Volatile Fluxes at Subduction Zones: the Model Perspective
Motivation

How much $H_2O$ is transported in & expelled from subducting slabs, and by what processes?

- mass transport (m scale to Earth scale)
- wedge & slab melting
- fate of slabs
- isotopic evolution
- rheology of slab & wedge
- interpretation of geophysical data
- seismicity
Calculate $H_2O = H_2O (t, x, y, z)$

1. Global subduction-zone database
2. Slab thermal model
3. Subducted sediment type & thickness
4. Hydration of slab @ trench
5. Phase relations $f(P,T,X)$
6. $H_2O$ distribution & loss
1. Subduction-Zone Database

- velocity; NZ = 30 mm/a (slow; median = 65 mm/a)
- plate age; NZ = 100 Ma (old; median = 55 Ma)
2. Thermal Models

*Syracuse et al.* [2010]
2. Thermal Models

*Syracuse et al. [2010]*

slab top: 675–925°C beneath arc

slab Moho: 150–800°C beneath arc

more variation among arcs
Temperatures Match H$_2$O/Ce

Cooper et al [2012]
3. Sediment Composition

Plank & Langmuir [1998]
3. Subducted Sediment Thickness

*Clift & Vannucchi* [2004]; *Scholl & von Huene* [2007; 2009]

account for sediment accretion & closing of pore space

NZ: 400 m terrigenous
4. Hydration of Incoming Crust

Jarrard's [2003] age-based alteration model; does not consider spreading rate
4. Hydration of Incoming Mantle
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Nicaragua: 10 km of 15% serpentine  
*Ivandic et al.* [2010];  
*Lefeldt et al.* [2012]

Costa Rica: 5 km of \( \leq 30\% \) serpentine  
*van Avendonk et al.* [2011]

Lombok: 5 km of 20% serpentine  
*Planert et al.* [2010]

Chile: 7 km alteration  
*Contreras-Reyes et al.* [2008]
4. Hydration of Incoming Mantle

Tonga: 24 km of 30% serpentine

Contreras-Reyes et al. [2011]

Tonga: ≤8 km of 60% serpentine

Savage [2012]

Conclusion:
15 km of 2 wt% H$_2$O ??

Model:
2 km of 2% H$_2$O
5. Calculate Phase Relations $f(P,T,X)$

- *Perple_X* Gibbs free energy minimization [Connolly & Petrini, 2002]

- $\text{Na}_2\text{O-}\text{CaO-}\text{K}_2\text{O-}\text{FeO-}\text{MgO-}\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O-}\text{TiO}_2 \pm \text{Cr}_2\text{O}_3 \pm \text{MnO} \pm \text{CO}_2$
  (NCKFMASHT)

- standard solution models

- weaknesses:
  - solution models imperfect (e.g., $\text{K}_2\text{O}$ in amphibole)
  - no good melt model
5. Perple_X Phase Diagram Example
6. H$_2$O Content: Upper Igneous Crust

Syracuse et al. [2010]

H$_2$O-saturated melting???

80 km coupling

most dehydration
Upper Igneous Crust, NZ

Diagram showing the pressure (P) and temperature (T) conditions for an upper igneous crust, with various mineral phases and reactions indicated. The diagram includes a color scale for H2O content.
Lower Igneous Crust
Lower Igneous Crust, NZ

![Graph showing phase changes in the lower igneous crust with varying pressures and temperatures. The graph includes labels for different minerals and reaction paths.](image-url)
Slab Uppermost Mantle

coldest: no dehydration

main dehydration
Oceanic Sediment

- Chert & carbonate carry little H$_2$O
- K-rich sediment carries significant H$_2$O

[Diagram showing phase relationships under varying pressures and temperatures]

- Melting indicated in the diagram.
Sediment, NZ

melting??

Aleutian turbidite

sediment

talc
lawsonite phengite ecolite'

lawsonite phengite ecolite'

lawsonite phengite ecolite'

dissolution

phengite ecolite'

mica out

P(GPa)

T(C)

z (km)

MgO, % H2O

0

200

400

600

800

1000

1200

1400

1

2

3

4

5

0.1

1

2

3

4

5

2

3

4

5

2

3

4

5
NZ Facies & H$_2$O

metamorphic facies

- hydrous wedge
- blueschist
- hydrous eclogite
- anhydrous eclogite
- hydrous mantle
- anhydrous mantle

H$_2$O content
NZ Facies & H₂O Loss

metamorphic facies

- hydrous wedge
- blueschist
- hydrous eclogite
- anhydrous eclogite
- hydrous mantle
- anhydrous mantle

cumulative H₂O loss

- wedge peridotite + sediment + volcanic
- slab peridotite
- gabbro
Global $\text{H}_2\text{O}$ Loss with Depth

van Keeken et al. [2011]

“Tokyo subway map”
Global $\text{H}_2\text{O}$ Loss with Depth

van Keeken et al. [2011]
Summary: Global Slab H$_2$O Flux

- **most sediment H$_2$O**
- **most igneous H$_2$O**
- **most mantle H$_2$O**

Hacker [2008]
Overestimate of Trench Input?

assuming steady-state ocean \cite{Paral2012} suggests overestimate; perhaps less serpentininite?
(De)Hydration & Seismicity

classic double seismic zone

upper seismic zone EQ correlated with blueschist or hydrous eclogite

lower seismic zone EQ correlated with antigorite or chlorite

Hacker et al. [2003]
Hydration–Seismicity Hypothesis

presence of fluid permits intermediate-depth earthquakes

not dehydration embrittlement
Blueschist-Out Limits Upper Seismic Zone

Van Keken et al. 2012
Blueschist-Out Limits Upper Seismic Zone

van Keken et al. [2012]
Dehydration = Slow & Seismic

$V_P < 7.2 \text{ km/s}$ suggests fluid

*Shina et al. [2012]*
‘Serpentine’ -Out Limits Lower Seismic Zone

Cascadia [Abers et al., 2008]

Nankai [Hirose et al., 2008]

‘antigorite’ out
‘Serpentine’ -Out Limits Lower Seismic Zone

van Keeken et al. [2013 EGU]
NZ Seismicity & Calculated Dehydration

Reyners et al. [2011]
How Does Lower Seismic Zone Hydrate?

outer rise quakes [Seno & Yamanaka, 1996]

bending at outer rise pumps fluid downward [Faccenda et al., 2009]
How Does Lower Seismic Zone Hydrate?

unbending stresses drive fluid into slab core [Faccenda et al., 2012]
Hot & Cold Slab Seismicity Different

most cold slabs: upper zone EQs in crust

hot slab: EQs in mantle

Abers et al. [2013]
EQ Where Clapeyron Slope $> 0$

Abers et al. [2013]
EQ if Fluid > Porosity

Abers et al. [2013]
Summary: Slab H₂O Cycle

- hotter zones have sediment dehydration melting
- most slabs *may* have hydrous melting
  - depends on fluid flow
- slab mantle dehydrates at lowest T (~600°C)
  - hydration state & fluid flow critical
- most sediment/igneous/mantle H₂O expelled beneath forearc/arc/backarc
- large along-strike change in “NZ” zone
Summary: Seismicity & H$_2$O

- Seismicity generally in hydrated material

- Seismicity in crust/mantle limited by blueschist/‘antigorite’

- Lower plane may hydrate at outer rise or in slab

- Hot/cold zones upper plane EQs in mantle/crust

- Negative Clapeyron slopes control seismicity??
4 Key Questions to Address
Slab Heterogeneity

Blackman et al. [2003]

local hydration carries more H₂O to depth

[Wada et al., 2012]
Metasomatic Bulk Compositions

Marschall & Schumacher [2012]
Fluid Flow, Including Rehydration

Faccenda et al. [2012]

M Spiegelman, AGU 2012
Non-H$_2$O Mass Flow

Gerya et al. [2007]

Warren et al. [2008]

Hassenclever et al. [2011]