Melt Inclusions & Volatiles in Silicic Magmatic Systems

Photo by D. Harlow, USGS

Outline

- Generation of intermediate & silicic magma
- Melt inclusions – host crystals & inclusion textures
- Volatile concentrations in silicic magmas
- Vapor saturation & magma chamber configurations
- Processes that cause volatile variations
- Inferring vapor compositions
- Sulfur & chlorine

How are intermediate and silicic magmas formed?

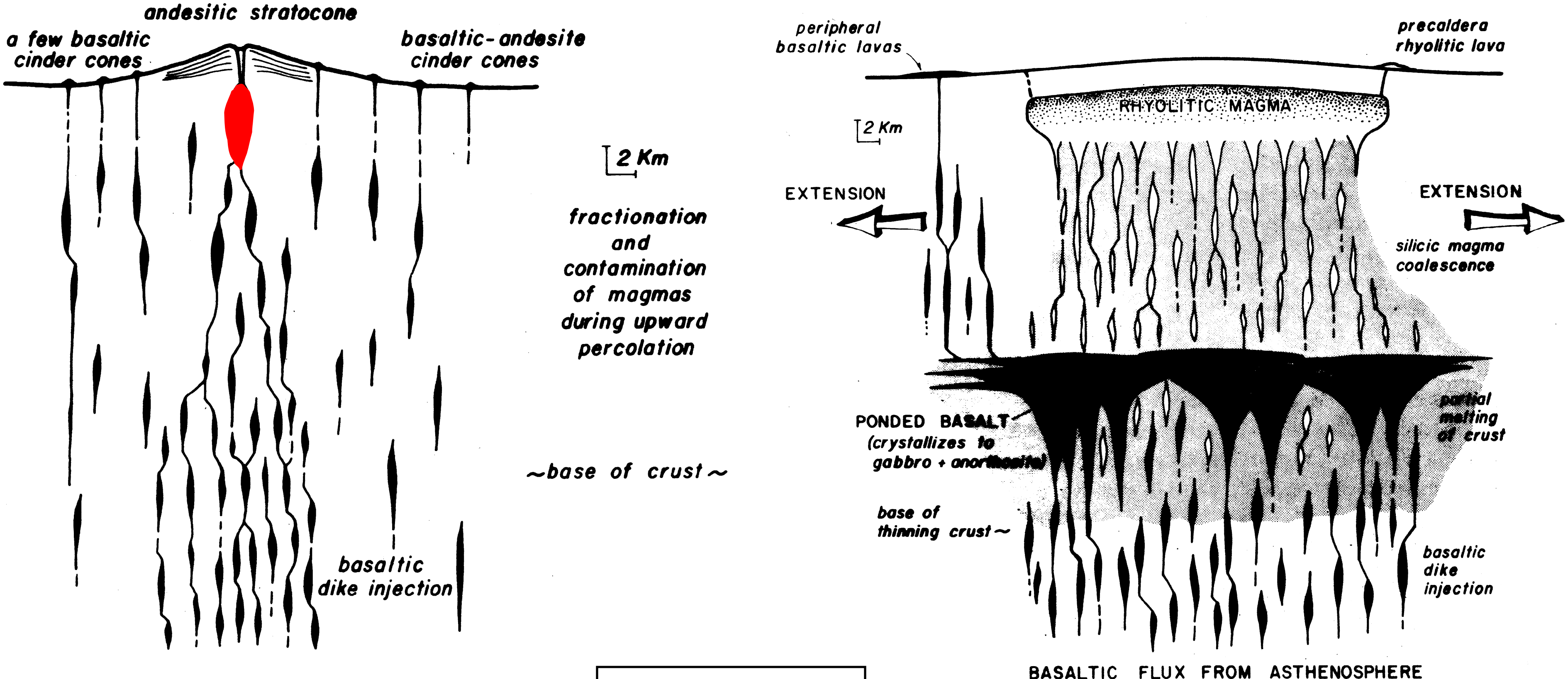
- Continental crust has mafic lower crust and more evolved granite-dominated upper crust

- Mantle-derived magmas in subduction zone settings are basalt to high-Mg andesite in composition

- Processes for forming more evolved magma:
  - Differentiation of primary mafic magmas by crystallization
  - Partial melting of older crustal rocks
  - Partial melting of earlier formed cumulates/plutons in the lower crust

Importance of Mafic Magma

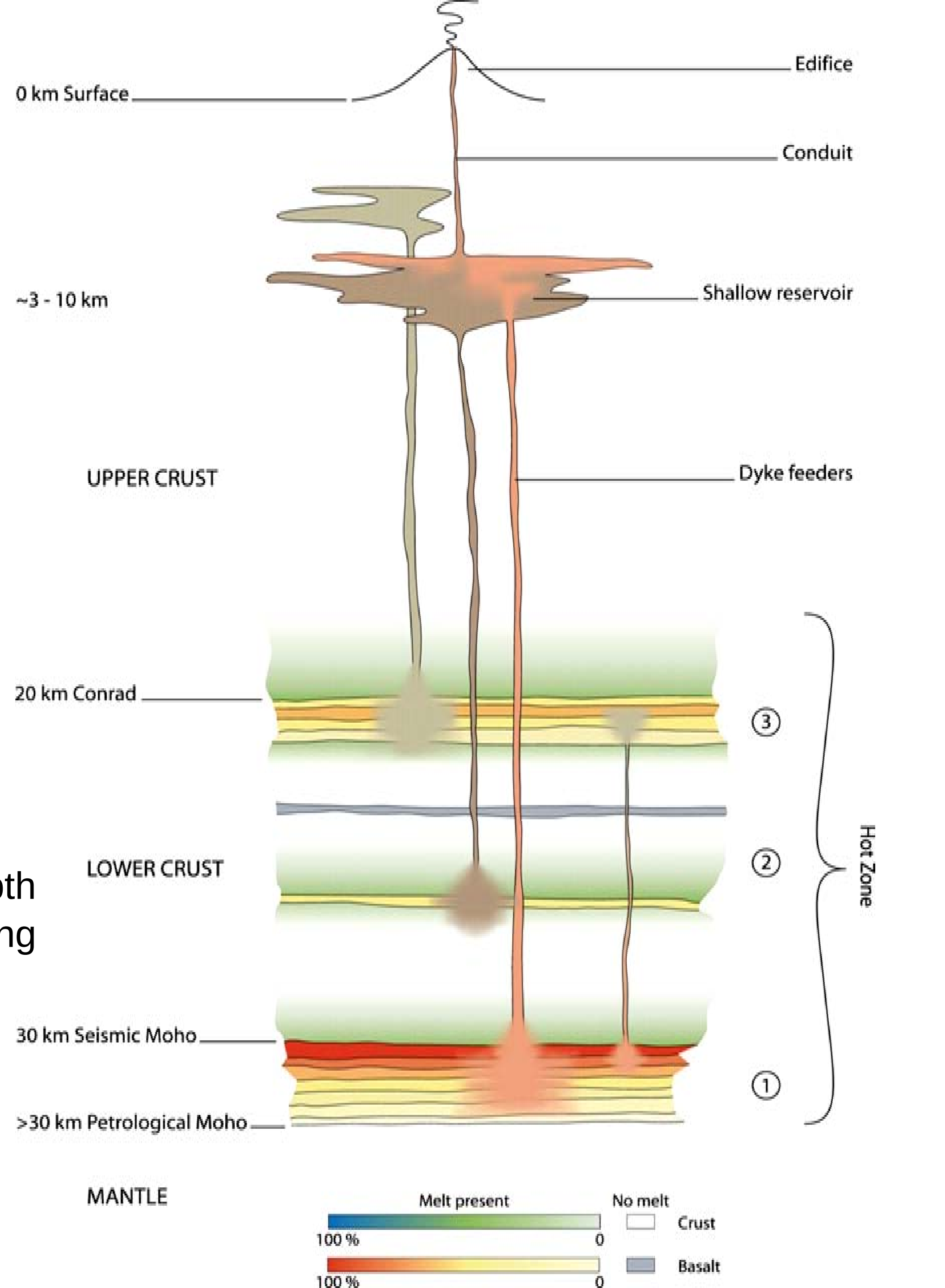
- Crustal magmatic systems are fundamentally basaltic – heat & mass
- Basaltic magma transfers volatiles from mantle to crust
- Mantle volatile sources include upper mantle & subduction-recycled components



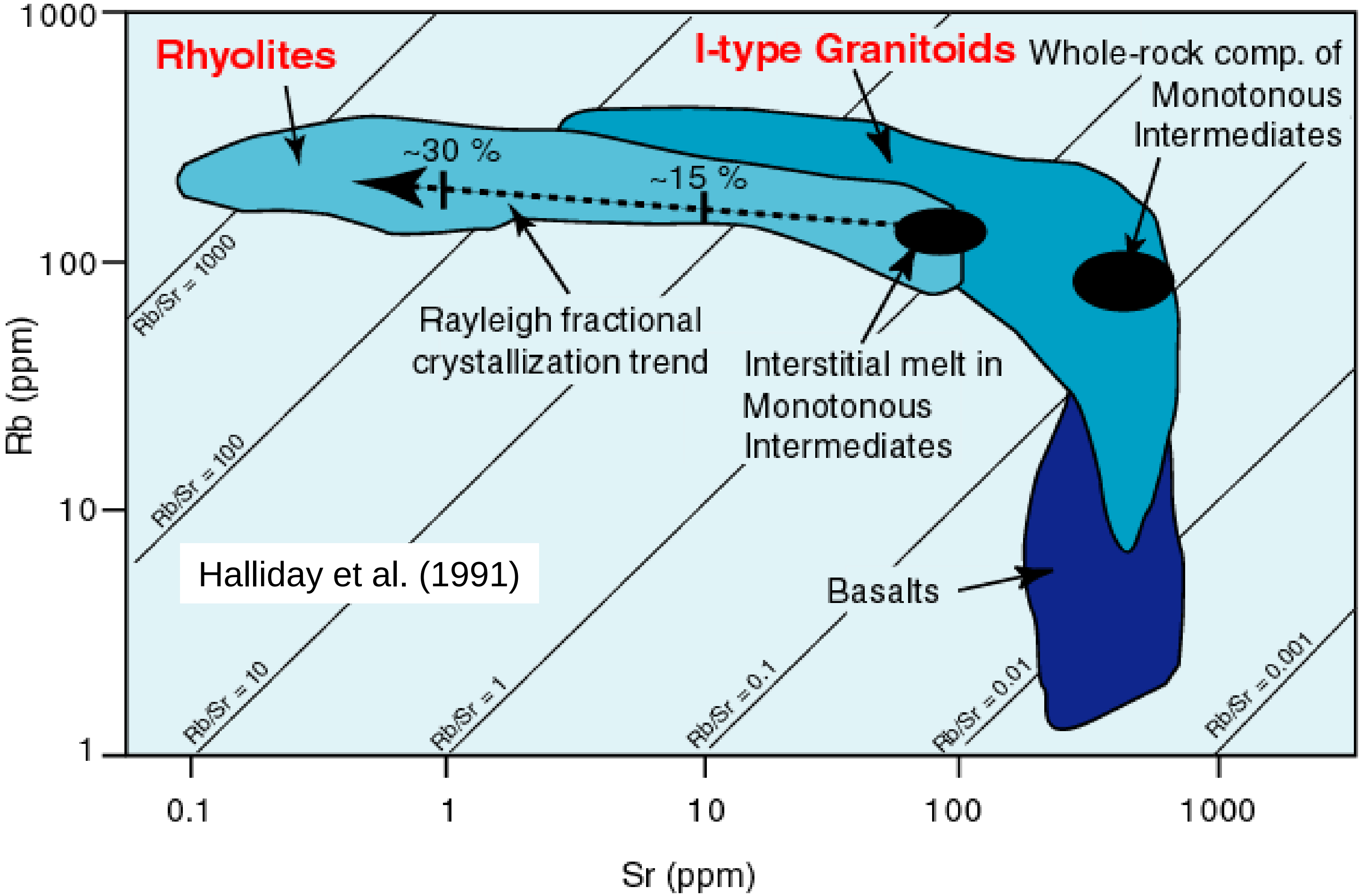
Hildreth (1981)

Conceptual representation of a deep crustal hot zone (Annen et al., 2006)

- Hydrous basaltic melts intruded into the lower crust as sills
- Heat & H_2O from the crystallizing basalt promote partial melting of the lower crust
- Mixing of residual & crustal melts
- Ascent of H_2O-rich melts into the upper crust
- Degassing & crystallization at shallow depth lead to large increases in viscosity & stalling of magma to form magma chambers

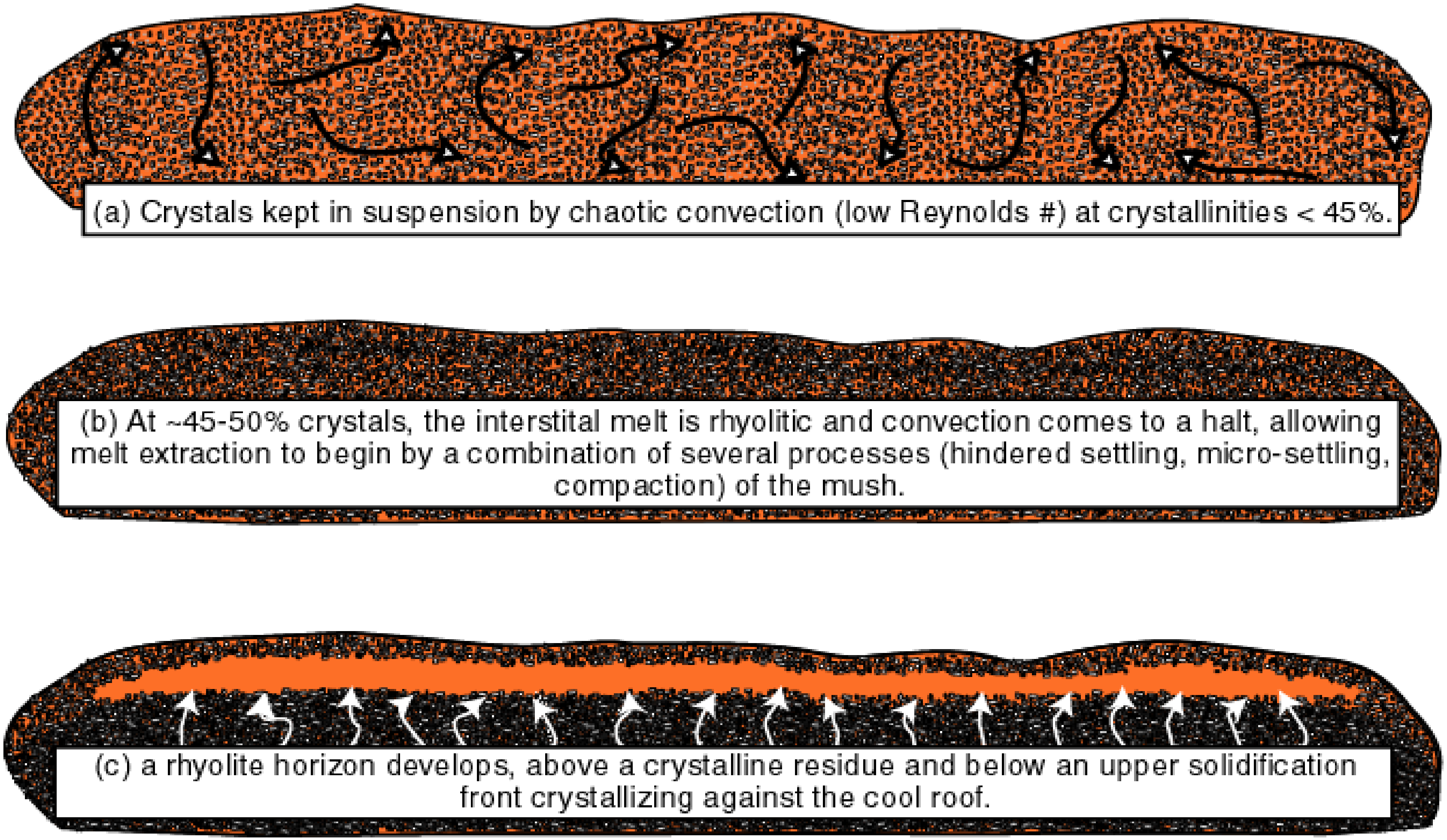


Strong crystal fractionation signature in rhyolites

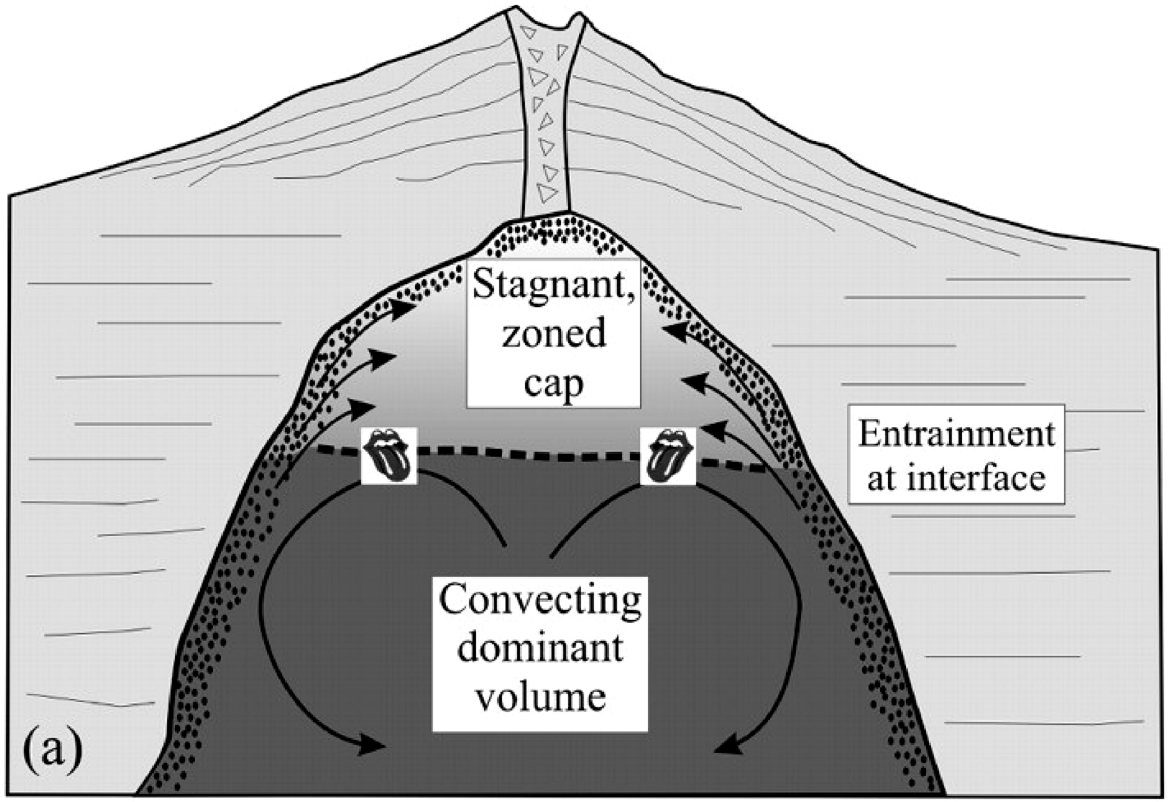


- Data suggest a genetic link between crystal-poor & crystal-rich rhyolites & I-type granitoids
- But how are viscous silicic melts physically separated from crystals?

Crystal mush model – Bachmann & Bergantz (2004)



An alternative model for formation of intermediate & silicic magma



Bachmann & Bergantz (2004)

Upward migration of low-density, residual melt from a crystallizing boundary layer is a popular, but problematic, hypothesis for shallow magmatic differentiation

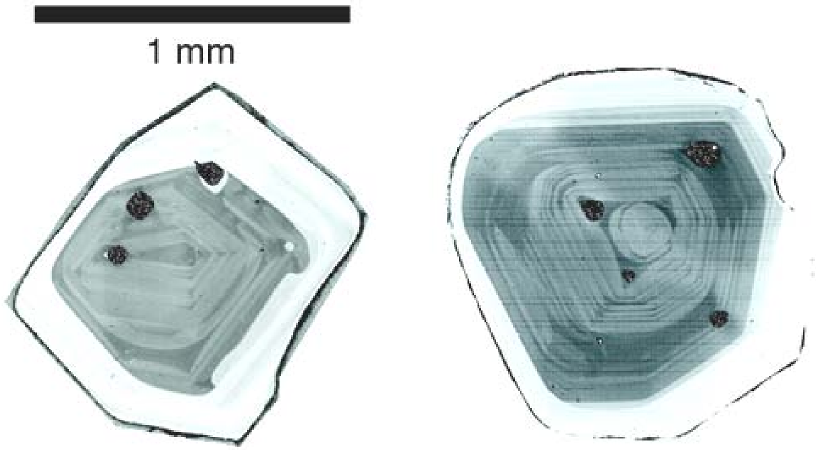
- Difficult to explain old, complexly zoned phenocrysts
- Large silicic magma bodies have sill-like aspect ratios
- Re-entrainment of magma in cap may be relatively rapid

What can we learn from melt inclusions about formation, crystallization & storage of silicic magmas?

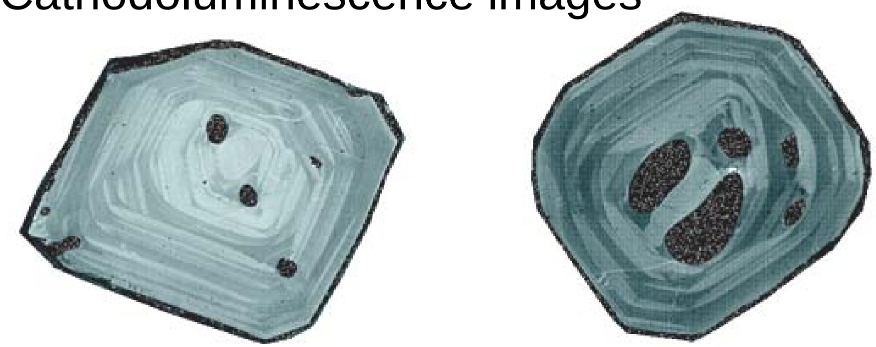
Quartz-hosted melt inclusions, Bishop Tuff

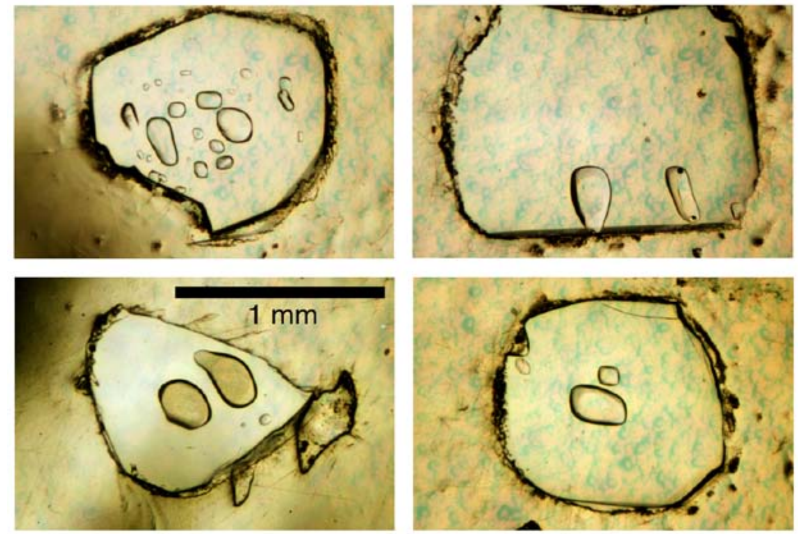
Montserrat – photo by B. Voight

Rhyolitic melt inclusions in quartz phenocrysts



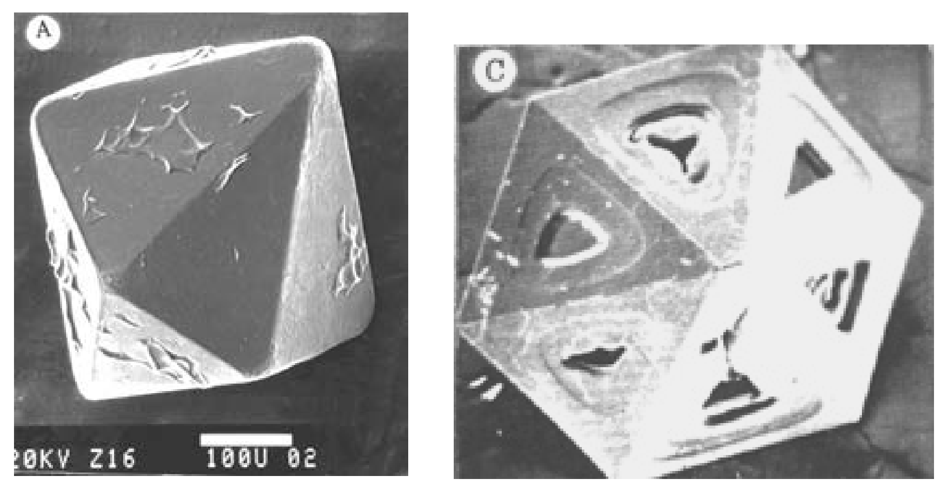
Cathodoluminescence images





Wafers for FTIR & microbeam analysis

Secondary electron images of bipyramidal quartz from the 1912 eruption of Katmai showing semi-skeletal growth form & trapping of inclusions (Lowenstern, 1995)



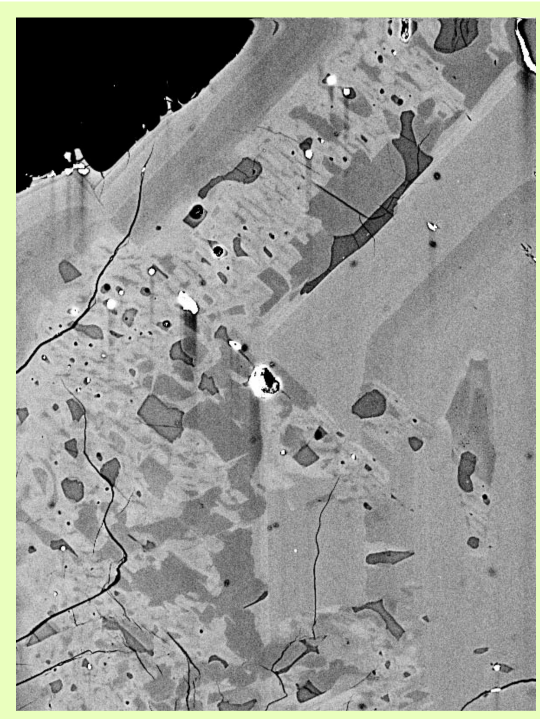
Rhyolitic melt inclusions – vapor bubbles & quench crystals

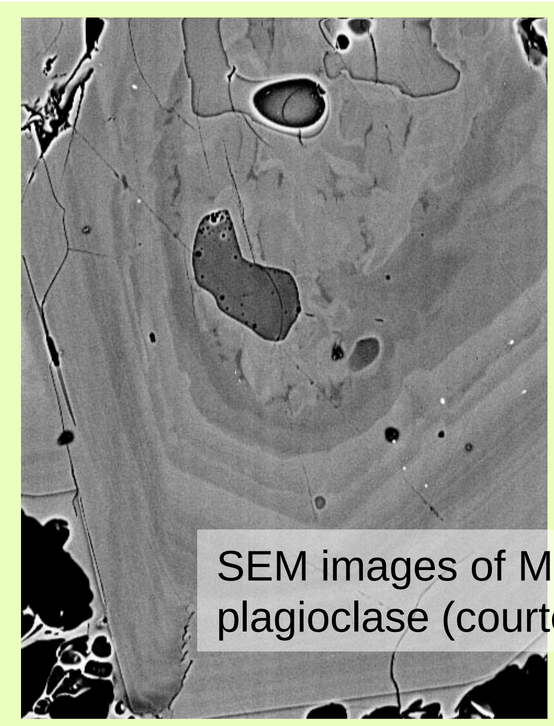
QuickTime™ and a
decompressor
are needed to see this picture.

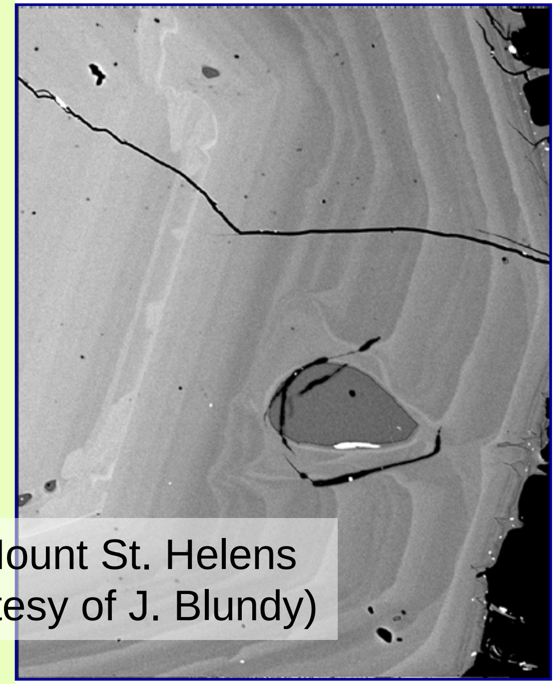
Wallace et al. (2003)

- Melt inclusions in high-silica rhyolities are typically bubble free (a)
- With slower cooling, inclusions develop a darker color (c), bubbles (b), & fine crystals (g, k, l)
- In some cases, bubbles nucleate on daughter crystals (g, h, l)
- Bubbles can also be caused by cracking (decrepitation) of the host

Rhyolitic melt inclusions in plagioclase







SEM images of Mount St. Helens plagioclase (courtesy of J. Blundy)

- Melt inclusions in plagioclase are often poorly sealed
- Vapor bubbles are common

QuickTime™ and a
decompressor
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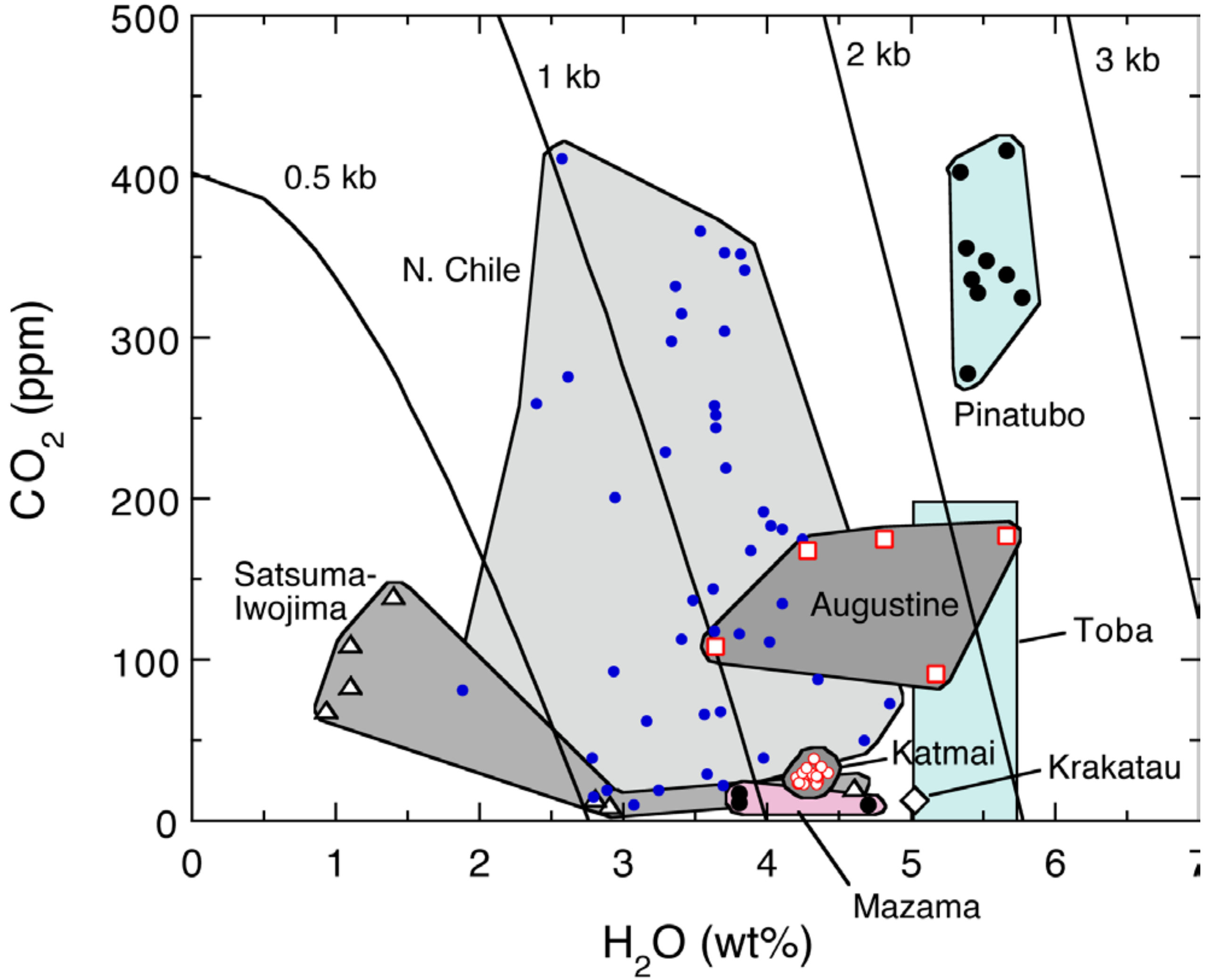
Transmitted light photomicrographs
Crater Lake (Bacon et al., 1992)

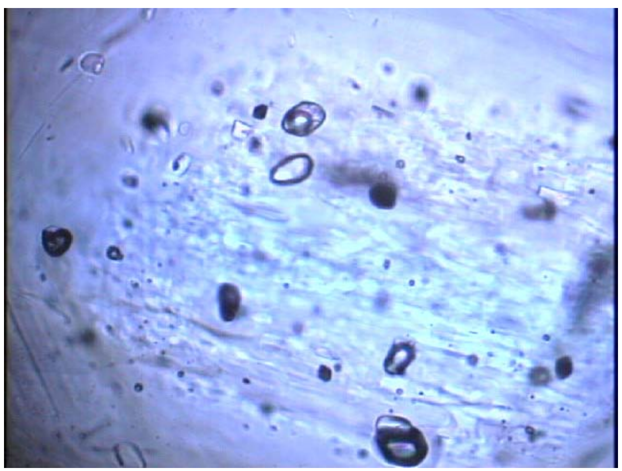
Volatiles in melt inclusions from subduction zone rhyolites



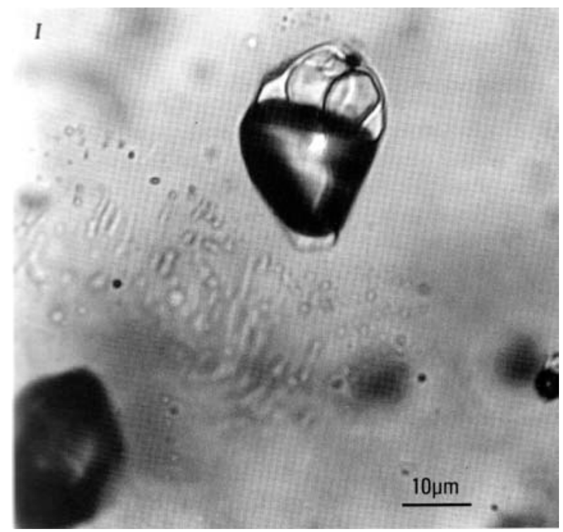
Wallace (2005)

Independent Evidence for Vapor Saturation

- Agreement between melt inclusion vapor saturation pressures & total pressure constrained by experimental phase equilibria
- Volcanic SO_2 and CO_2 emissions
- CO_2 vs. trace elements in melt inclusions
- Fluid inclusions in phenocrysts in volcanic rocks



Plagioclase phenocryst, Guagua Pichincha, Ecuador

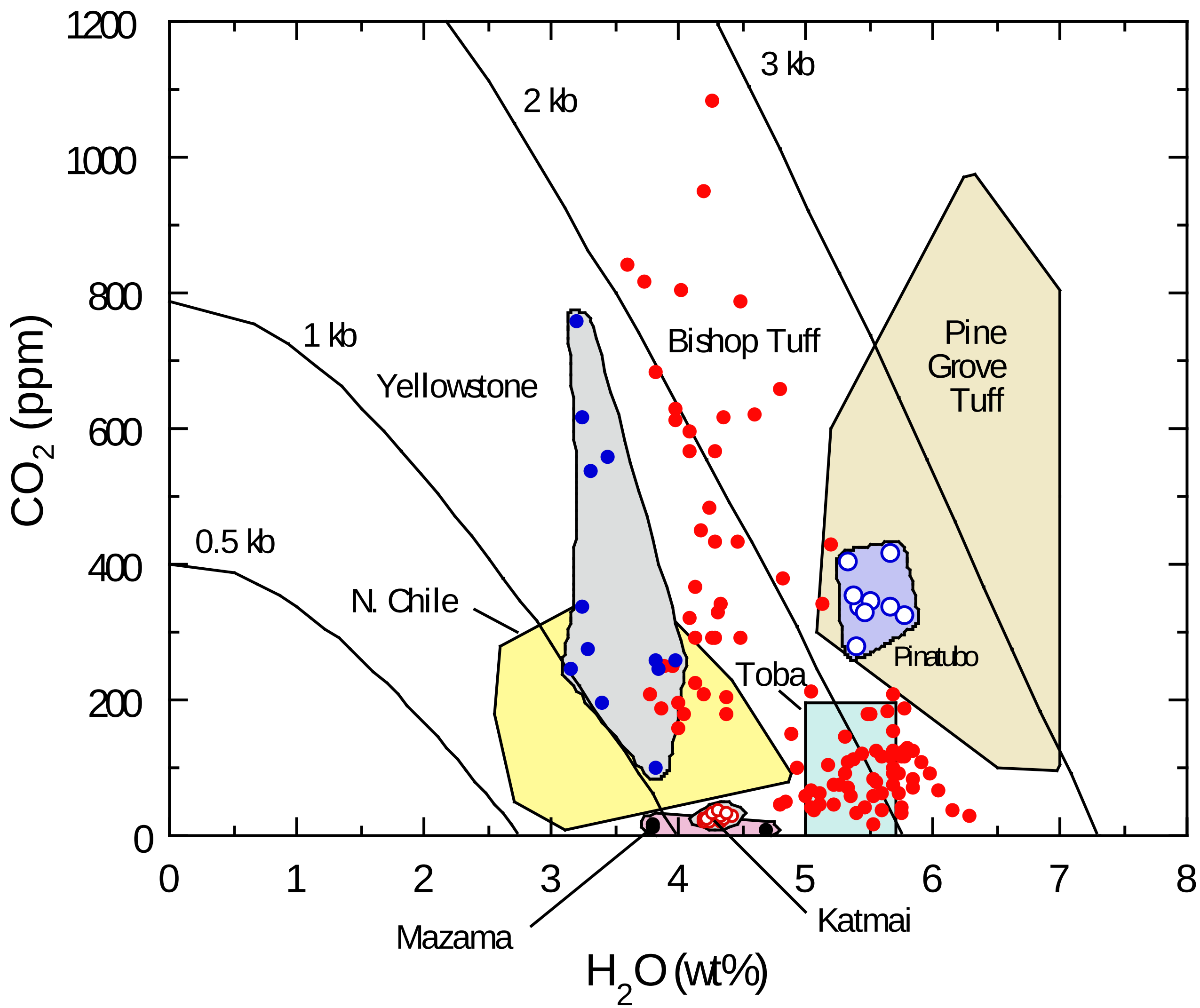


Quartz phenocryst, Pinatubo

Photo courtesy of Jake Lowenstern, USGS

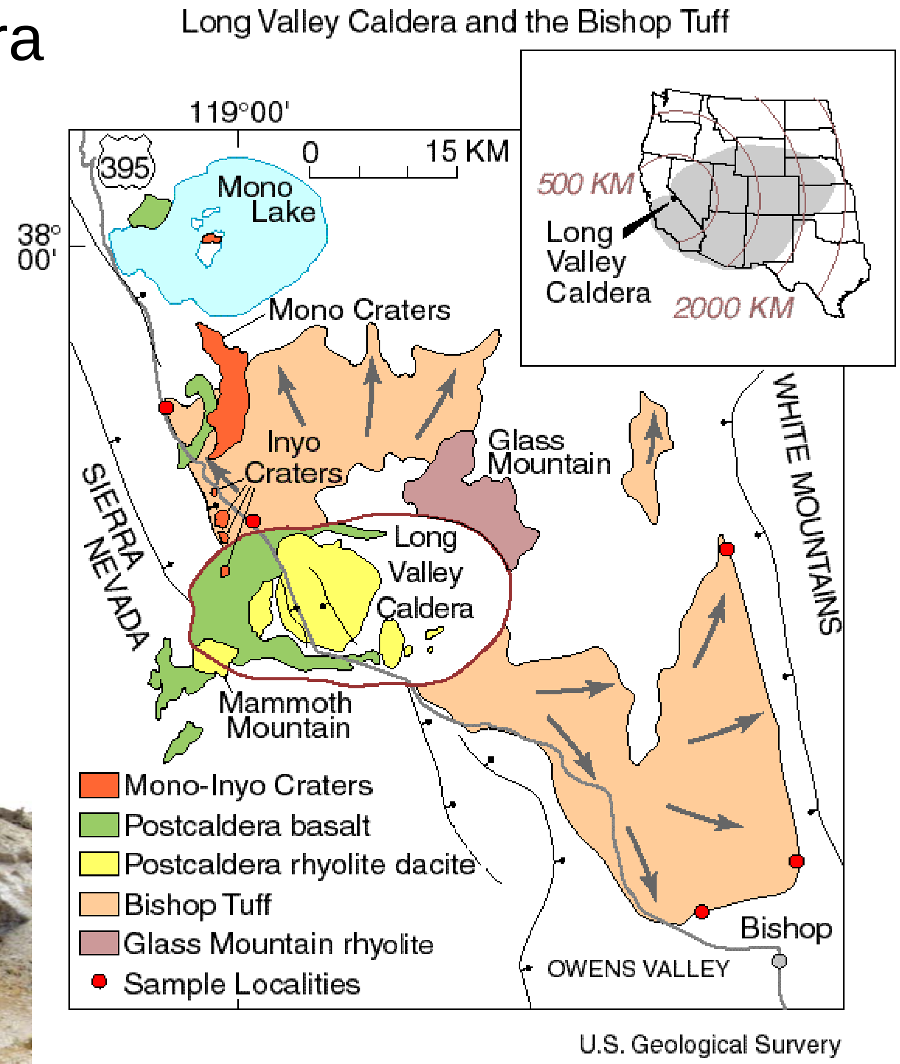
Pasteris et al. (1994)

Comparison of subduction zone & other rhyolites

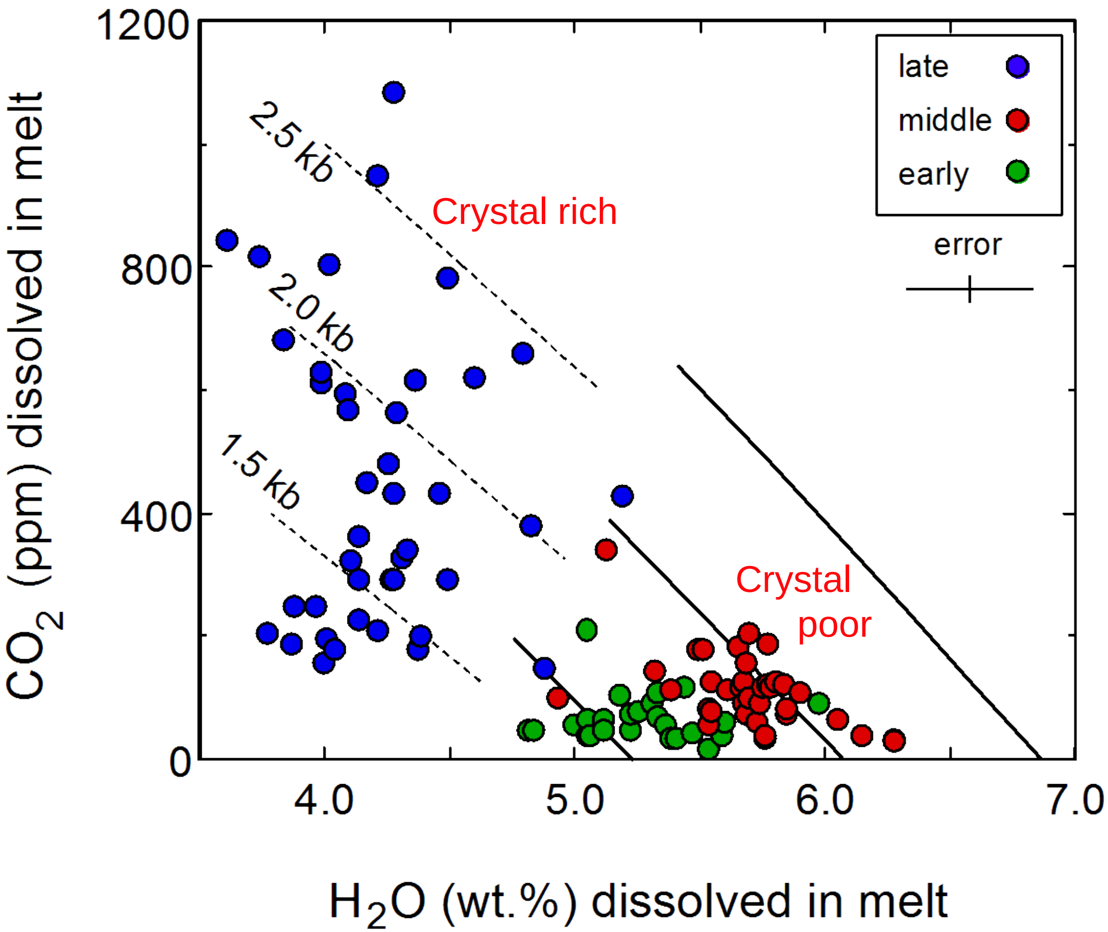


Data sources: Chesner & Newman (1989); Bacon et al. (1992); Lowenstern (1994); Wallace & Gerlach (1994); Gansecki (1998); Wallace et al. (1999); Schmitt (2001); Wallace (unpubl.)

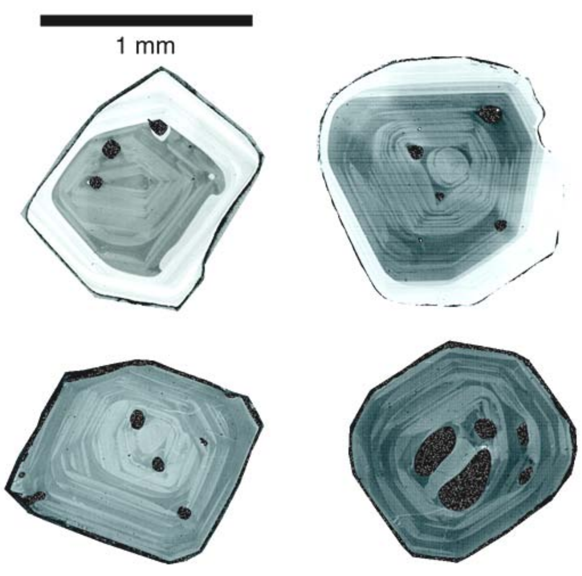
Bishop Tuff & Long Valley Caldera



Melt Inclusions from the Bishop Tuff, California

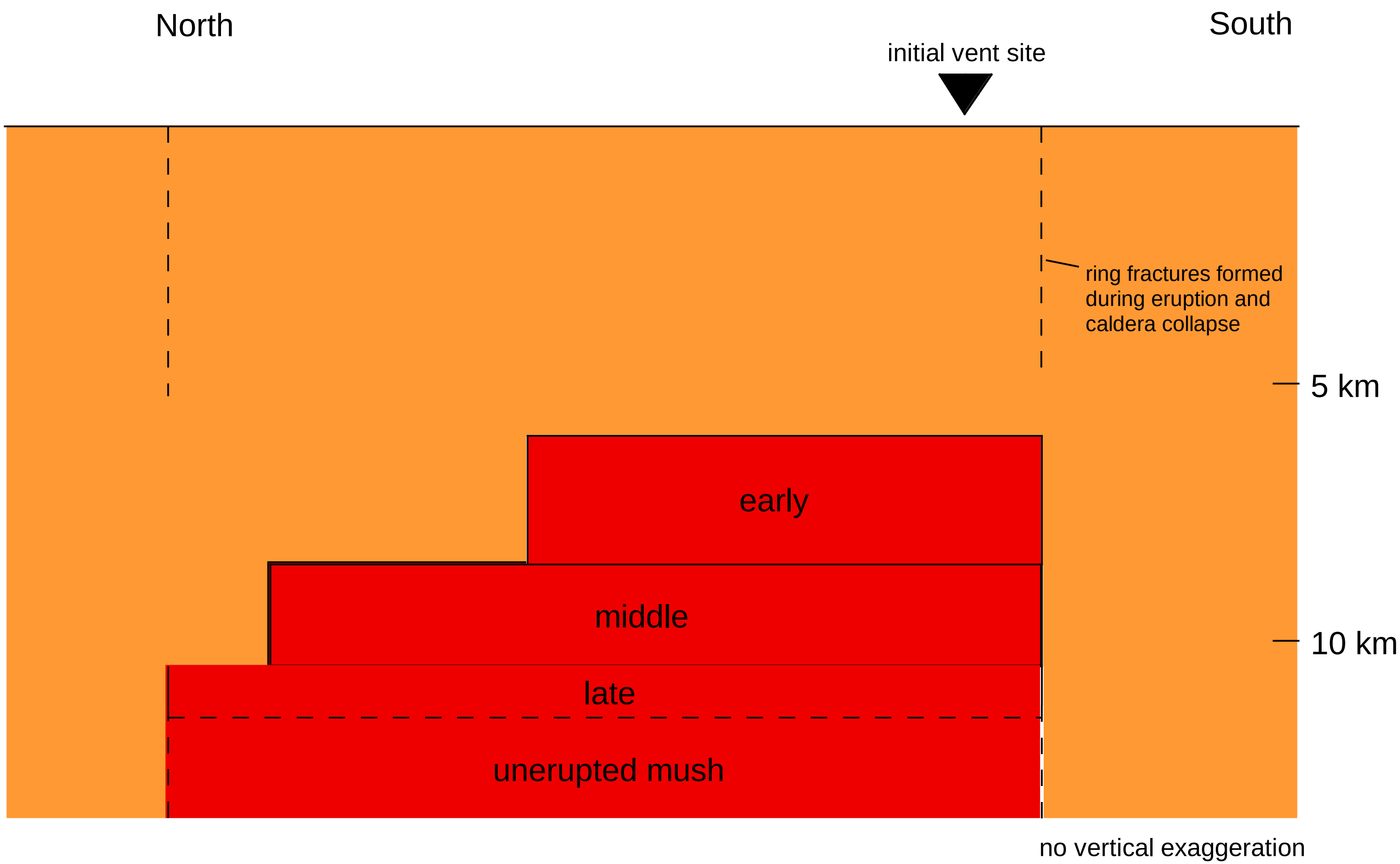


Cathodoluminescence images of quartz-hosted melt inclusion



Wallace et al. (1999)

Use of melt inclusions to infer magma body configuration



Configuration of pre-caldera magma body, Long Valley Caldera, CA

Wallace et al. (1999)

Late Bishop Tuff preserves evidence of pre-eruption intrusion of hot, CO_2-rich rhyolitic melt into crystal mush in lower part of magma chamber

Crystal-rich mush

Intrusion by hotter rhyolite
Dissolution of quartz

Quartz overgrowths trap
high CO_2 melt inclusions

Wark et al. (2007)

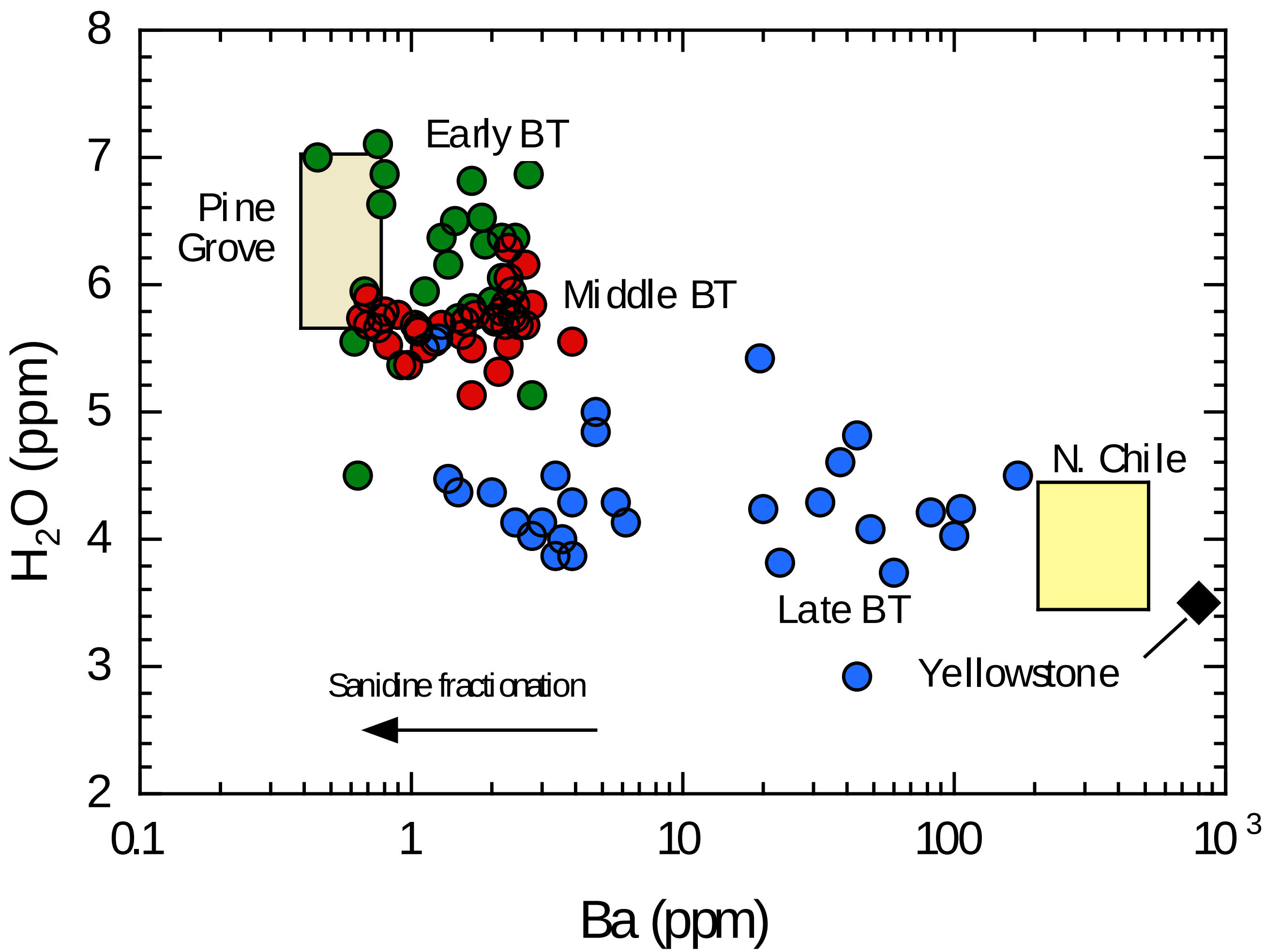
What processes cause variations in volatile contents?

Decompression – leads mainly to variations in CO_2

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

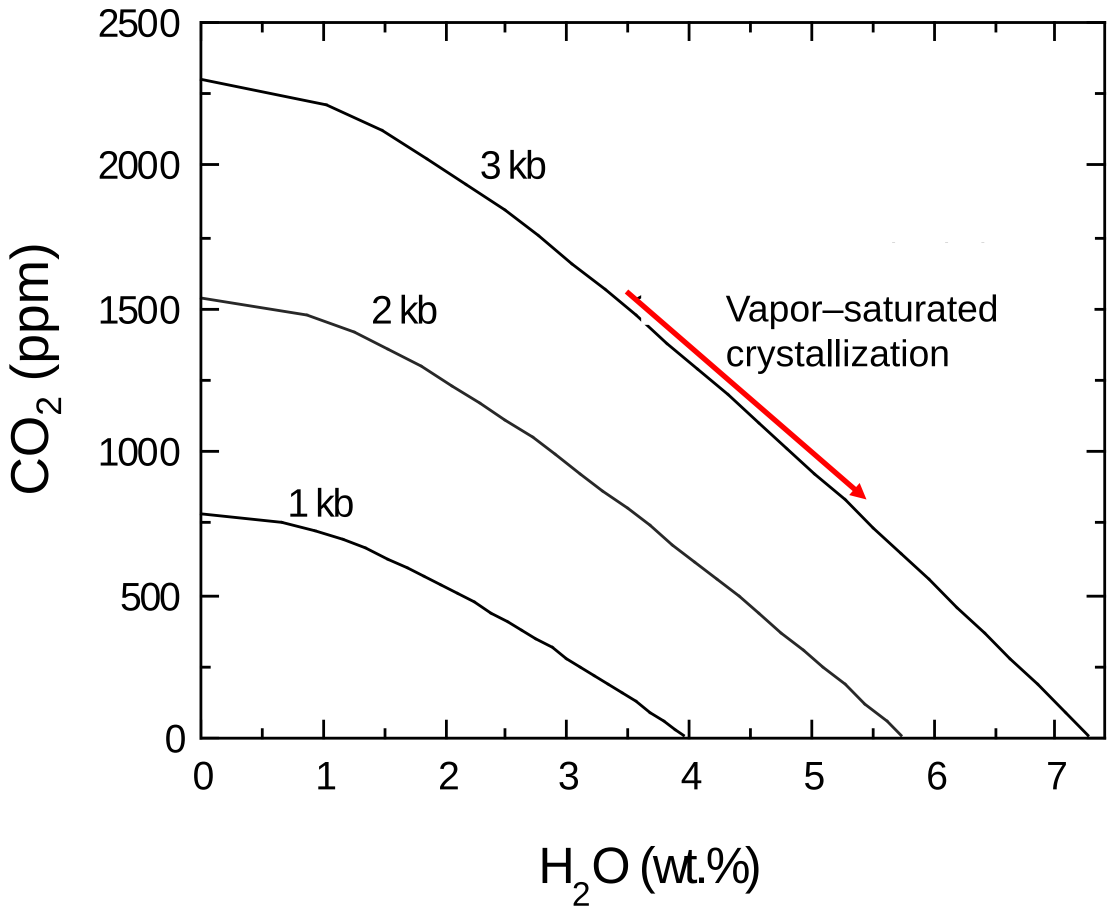
Tuff of Pine Grove, Utah (Lowenstern, 1994)

What causes variations in H_2O content?



- Variation of H_2O with Ba suggests fractional crystallization control on increasing H_2O contents

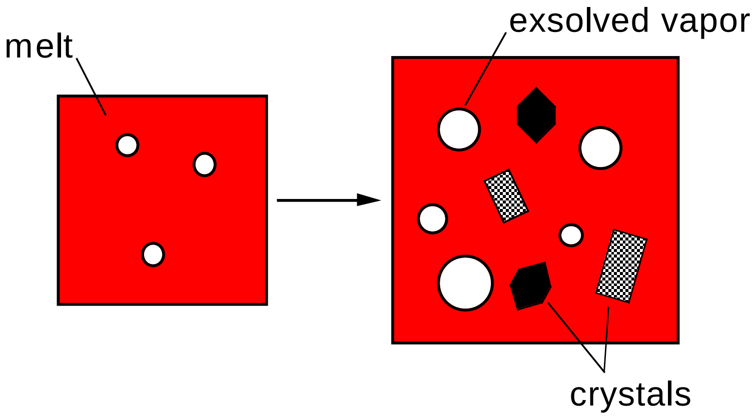
Vapor–Saturated Crystallization



Anderson et al. (1989)

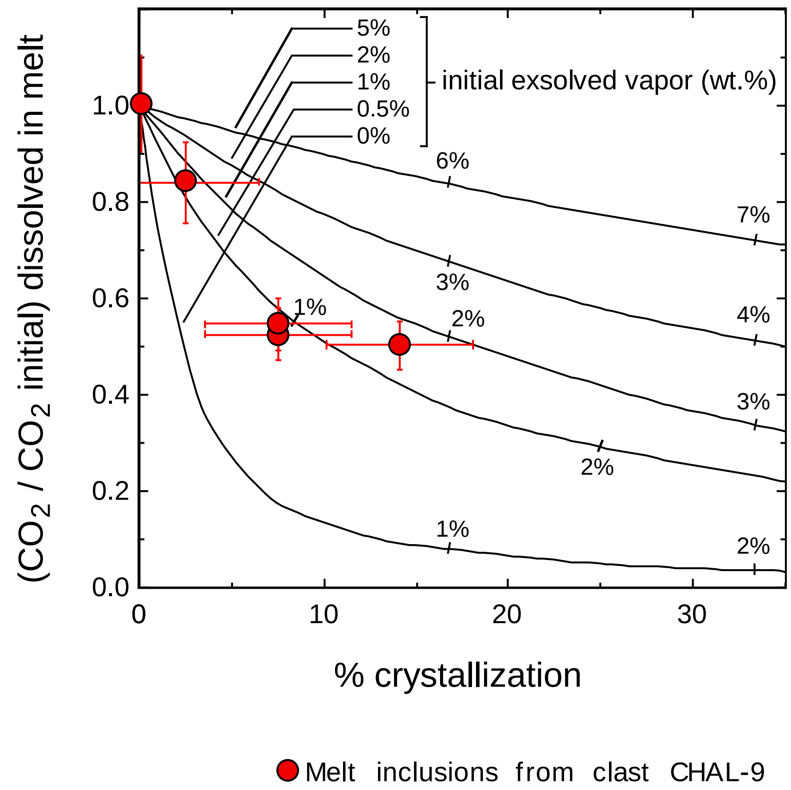
- Magmatic H_2O contents increase during vapor-saturated crystallization if CO_2 is present

Loss of CO_2 to Exsolved Vapor During Closed-System Crystallization



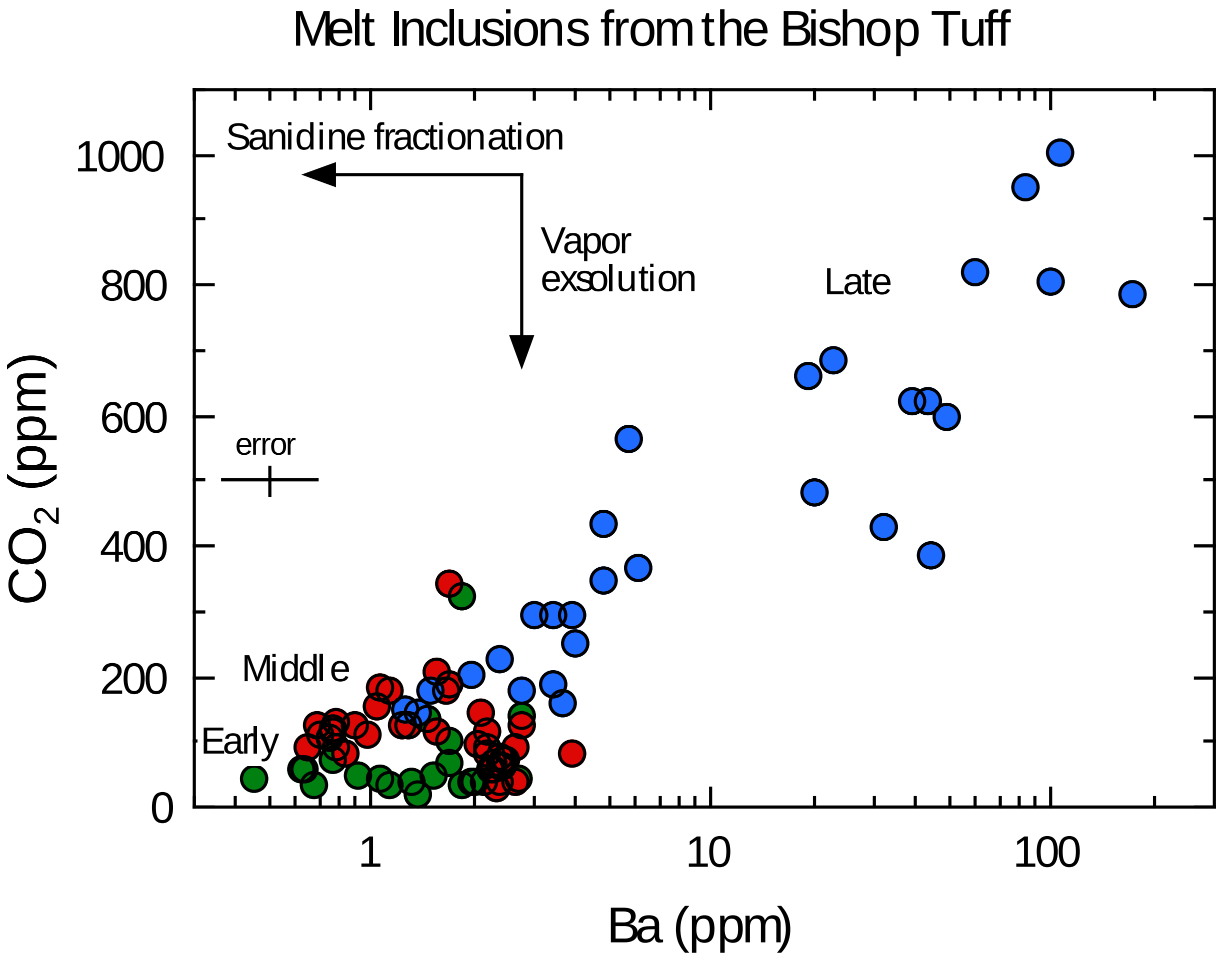
initial		**final**
crystal %	<	crystal %
vapor mass	<	vapor mass
volume	<	volume

CO_2 exsolution during vapor-saturated crystallization



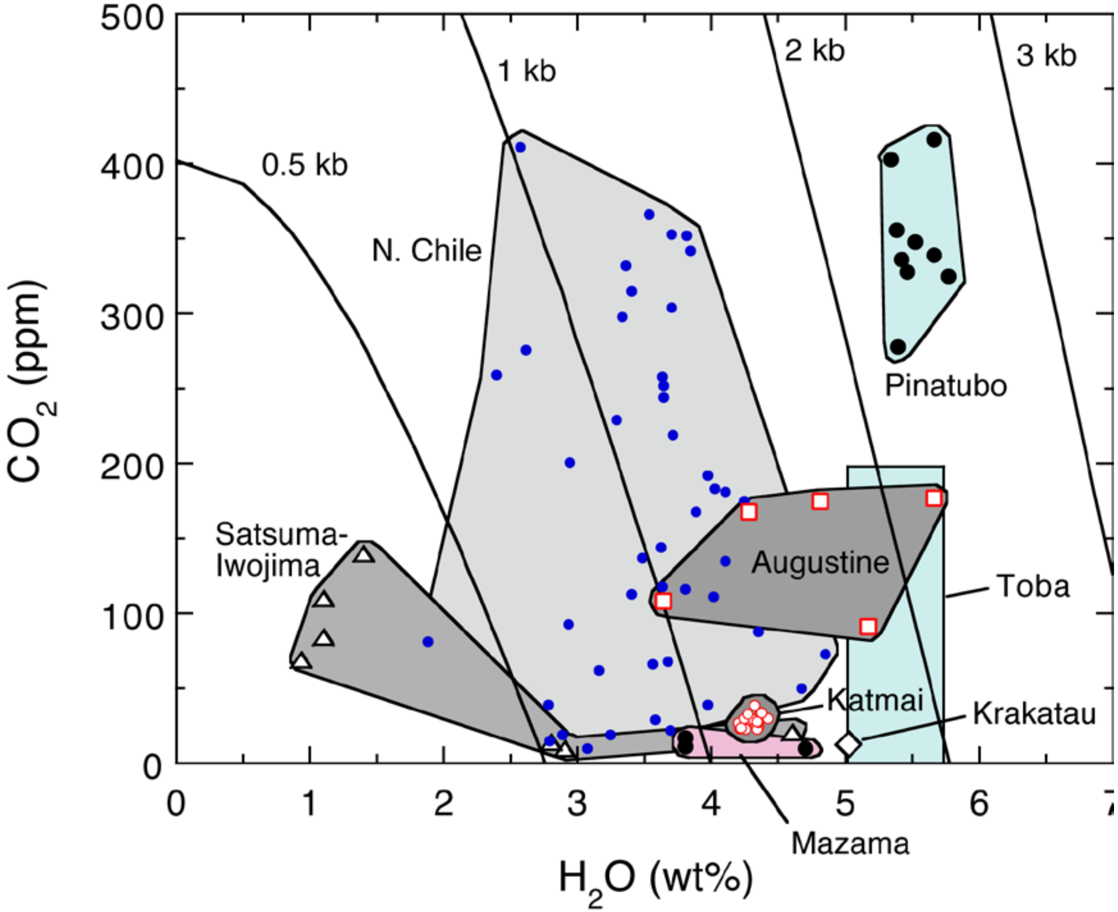
Wallace et al. (1995)

Loss of CO_2 to Exsolved Vapor During Vapor-Saturated Crystallization



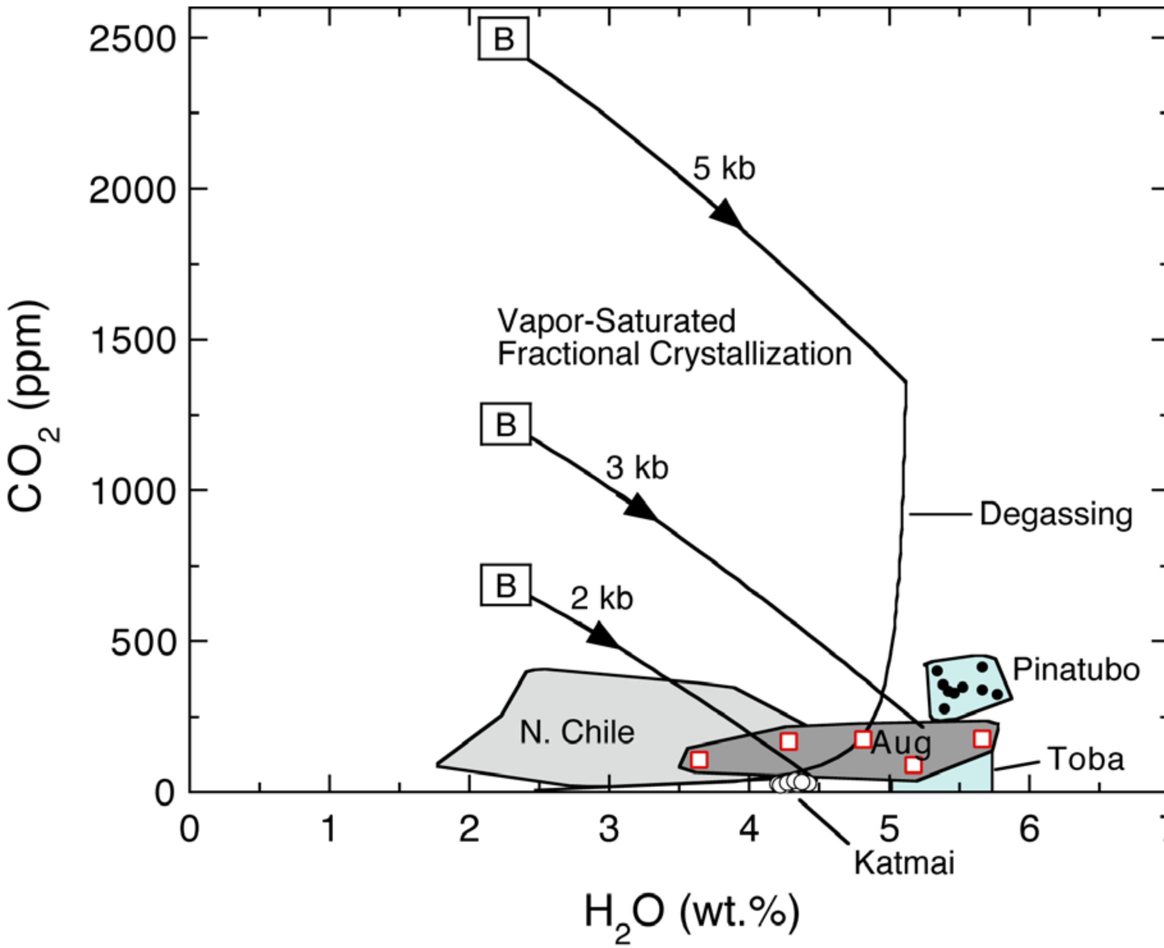
Wallace et al. (1999)

What can we infer about volatiles in magmas that are parental to rhyolites?



- Note that the range of H_2O in arc rhyolites is similar to that in arc basalts
- How are the two related?

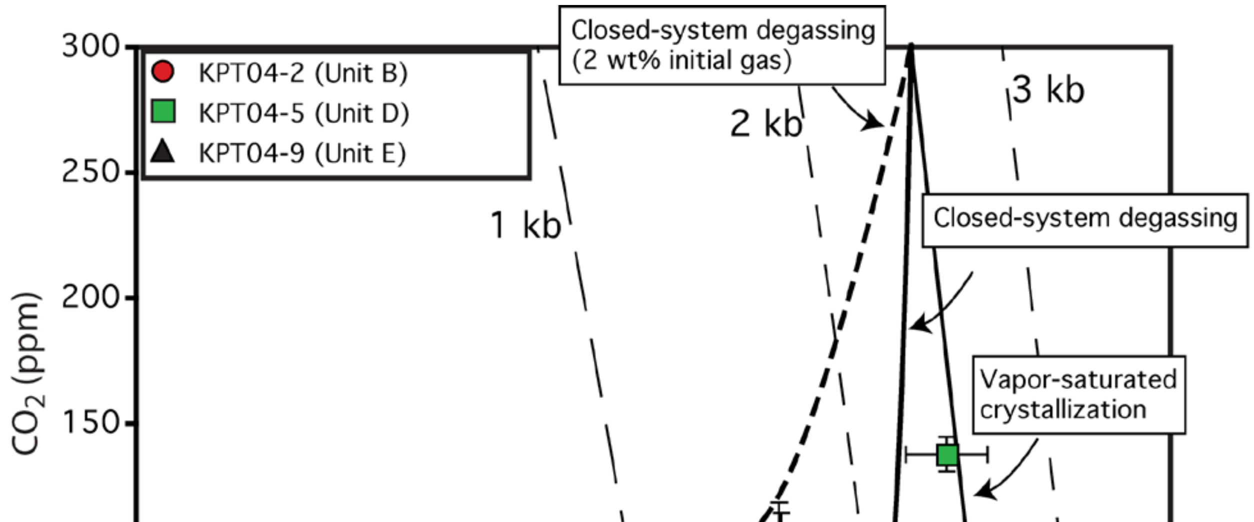
Effects of fractional crystallization & ascent into upper crust



Wallace (2005)

- Parental basaltic magmas must have relatively low H_2O, and/or
- Lower crustal melting must involve relatively H_2O-poor sources

Kos Plateau Tuff – quartz crystals recycled from mush(?)



[redacted]

- Crystal rich (≤40 vol%) rhyolitic tuff; eruptive volume >60 km^3
- Geologic evidence suggests magma chamber drawdown of ~1 km during eruption
- Crystals may mostly be derived from mush zone beneath & surrounding chamber

Effects of composition & temperature on S contents of magmas

QuickTime™ and a
decompressor
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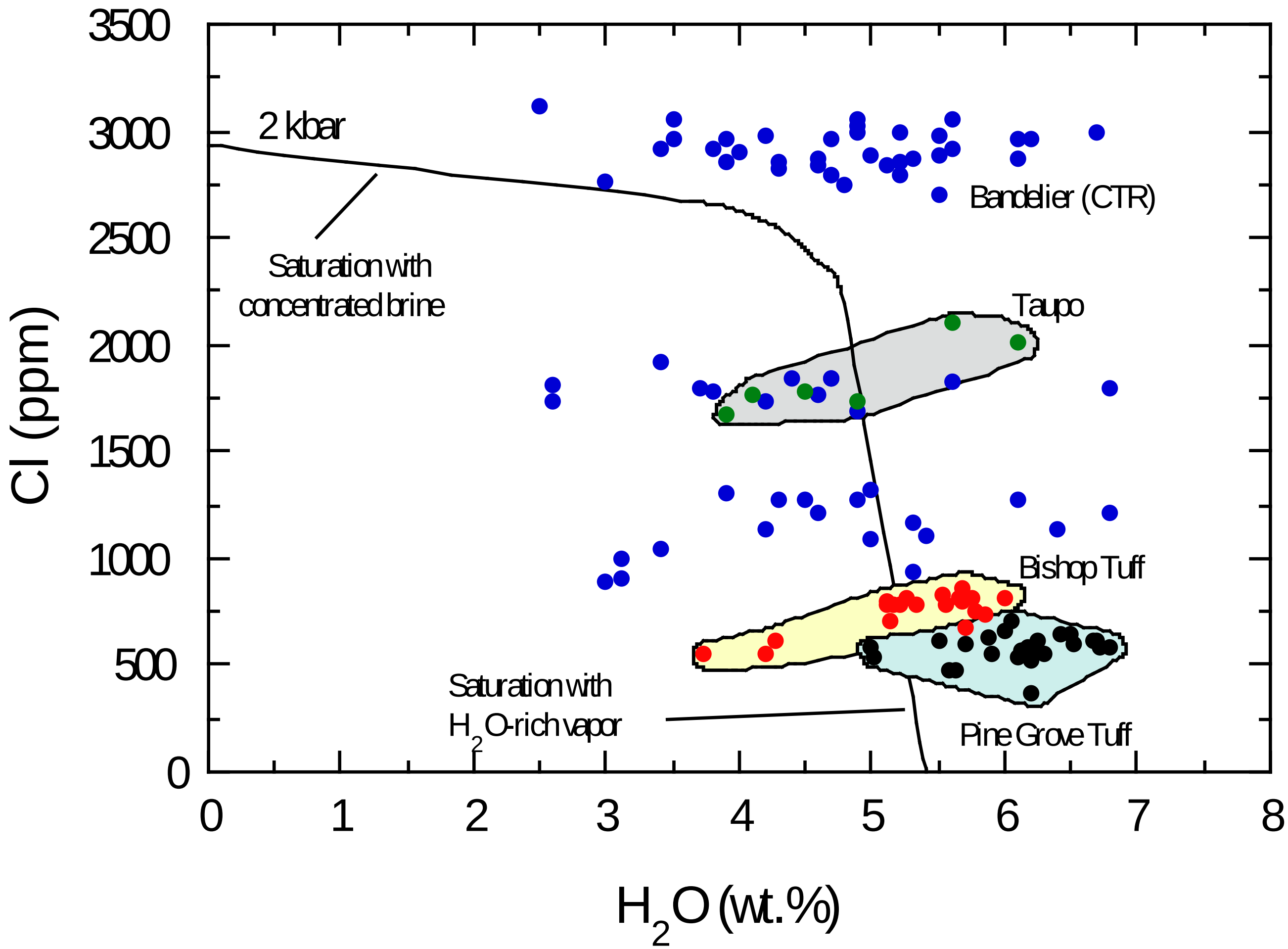
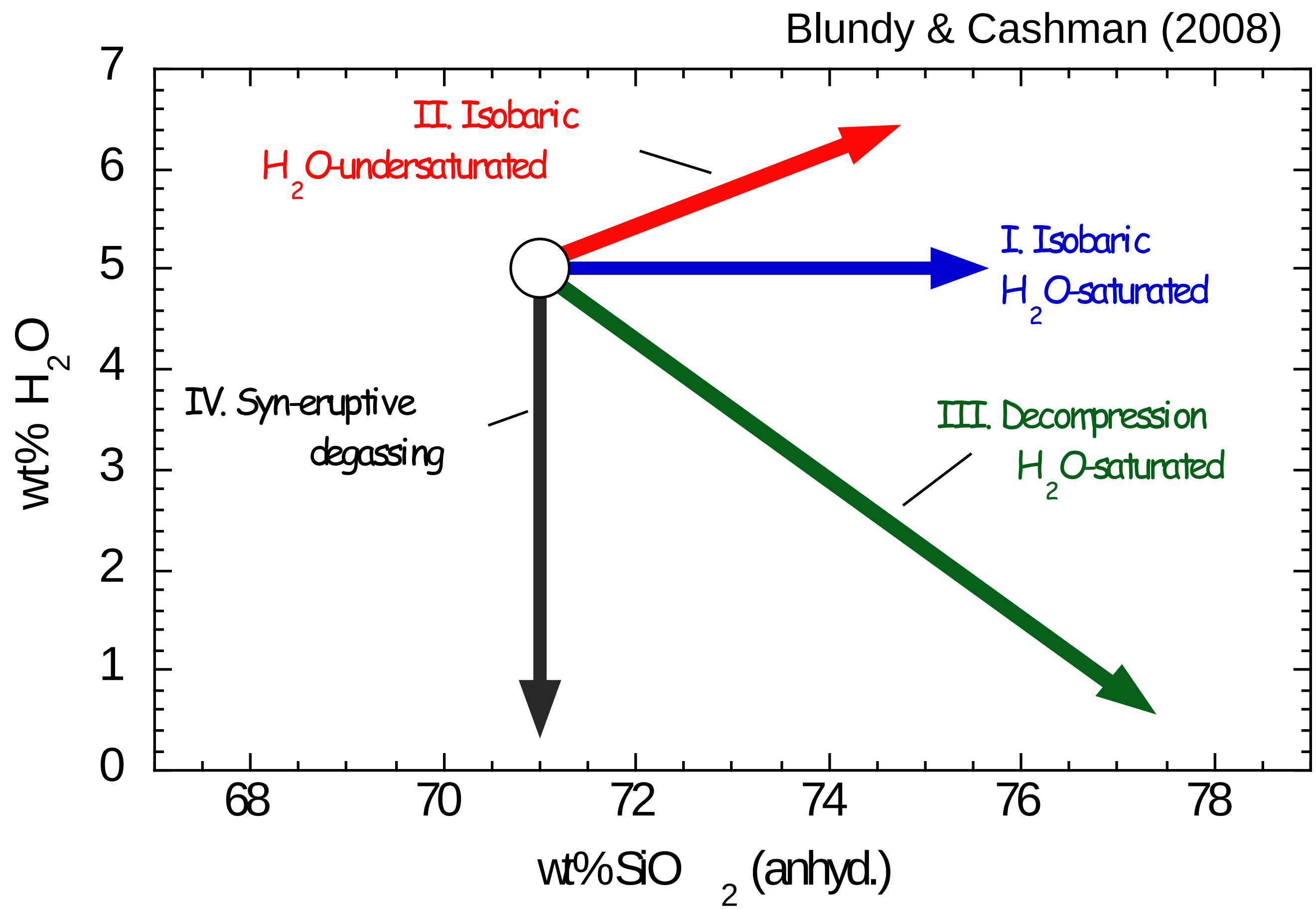
Shinohara (2008)

Chlorine in Rhyolitic Melt Inclusions



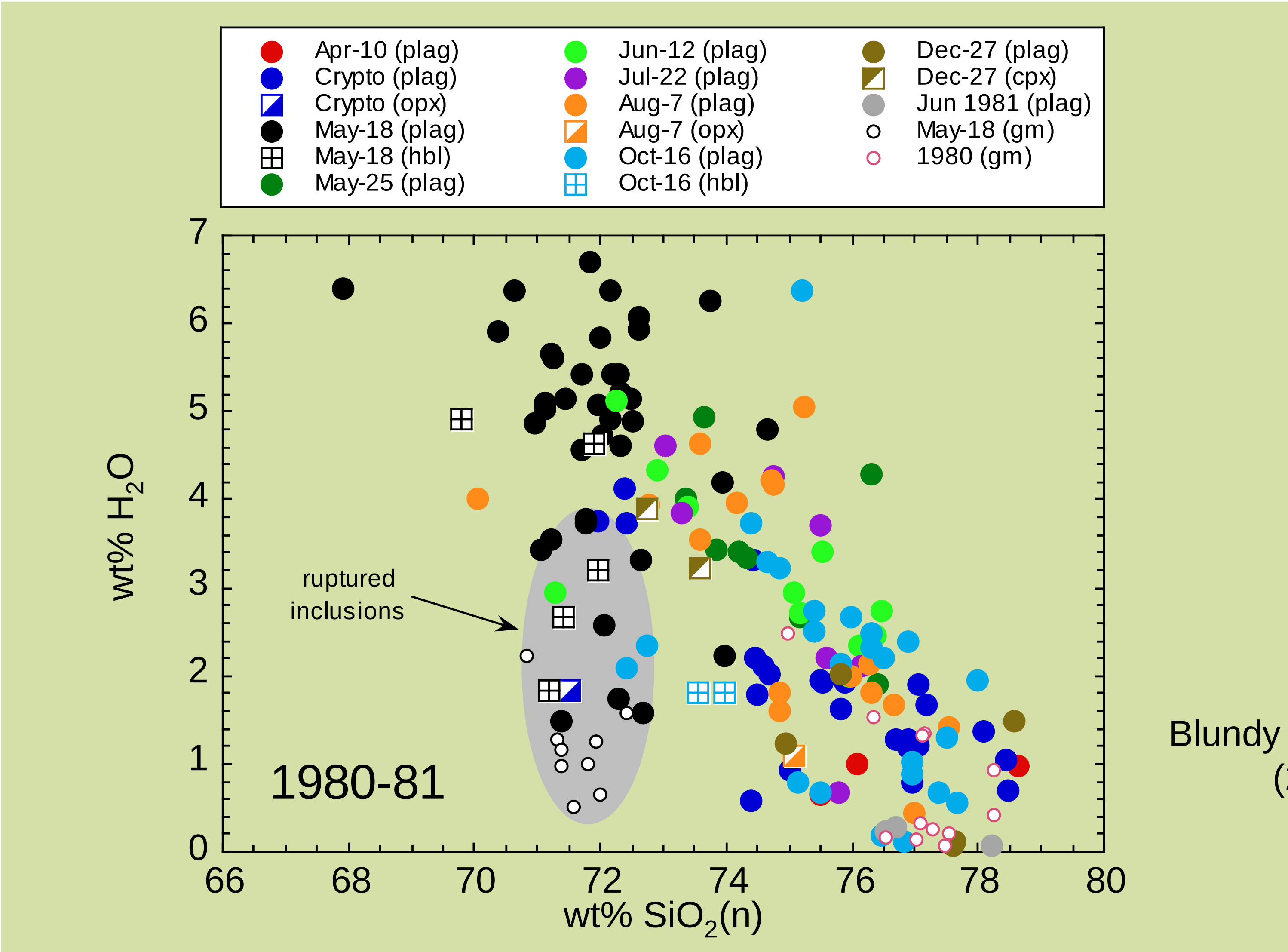
- Most non-mineralized rhyolites do not have enough Cl to be saturated with concentrated brine (hydrosaline melt)

Decompression-driven versus cooling-driven crystallisation



Inclusion populations record ascent trajectories – time and pressure variations

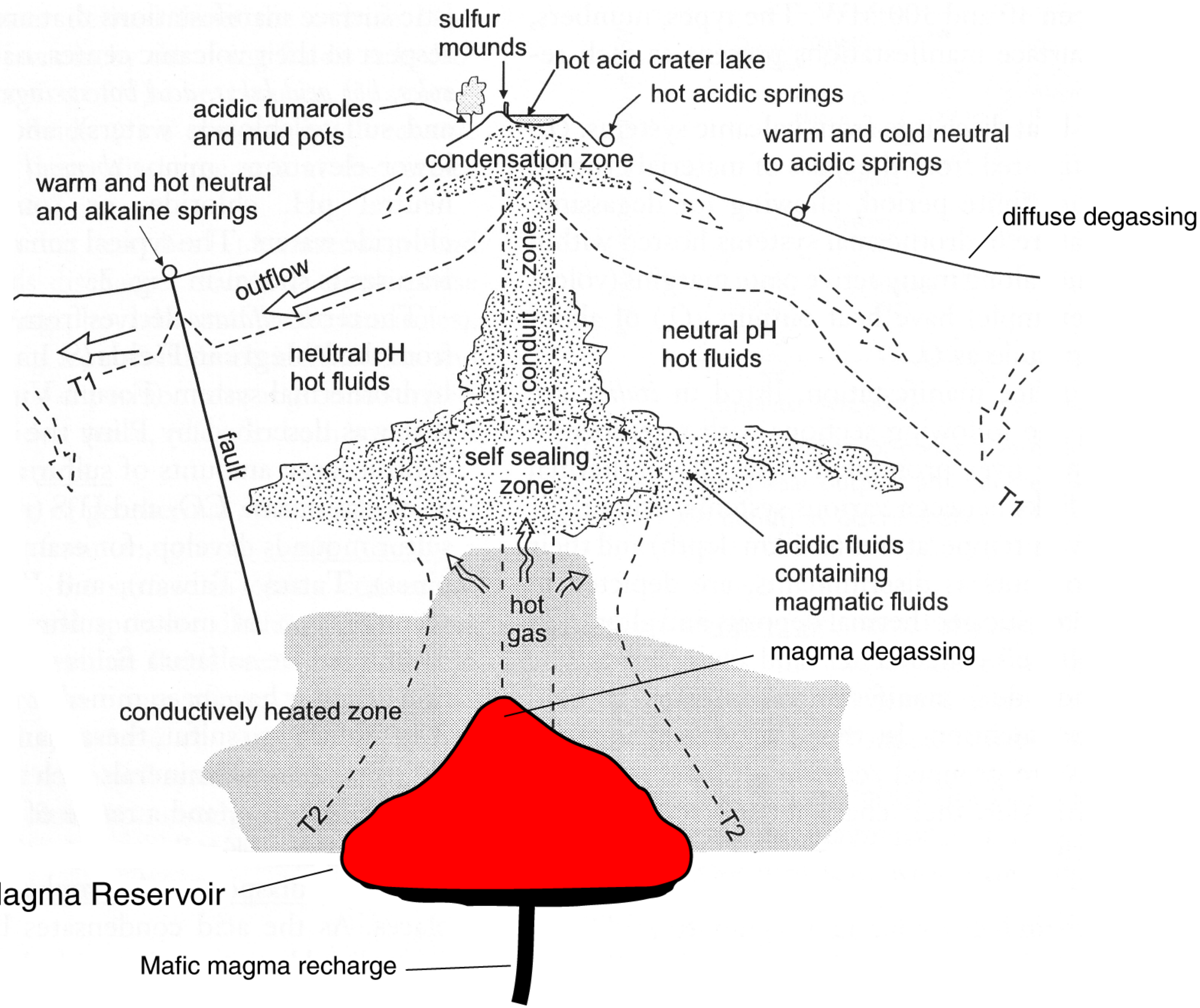
Decompression-driven crystallisation



Blundy & Cashman (2008)

- Decompression-driven crystallization (H_2O loss) is much faster than crystallization driven by cooling

Silicic magma bodies & hydrothermal systems



Modified from Hochstein & Browne (2000)

Melt Inclusions from Porphyry Copper Deposits

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

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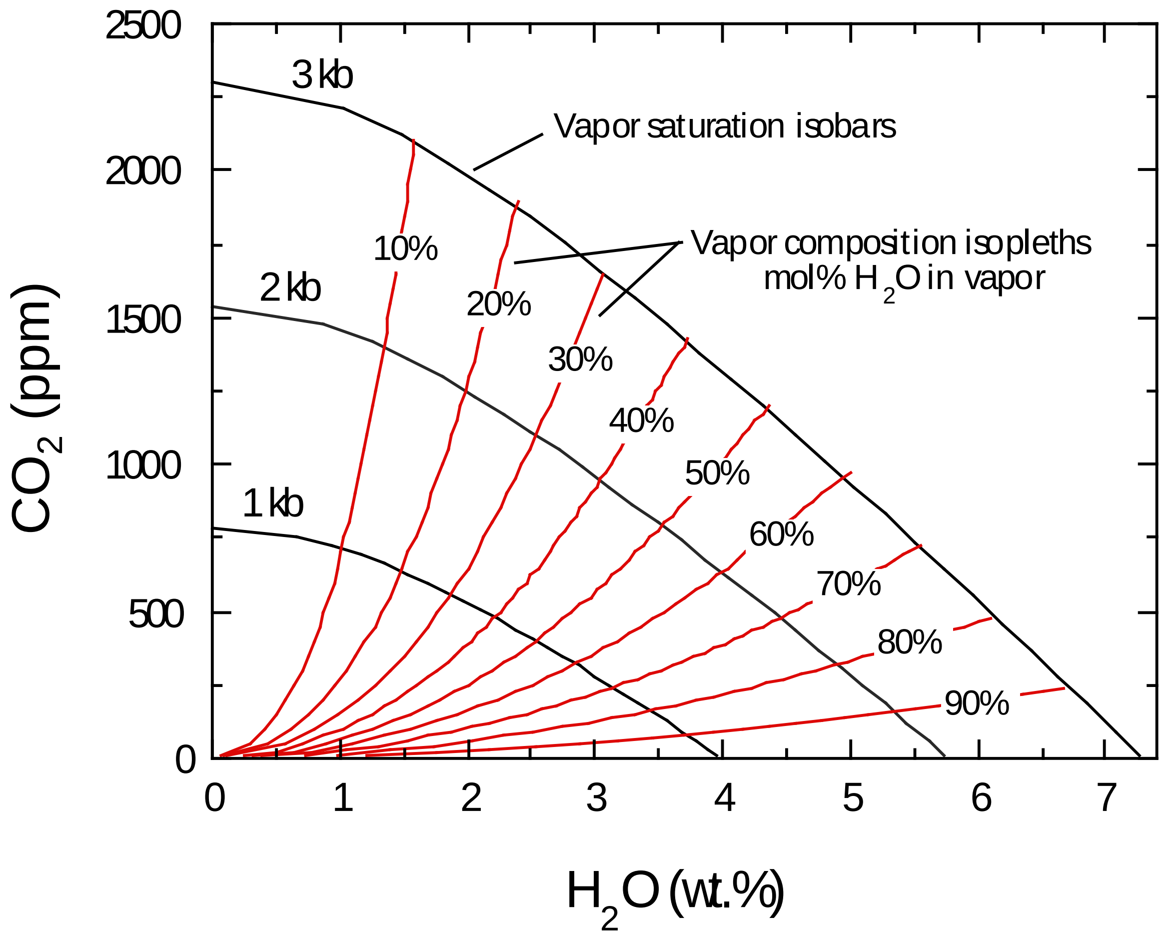
Student & Bodnar (2004)

Key points to remember:

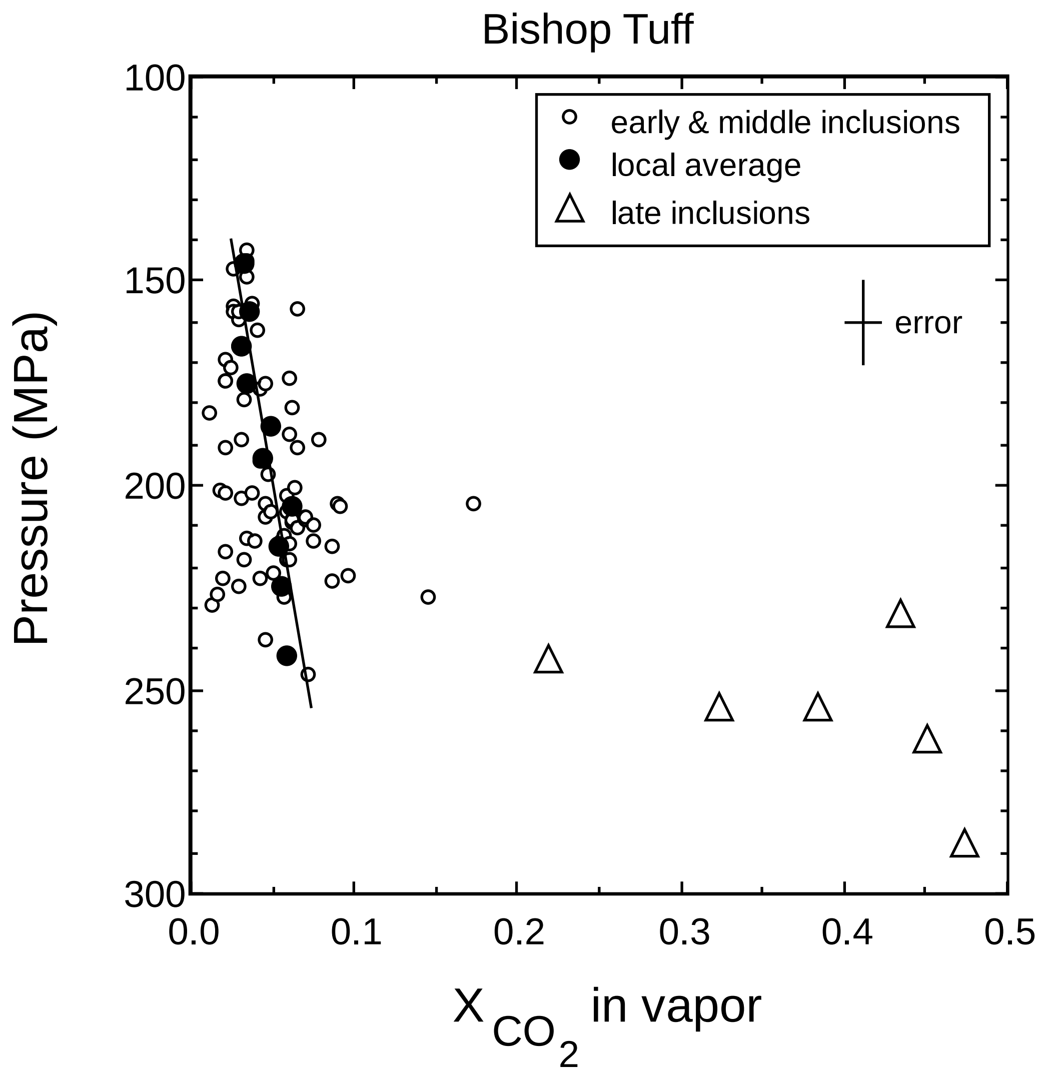
- Melt inclusions in rhyolitic systems preserve a complex record of magma crystallization, degassing, mixing and storage
- Melt inclusion H_2O & CO_2 data can be used to infer magma body configuration and depths of crystallization
- Rhyolitic magmas are typically vapor saturated in the upper crust. Some may be saturated with a hydrosaline melt (brine) phase
- Dissolved sulfur concentrations are low, but there may be considerable S as H_2S and SO_2 in the coexisting vapor phase

Inferring Vapor Composition from Melt Inclusion Data



Isobars & isopleths from VolatileCalc (Newman & Lowenstern, 2002)

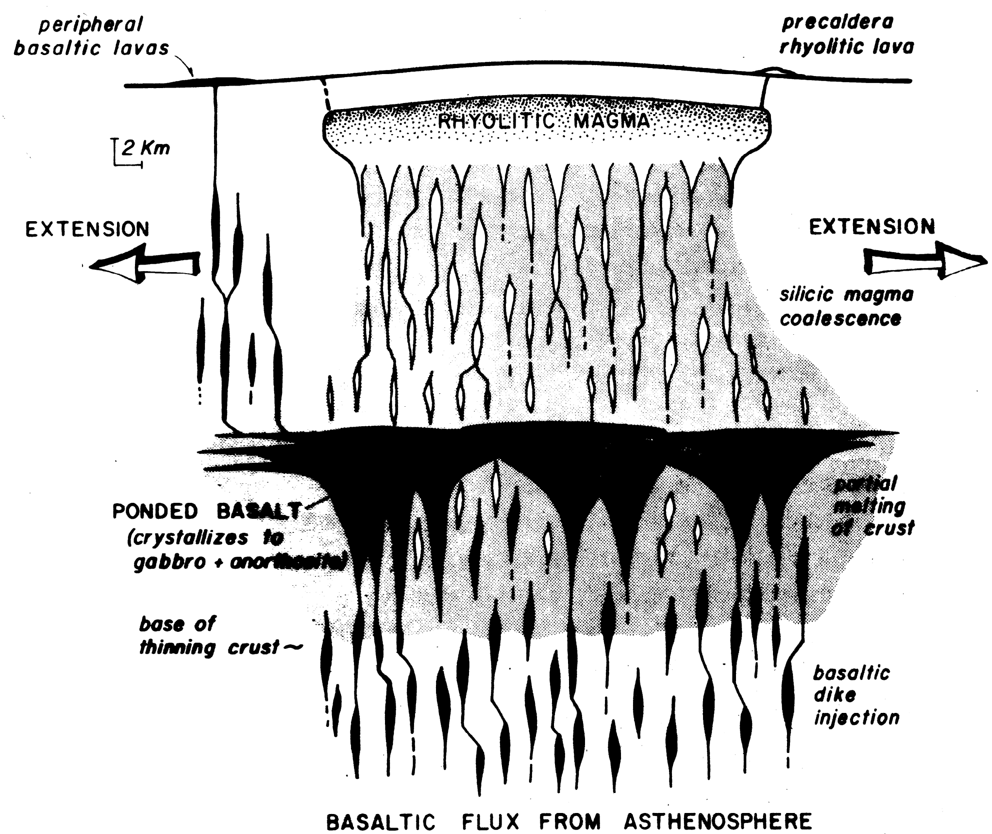
Exsolved Vapor Composition in Pre-Caldera Magma Body



Wallace et al. (1999)

Importance of Mafic Magma

- Crustal magmatic systems are fundamentally basaltic
- Basaltic magma transfers volatiles from mantle to crust

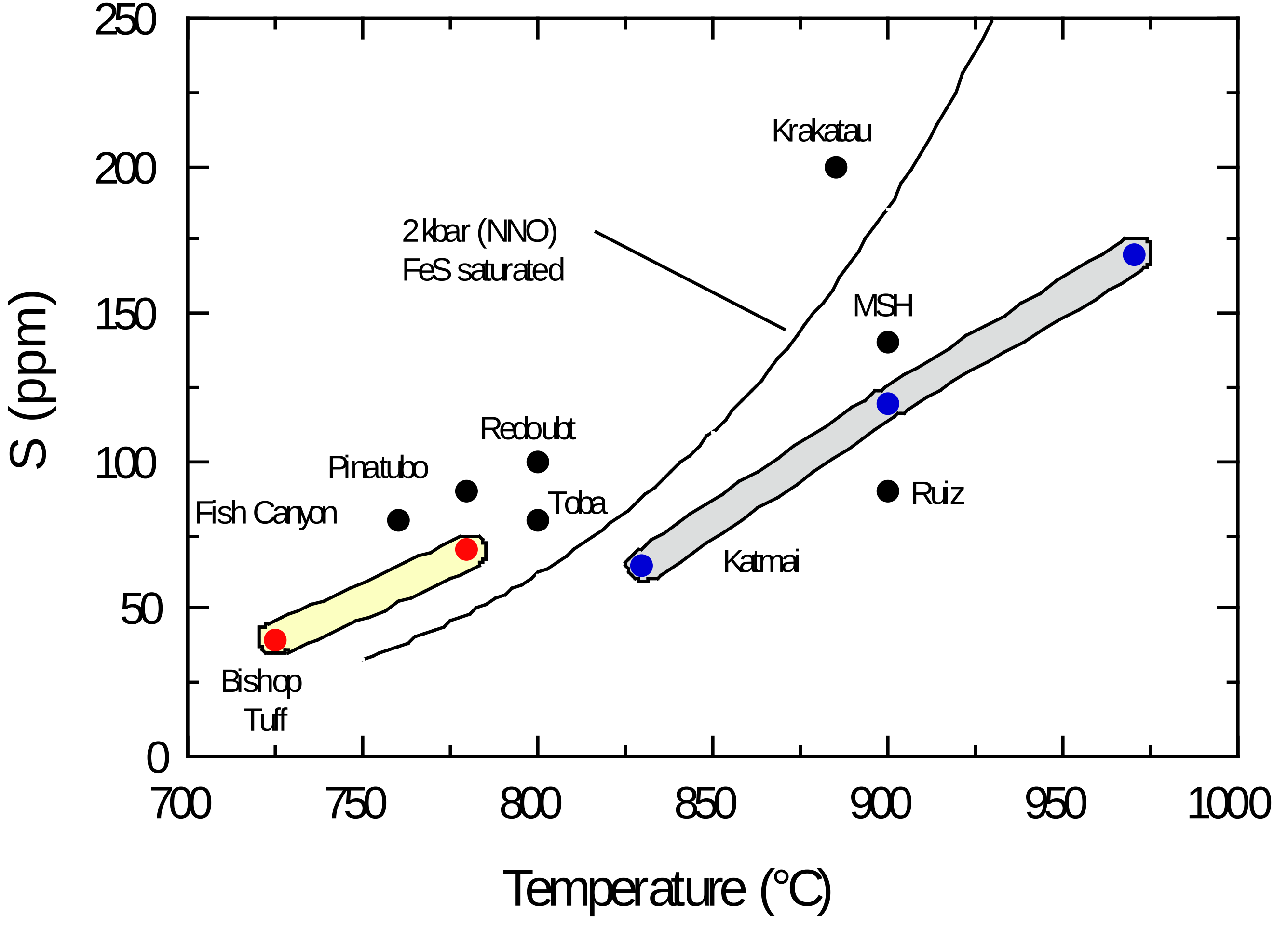


"Degassing of basalt crystallizing in the roots of these systems provides a flux of He, CO_2, S, halogens, and other components."

"[Stable isotope] data suggest that magmatic fluxes of C and S are dominated by mantle sources"

Hildreth (1981)

Sulfur in Rhyolitic Melt Inclusions



- Many rhyolitic magmas are sulfide saturated
- Saturation limit of S increases with temperature & oxygen fugacity