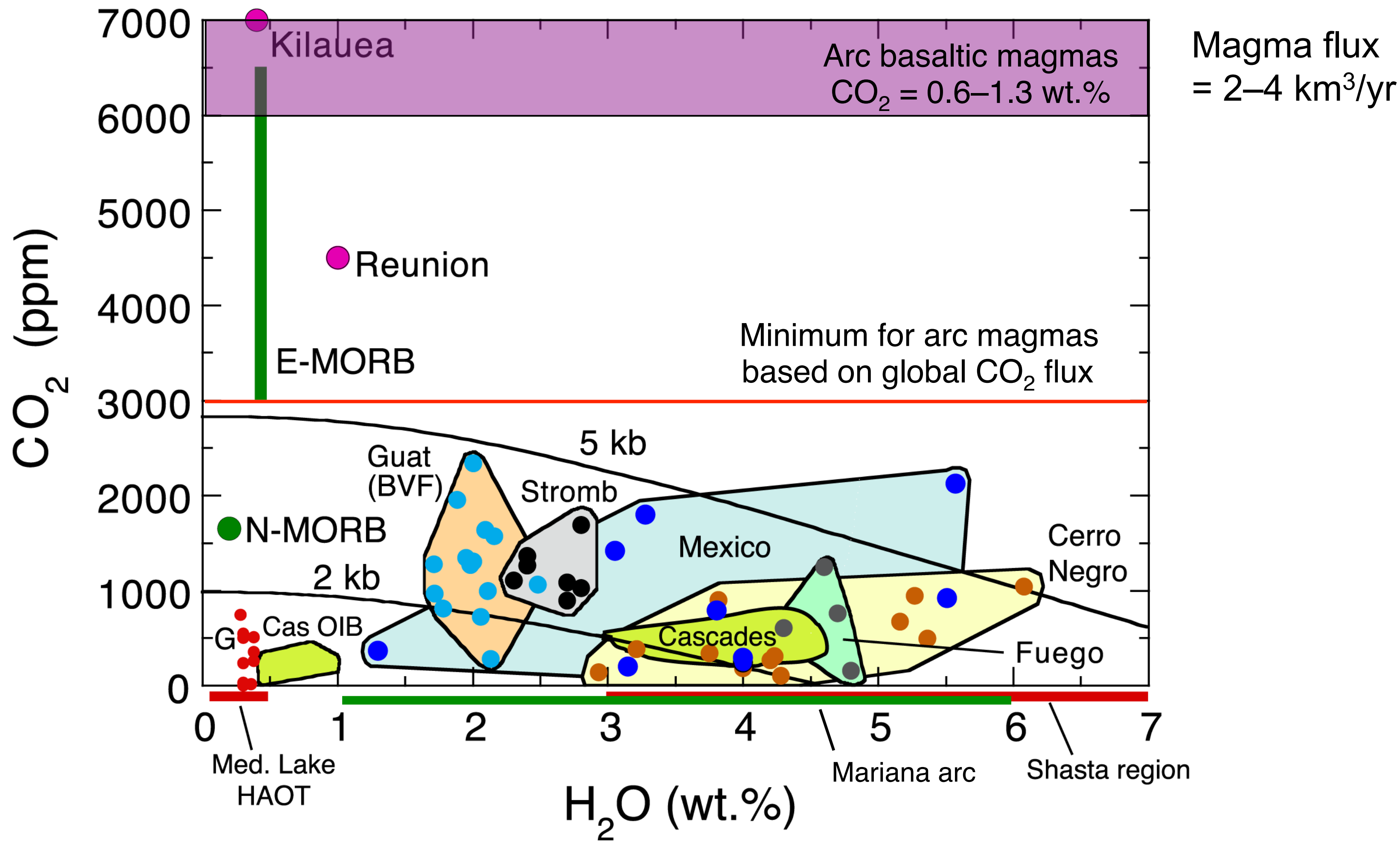
H_2O and CO_2 in Basaltic Magmas



Magma flux $= 8\ km^3/yr$

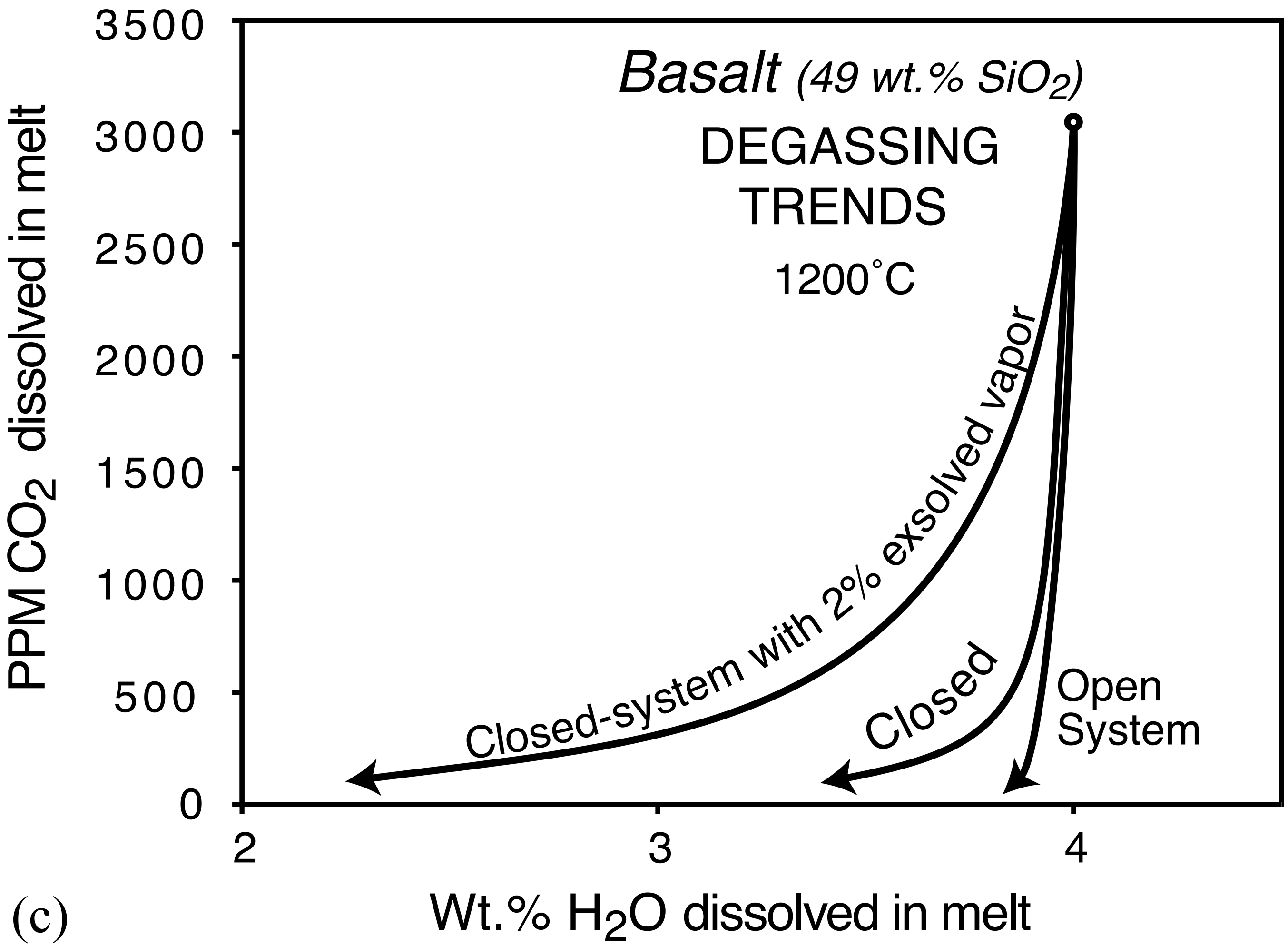
Wallace (2005)

H_2O and CO_2 in Basaltic Magmas



Wallace (2005)

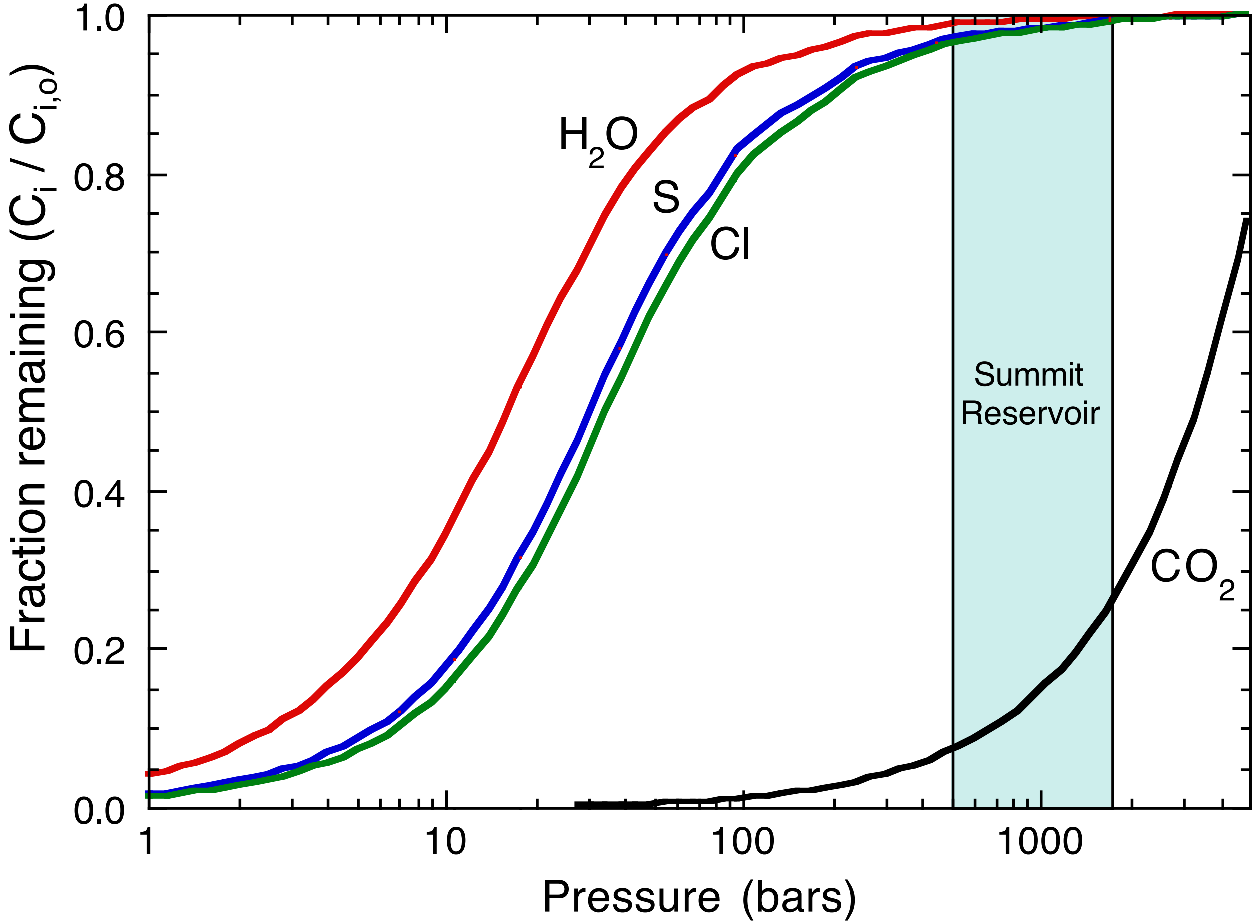
Effect of low CO_2 solubility on degassing



(c)

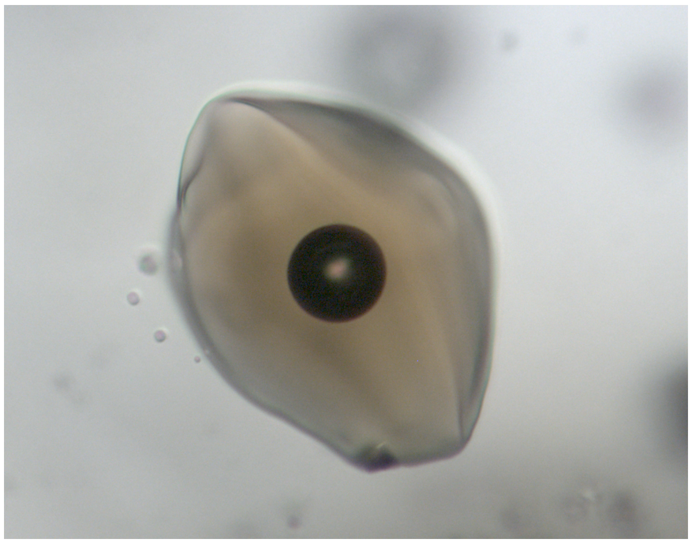
Newman & Lowenstern (2002)

Problem 1: Low CO_2 Solubility at Crustal Pressures



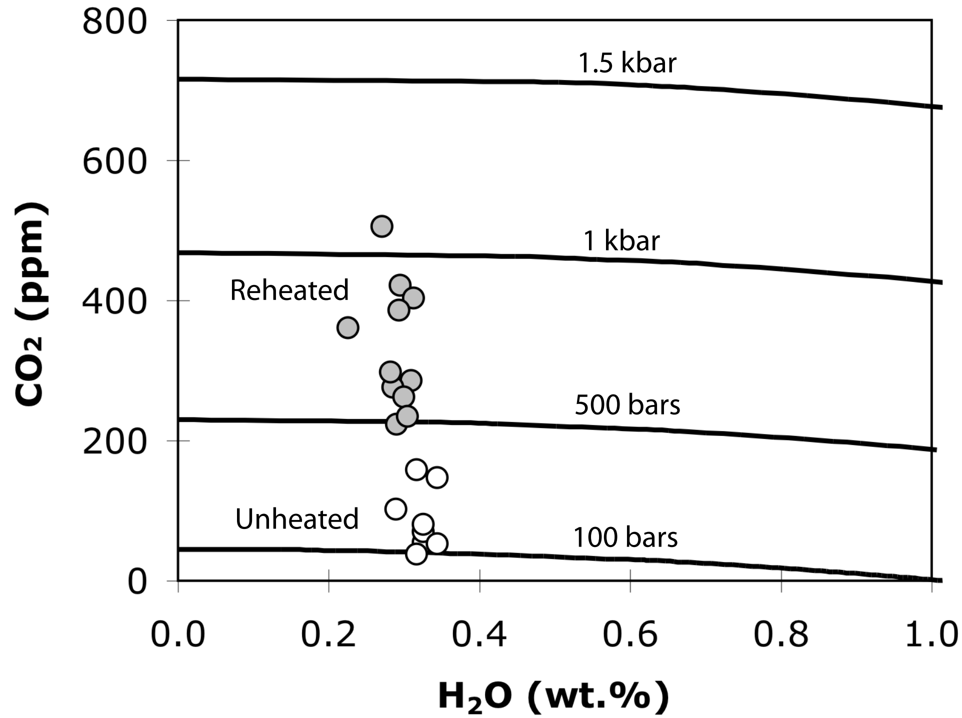
- When basaltic magma reaches the magma chamber beneath the summit of of Kilauea, most of the original dissolved CO_2 has already been degassed.

Problem 2: Formation of Shrinkage Bubbles



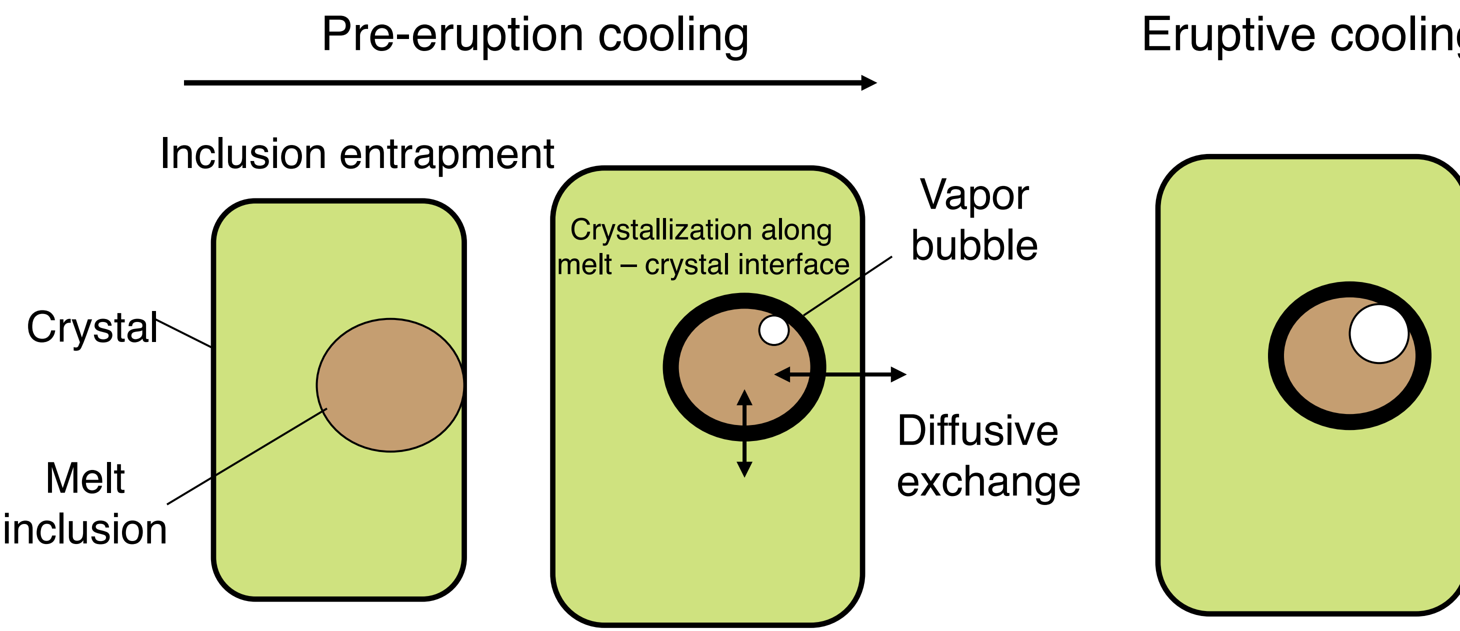
Mauna Loa melt inclusion

Experimental reheating data

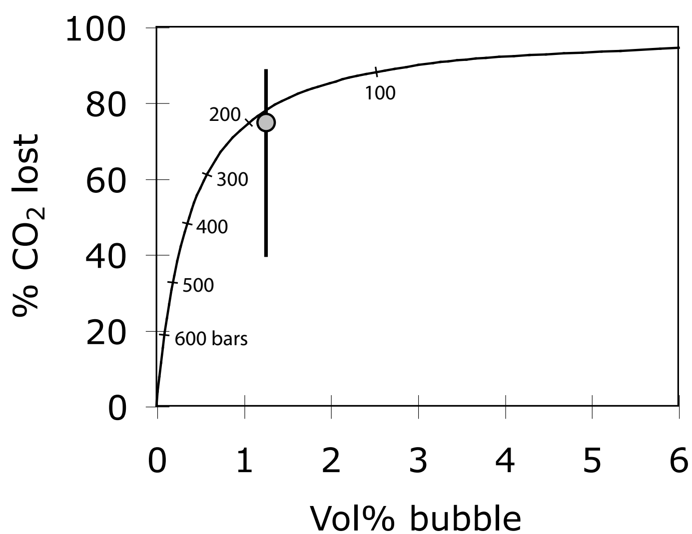


Wallace et al. (2015)

Post-Entrapment Modification of Melt Inclusions



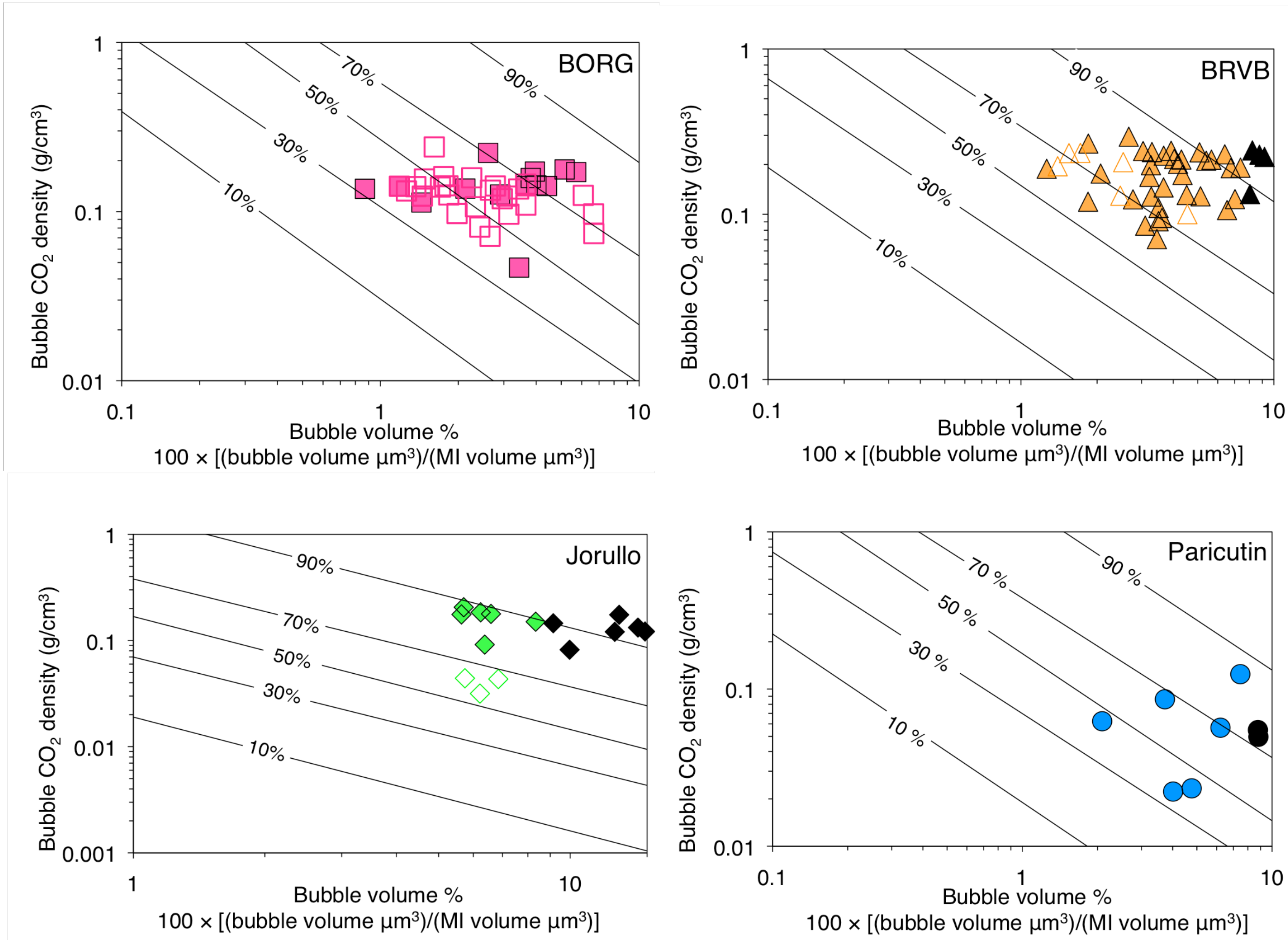
Modified from Wallace (2005)



Bubble expansion but little to no additional olivine crystallization or diffusion of CO_2 into the bubble

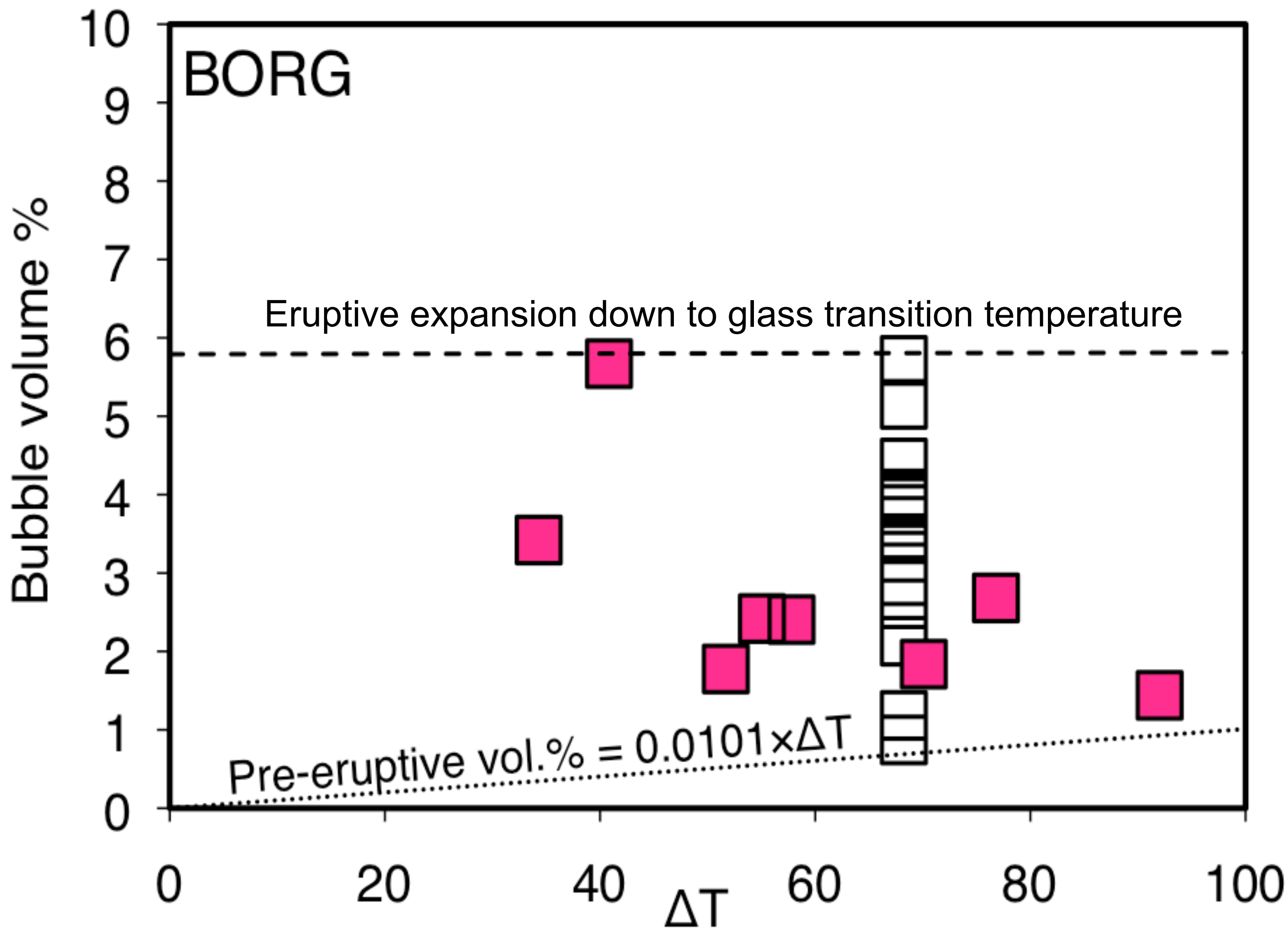
Wallace et al. (2015)

How Much CO_2 is Lost? – Raman Results on Bubble CO_2 Densities



Aster et al. (in prep.)

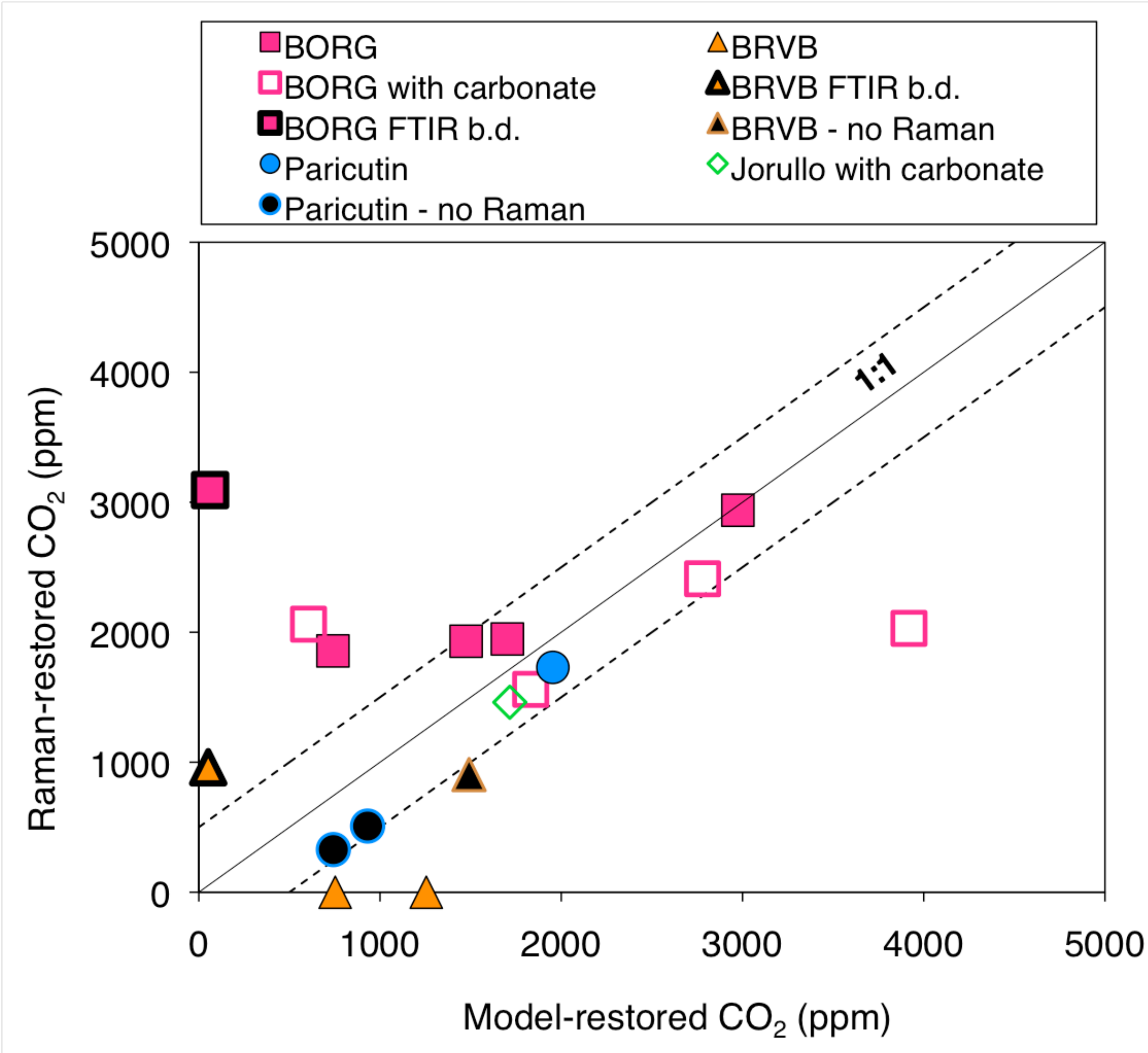
How Much CO_2 is Lost? – Modeling Crystallization & Cooling Contraction



ΔT = Temperature difference between trapping & eruption

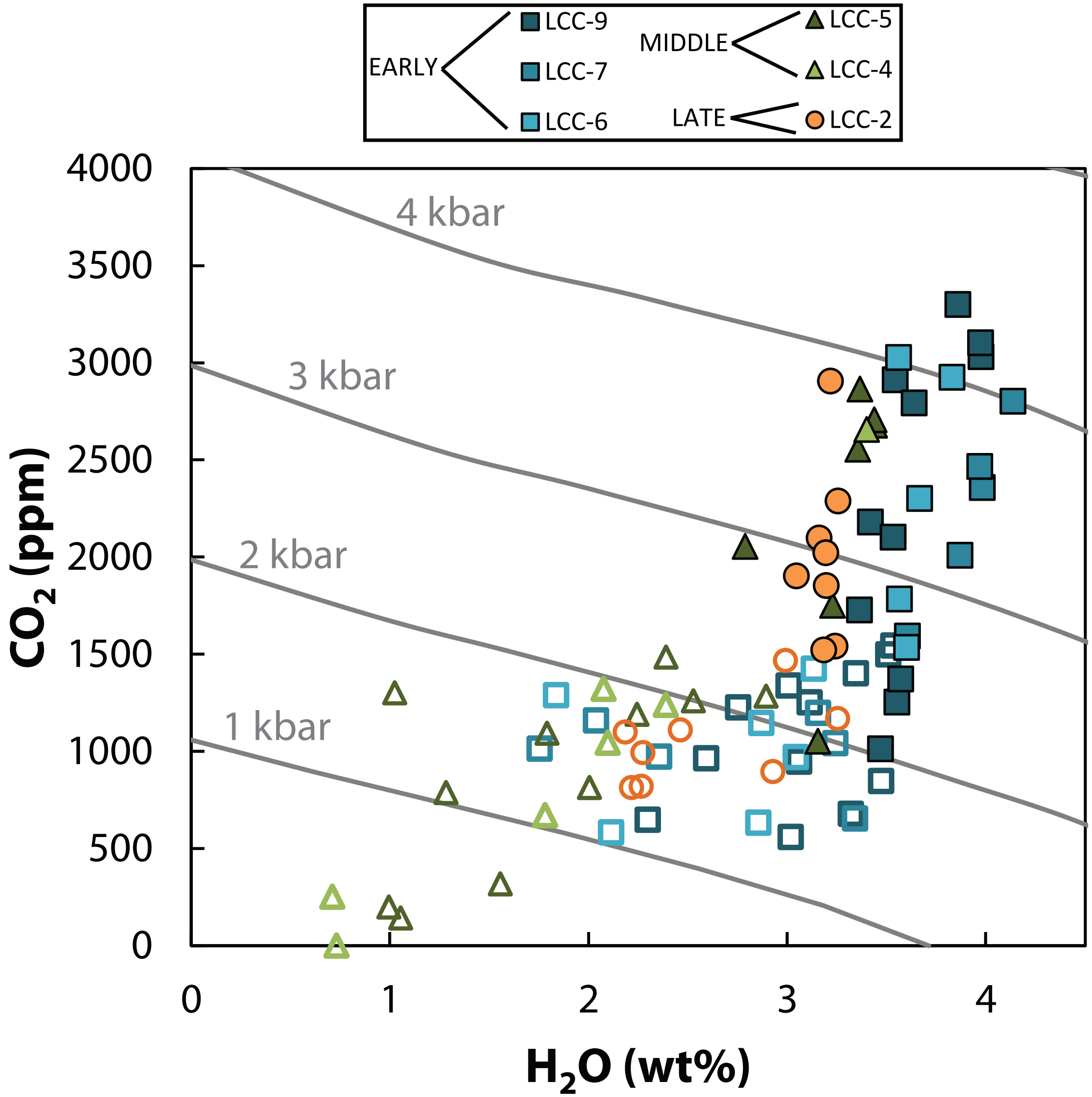
Aster et al. (in prep.)

Comparison of CO_2 Restoration Methods



Aster et al. (in prep.)

Comparison of Corrected vs. Measured Melt Inclusion Values



Walowski et al. (in prep.)

Minimum Arc Flux

8-32 (5000 ppm CO_2 & magma flux 2 - 8.5 km^3/yr)

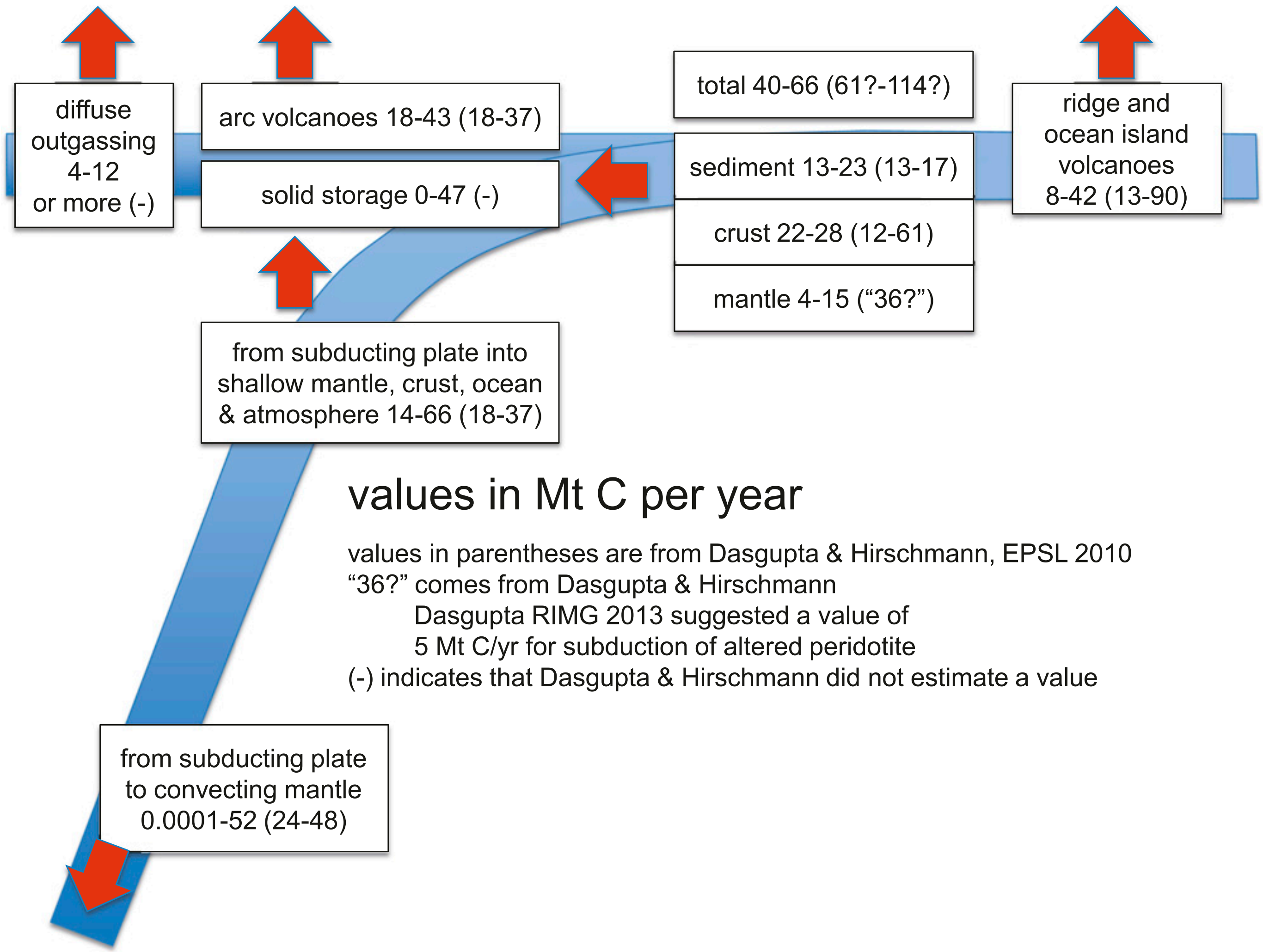


Fig. 5. Major fluxes of carbon estimated in this paper, with values from Dasgupta and Hirschmann (1) for comparison.

Kelemen & Manning (2015)

Summary Questions

- How much hydration & carbonation of oceanic upper mantle occurs during bend faulting at the outer rise?

- What happens to H_2O & CO_2 stored in the forearc wedge?

- How do fluids & melts migrate through the slab & wedge?

- How do variations in mantle temperature modulate subduction inputs?

- How much CO_2 is really in arc magmas?