



# Volatiles in Basaltic Melt Inclusions

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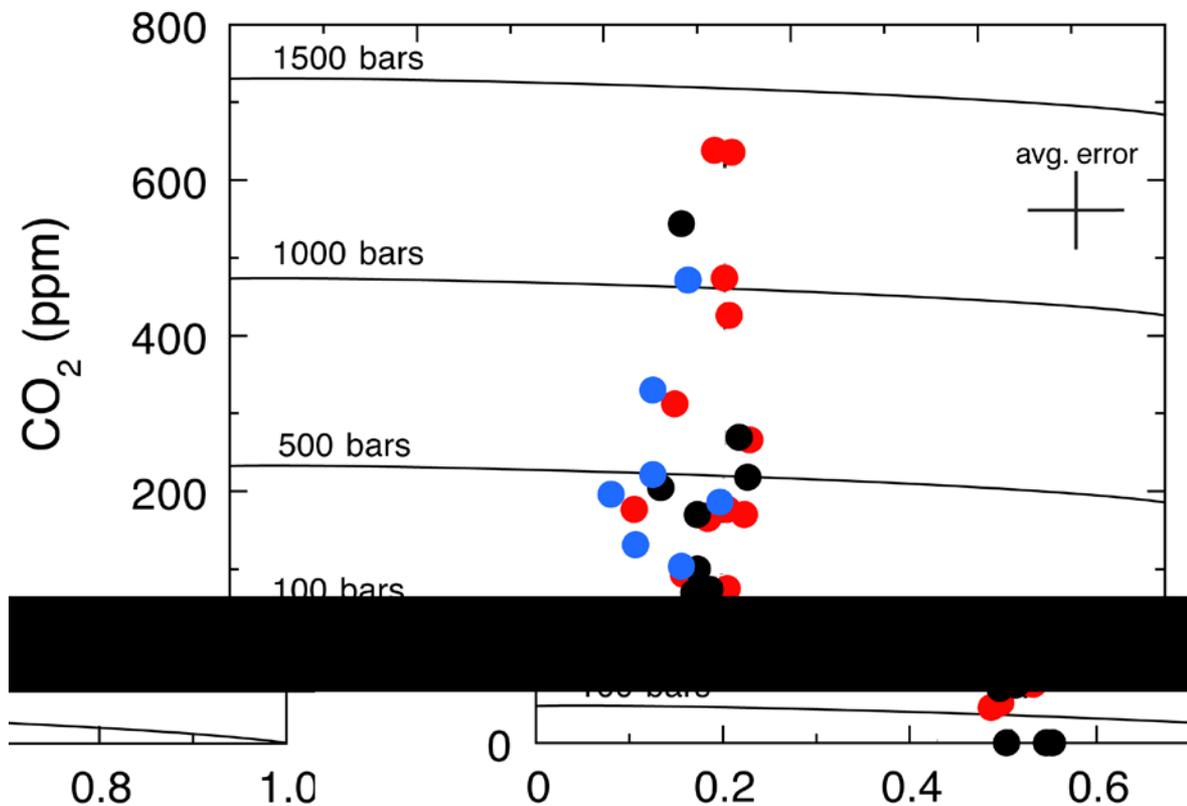
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# Outline

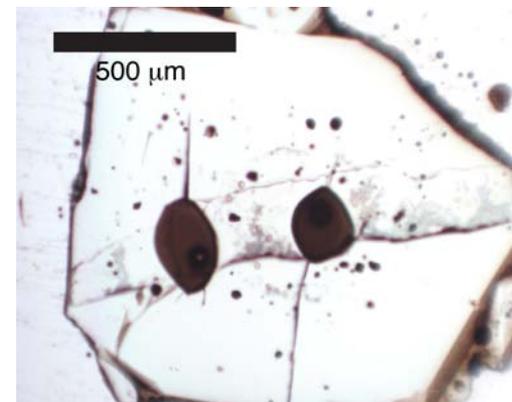
- Inferring trapping pressures from H<sub>2</sub>O-CO<sub>2</sub> data
- Post-entrapment modification of melt inclusion volatile contents
- Degassing of volatiles recorded in melt inclusions
- Melt inclusion evidence for gas fluxing in upper crustal magma bodies and conduits
- Initial (pre-degassing) volatile contents of mafic magmas from different tectonic environments

# H<sub>2</sub>O and CO<sub>2</sub> in variations basaltic melt inclusions



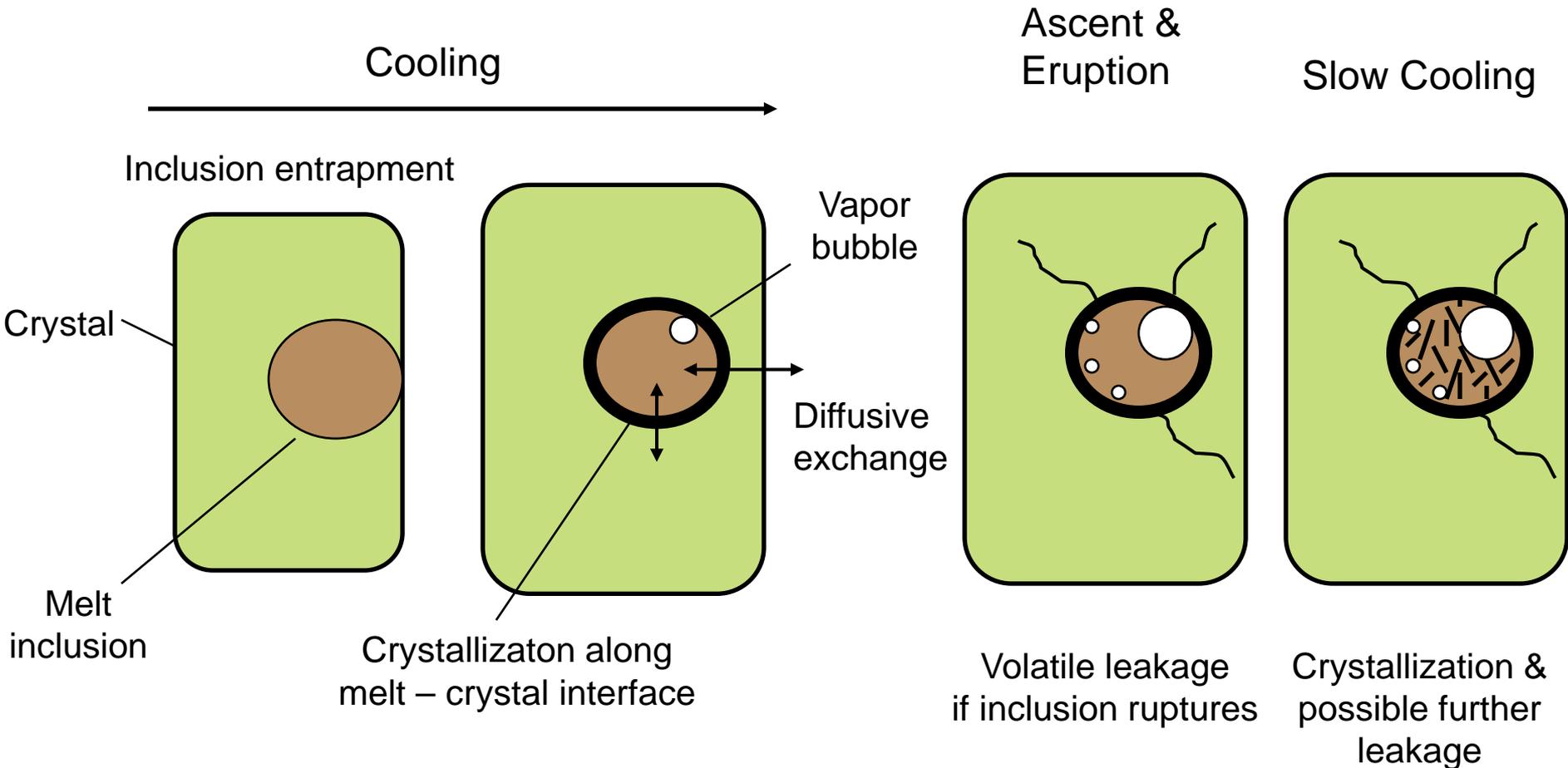
Melt inclusions from Keanakakoi Ash, Kilauea, Hawaii (Hart & Wallace, unpublished)

- Phreatomagmatic ash (lower)
- Strombolian scoria lapilli (middle)
- Co-surge vitric ash (upper)



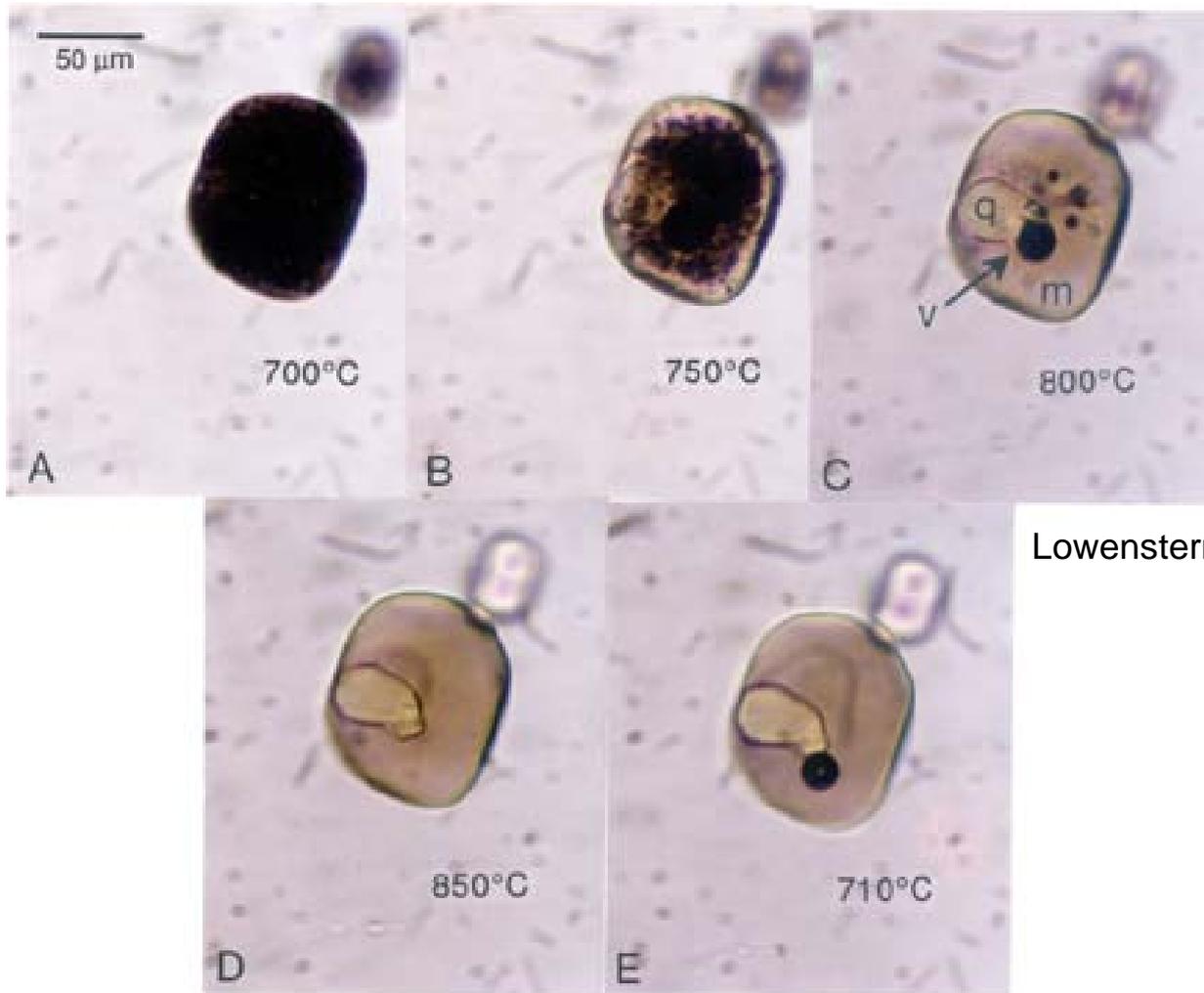
- Melt inclusion data from a single volcano or even a single eruptive unit often show a range of H<sub>2</sub>O and CO<sub>2</sub> values.
- Must consider possible post-entrapment modification processes before interpreting in terms of original trapping pressure

# Post-Entrapment Modification of Melt Inclusions



- Melt inclusions in tephra deposits are often naturally quenched to glass, making them preferable to inclusions from lava flows

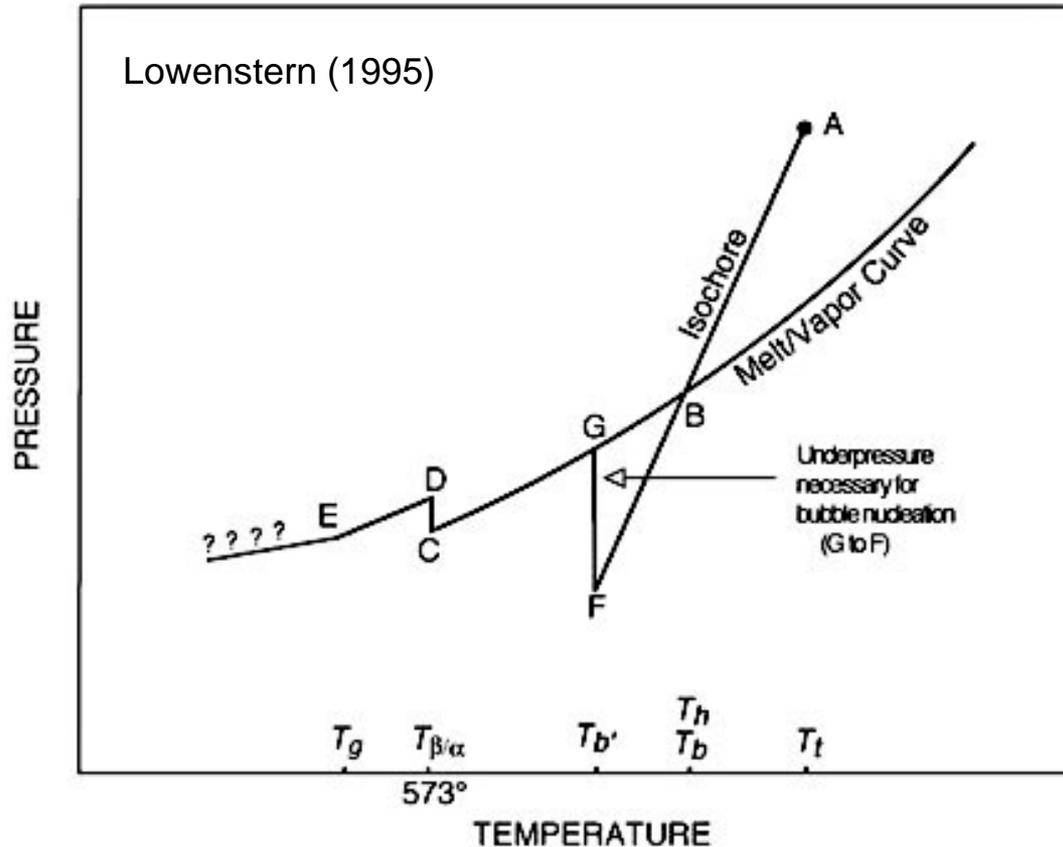
# Formation of shrinkage bubble



Lowenstern (1994)

- Heating stage experiment on quartz-hosted melt inclusion from Pantelleria
- Vapor bubble nucleates during cooling (E)

# Pressure vs. temperature for a melt inclusion in quartz



- Silicate melt has much greater thermal expansion than crystals
- On cooling, if no vapor bubble is present, pressure in an inclusion decreases rapidly
- Once a vapor bubble nucleates, pressure decreases more slowly
- Low solubility  $\text{CO}_2$  partitions strongly into the vapor bubble

# CO<sub>2</sub> loss to shrinkage bubbles in basaltic melt inclusions

- Shrinkage bubble size in basaltic melt inclusions is commonly ~2 to 4 vol% of inclusion, indicating a post-trapping temperature interval of  $\leq 100^\circ \text{ C}$ .
- Larger vapor bubbles may be primary bubbles that were co-entrapped together with silicate melt at the time of formation.
- CO<sub>2</sub> loss been demonstrated in heating experiments on olivine (Fo<sub>88</sub>) from a Mauna Loa picrite (Wallace & Kamenetsky, unpublished).
- Naturally glassy melt inclusions were re-homogenized at  $1400^\circ \text{ C}$  for <10 min.
- Results showed that as much as 80% of the initial CO<sub>2</sub> can be transferred to a shrinkage bubble over a cooling interval of  $\sim 100^\circ \text{ C}$ .

# Post-entrapment diffusive loss of H<sub>2</sub>O from melt inclusions

- It is well established that hydrogen can diffuse rapidly through olivine by coupled diffusion of protons & metal vacancies (Demouchy & Mackwell, 2006).
- Diffusion of molecular H<sub>2</sub>O in olivine has been reported (Portnyagin et al., 2008)
- Heating stage experiments (1 atm) show that substantial H<sub>2</sub>O is lost from olivine-hosted melt inclusions on timescales of hours
- Must use short heating times when rehomogenizing inclusions. Best to always use naturally glassy inclusions from tephra

Relative H<sub>2</sub>O content

MI from Piton de la Fournaise  
Heating at 1190° C & 1 atm.  
Multiple heating & quenching cycles

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

Time (hours)

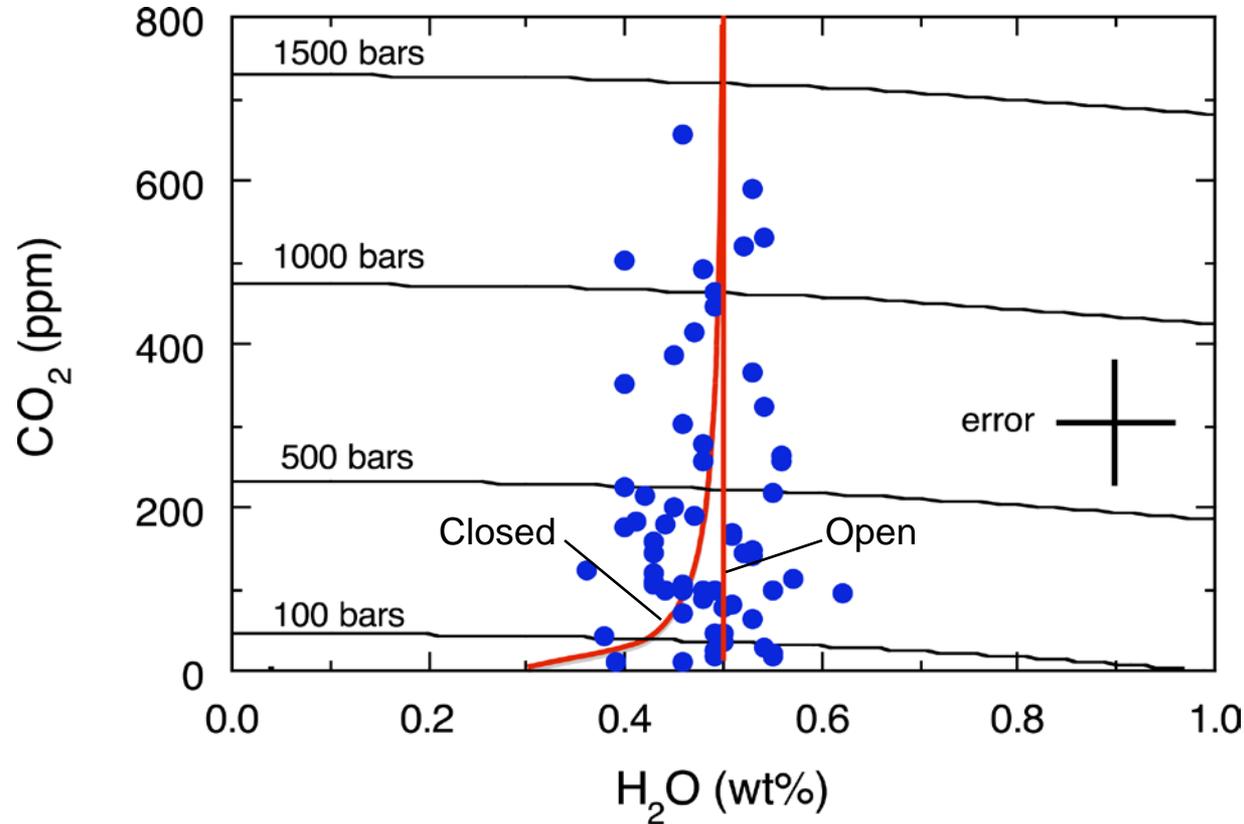
Massare et al. (2002)

# H<sub>2</sub>O variations in melt inclusions

Diffusive loss or variable melt degassing before inclusion entrapment?

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decompressor  
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# Degassing & variable trapping pressure during magma ascent



Closed-system degassing  
Exsolved gas remains entrained  
in melt & maintains equilibrium.

Open-system degassing  
Exsolved gas is continuously  
separated from melt

Melt inclusions from Keanakakoi  
Ash, Kilauea, Hawaii (Hart &  
Wallace, unpublished)

- In many cases, variations in H<sub>2</sub>O & CO<sub>2</sub> reflect variable degassing during ascent before the melts were trapped in growing olivine crystals (polybaric crystallization)

# Degassing of H<sub>2</sub>O-rich basaltic magma from an arc volcano

Cerro Negro, Nicaragua, 1867 eruption

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decompressor  
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Roggensack (2001)

# Why do many MI data sets not follow equilibrium degassing paths?

Melt inclusions from Mount Etna



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## Melt inclusions from Central Mexico cinder cones

Deviations from equilibrium degassing paths are observed for many melt inclusions

But a subset of the data (with low  $\text{CO}_2$ ) follow the equilibrium paths

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

Johnson et al. (in review)

# Gas fluxing of magma in upper crustal magma bodies & conduits

- Combined effect of open-system addition of CO<sub>2</sub>-rich gas to ascending or stored magma (Anderson et al., 1989; Wallace, 2003; Rust et al., 2004; Spilliaert et al., 2006; Johnson et al., 2008)
- This process is consistent with:
  - high CO<sub>2</sub> in primary magmas (e.g. Kilauea, Gerlach et al., 2002; Etna, Allard et al., 1999)
  - high CO<sub>2</sub> flux at basaltic volcanoes (Fisher & Marty, 2005; Wallace, 2005, for reviews)
  - high CO<sub>2</sub>/SO<sub>2</sub> ratios in gas emissions with increasing explosivity of eruption (e.g. Burton et al., 2007; Aiuppa et al. 2007)
- If this interpretation is correct, such a process should be common at open-conduit basaltic volcanoes

# Effects of Gas Fluxing

## Melt inclusions from Mount Etna

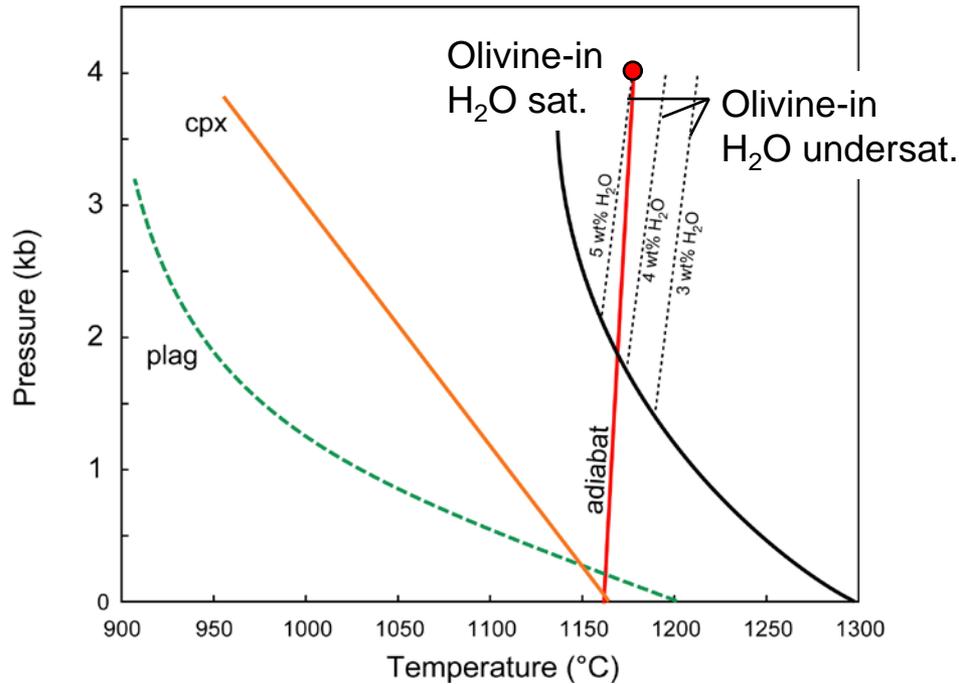
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decompressor  
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CO<sub>2</sub>-flushed magma  
ponding zone. Causes  
dehydration of magma

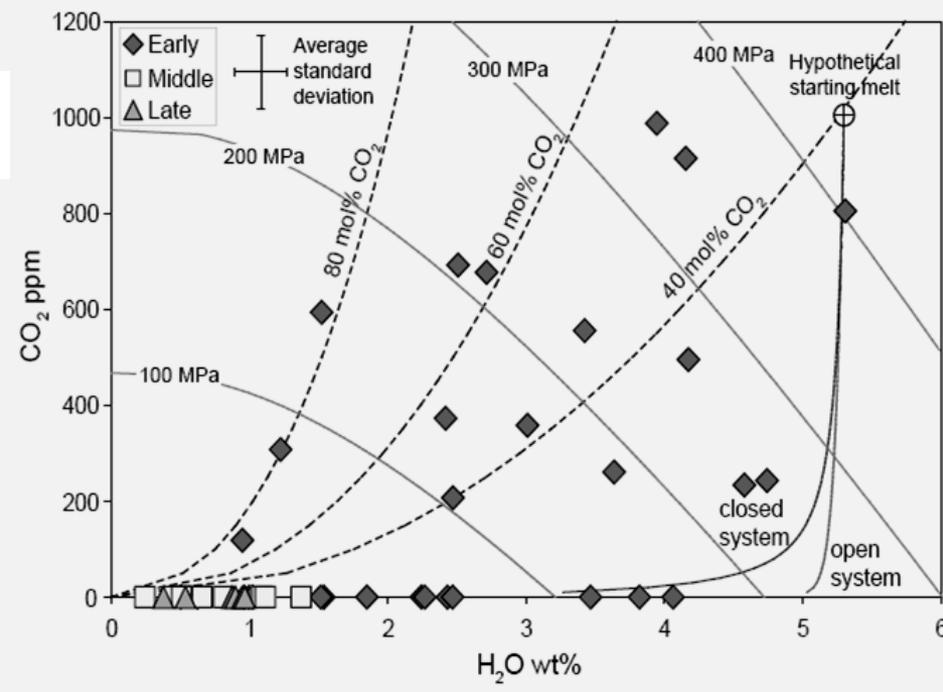


# Gas fluxing, H<sub>2</sub>O loss and crystallization

Jorullo (Mexico), a monogenetic mafic cinder cone (Johnson et al., 2008)



Phase diagram for early Jorullo melt composition (10.5 wt.% MgO) constructed using MELTS and pMELTS.



Jorullo melt inclusions

- CO<sub>2</sub>-rich gas fluxing depletes melt in H<sub>2</sub>O and thereby causes olivine crystallization

# Sulfur Degassing

Wade et al. (2006)

Arenal

Fuego

Cerro Negro

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decompressor  
are needed to see this picture.

- Sulfur solubility in arc basaltic magmas is equal to or higher than H<sub>2</sub>O
- This causes S to correlate with H<sub>2</sub>O in some cases & to remain dissolved as H<sub>2</sub>O is lost in others

# Sulfur degassing recorded in 2002 Mount Etna melt inclusions

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decompressor  
are needed to see this picture.

- Loss of S is shown only by melt inclusions with lower H<sub>2</sub>O contents

Spilliaert et al. (2006)

# Effects of pressure & oxygen fugacity on sulfur degassing

Johnson et al. (in review)

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

- S solubility model of Scaillet & Pichavant (2005) can be used to calculate the vapor-melt partition coefficient for S (curves)
- $D_S$  values estimated from melt inclusion data are shown by symbols

# H<sub>2</sub>O loss, crystallization, and incompatible behavior of S & Cl

- H<sub>2</sub>O loss from degassing magma causes crystallization
- The resulting crystallization causes an increase in incompatible S & Cl that partially or totally offsets any loss by degassing

Etna 2002 eruption

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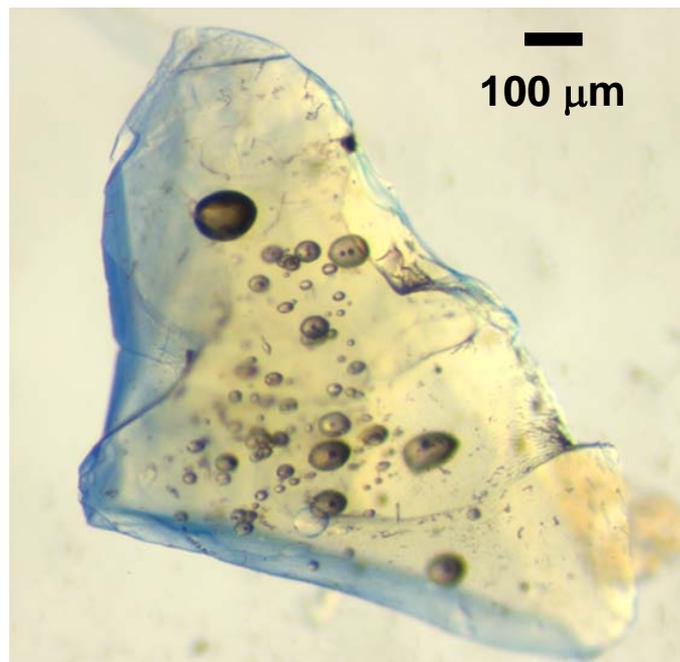
# Evidence for Cl loss by degassing

- Effects of crystallization & degassing can be distinguished by using ratios of S & Cl to another incompatible element

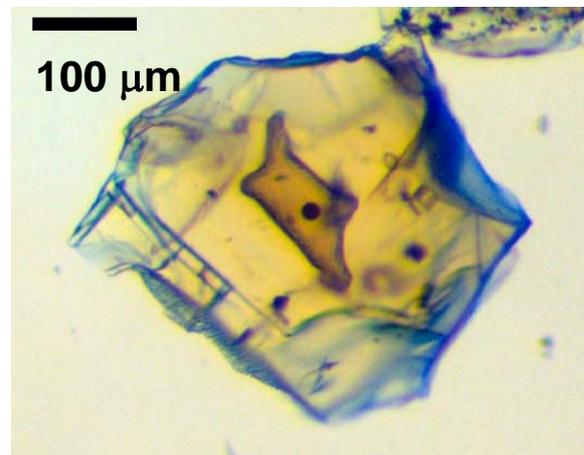
Melt inclusions from Central Mexico cinder cones

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# Primary (or Initial) Volatile Contents of Mafic Magmas



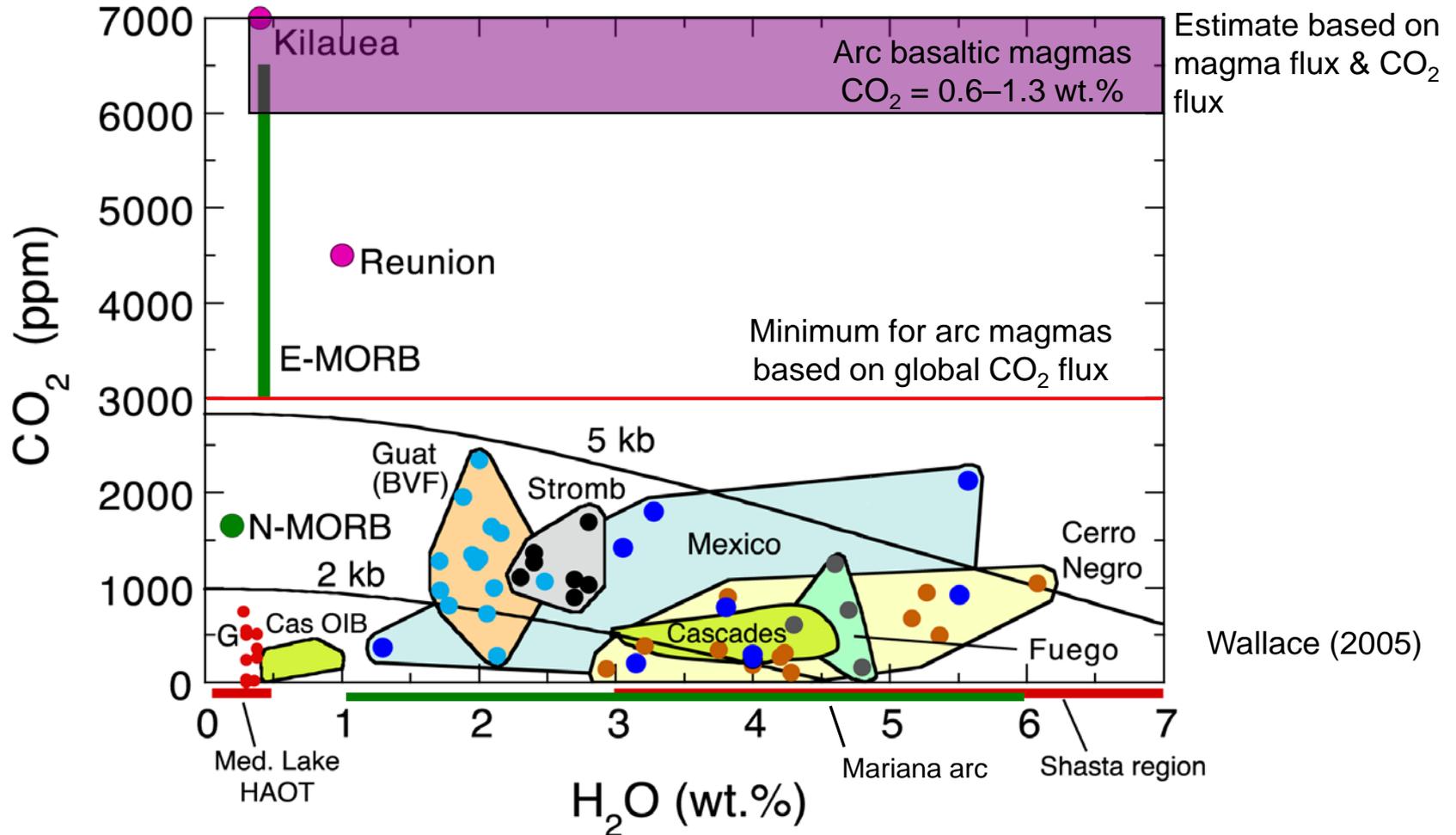
Blue Lake Maar, Oregon Cascades



Jorullo volcano, Mexico

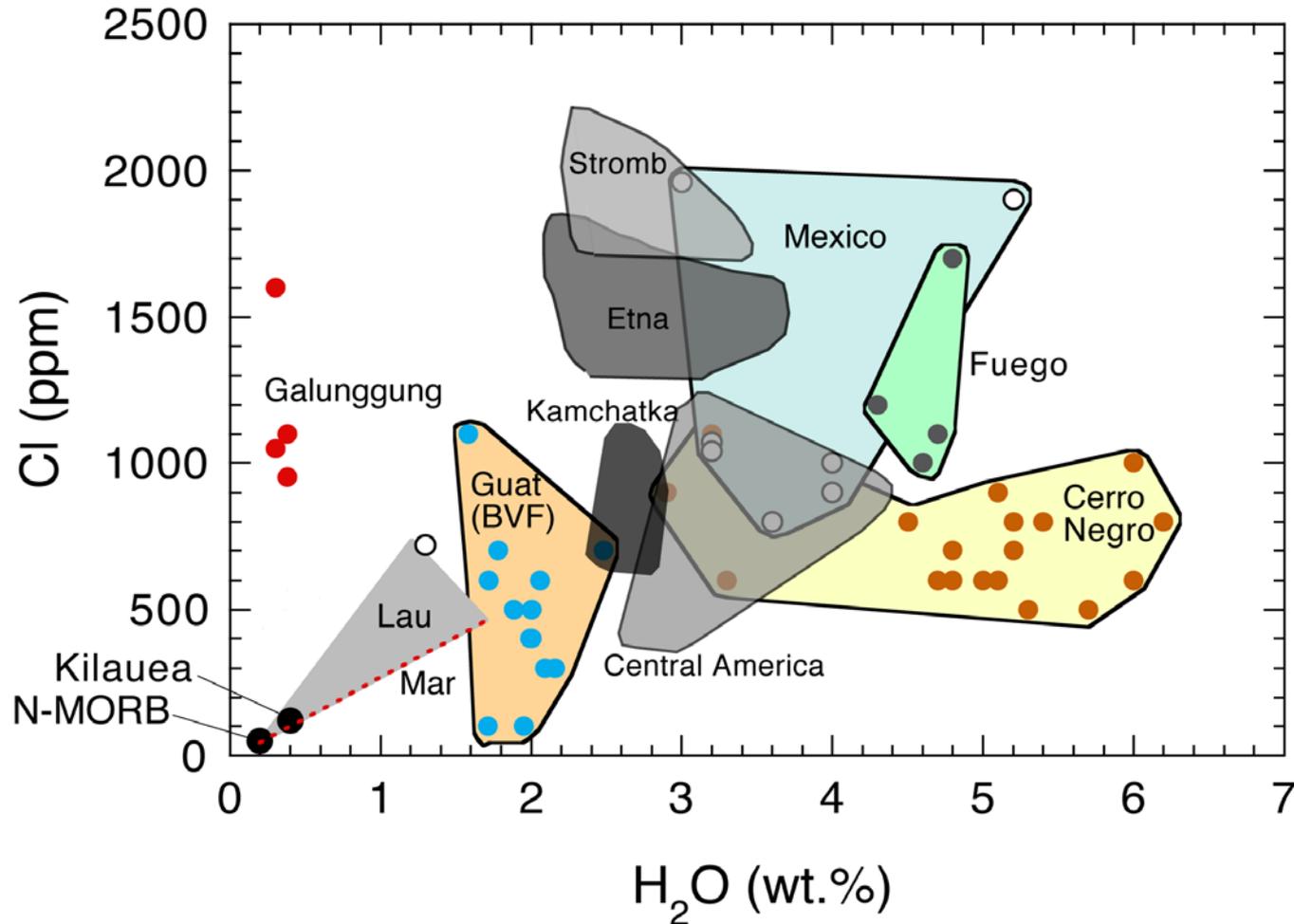
- How do we see through the “haze” of degassing & other post-entrapment effects?
- The general approach is to analyze a large number of MI from a given eruptive unit & use the highest measured concentrations as a minimum indication of the undegassed volatile content of the magma

# H<sub>2</sub>O and CO<sub>2</sub> in Basaltic Magmas



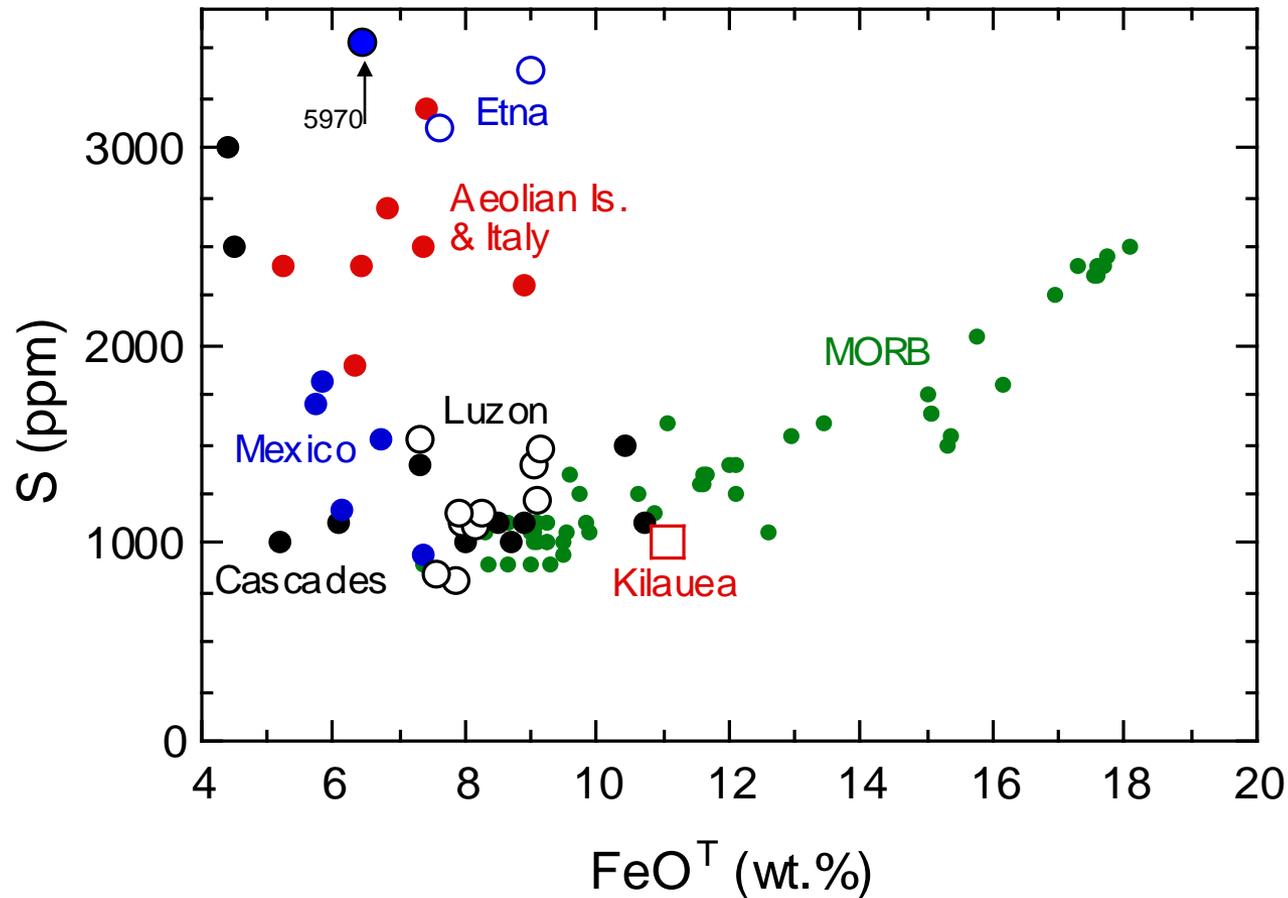
- MORB & OIB have relatively low H<sub>2</sub>O contents
- H<sub>2</sub>O contents of arc basaltic magmas are high & quite variable
- CO<sub>2</sub> contents of arc magmas are lower than estimates based on global arc CO<sub>2</sub> flux

# Chlorine in Basaltic Magmas



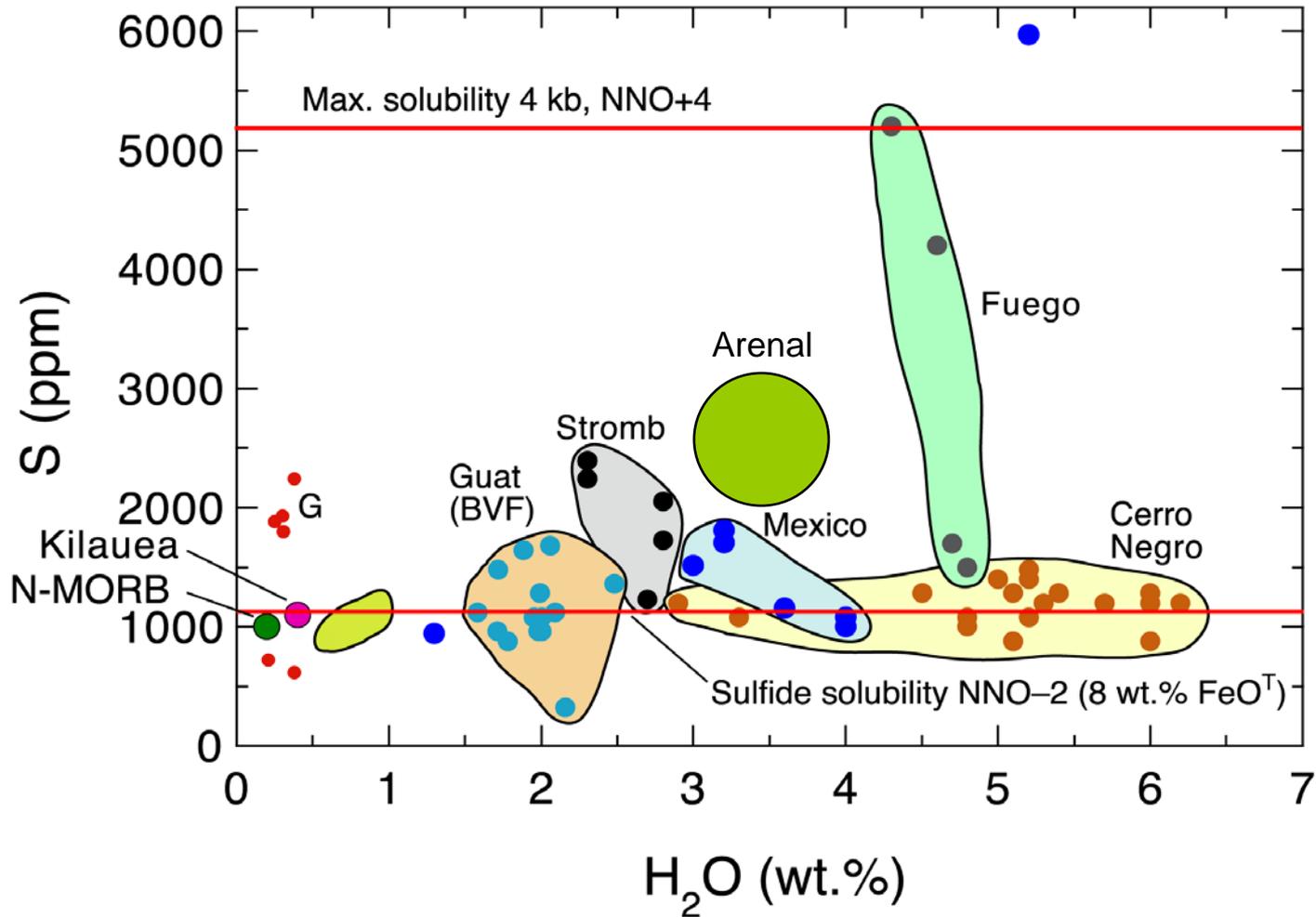
- Cl contents in arc and back-arc magmas are much higher than in MORB
- Indicates substantial recycling of seawater-derived Cl into the mantle wedge

# Sulfur concentrations in melt inclusions & submarine basaltic glasses



- S contents of arc magmas are typically higher than for MORB

# Sulfur in Subduction Zone Basaltic Magmas



## Key points to remember:

- Post-entrapment shrinkage bubble formation mainly affects CO<sub>2</sub> because of its low solubility
- Post-entrapment diffusive loss of H can occur from melt inclusions, though timescales and mechanisms affecting natural melt inclusions are still uncertain
- Large variations in H<sub>2</sub>O and CO<sub>2</sub> for inclusions from a single volcano or even a single eruptive unit are common. In most cases, appear to reflect trapping of inclusions at variable pressures in the upper crust during magma ascent & degassing
- Data commonly do not follow equilibrium degassing paths for H<sub>2</sub>O and CO<sub>2</sub>. This may be related to strong fluxing of CO<sub>2</sub>-rich gases from deeper in the magma system.
- S and Cl tend to be relatively soluble during degassing. S commonly degasses with H<sub>2</sub>O, but Cl is even more soluble & is less affected by degassing.
- Subduction zone basaltic magmas have much higher H<sub>2</sub>O and Cl than MORB & OIB. S is also higher. Less is known about primary CO<sub>2</sub> contents of magmas because low solubility causes it to degas early.



