Unlocking the Secrets of the Mantle Wedge: New Insights into Melt Generation Processes in Subduction Zones

T.L. Grove, N. Chatterjee, E. Medard, S.W. Parman, C.B. Till
Reginald Aldworth Daly (1871 – 1957) : 
Bowie Medalist (1946)

The Quintessential AGU member

• Igneous petrology
• Volcanology
• Paleo-climate
• Mineral Physics
• Geodynamics

Let us take a moment to recount some of Daly’s thoughts and contributions to the subject of today’s lecture.
On island arcs in subduction zones:

Daly wrote about these features in his 1933 book “Depths of the Earth and Origin of Magmas”

“Each of these areal groupings of units clearly represents and important genetic problem”

He also endorsed DuToit’s theory of continental drift (1927)
Between 500 bars and 2000 bars the solubility increases nearly as the square root of the pressure, a rule that applies also to the solubility of hydrogen in some molten metals, within, however, a different range of pressures. Above 2000 bars the solubility of the water increased still more slowly with pressure. Goranson's pressure-solubility curve indicates at zero pressure an increase of solubility per bar of 0.0108 per cent of water. Extrapolation to 10,000 bars gives saturation at about 10 per cent of water by weight, instead of about 100 per cent as

**On the importance of H$_2$O in magma generation:**

Daly wrote the following about the solubility of H$_2$O in his 1933 book “ Depths of the Earth and Origin of Magmas”

He also noted:

“Other experiments are needed on the solubility of water in basic melts, these representing the dominant magmas in volcanoes of long life.”
He also developed a theory of the characteristics of the Earth’s deep interior structure – “The Glassy Shells”

One of the first systematic efforts to relate geophysical measurements to Earth material properties.
New experiments on H2O-saturated melting of mantle peridotite - The role of H2O in mantle wedge melting processes

1) Chemical transport processes from subducted slab to the overlying wedge. Melting from top to bottom in the wedge. Field and experimental evidence.

2) Element transport from slab to wedge > Melts? Fluids? Or more complex processes?


T.L. Grove, N. Chatterjee, E. Medard, S.W. Parman, C.B. Till
Topic 1: Chemical transport processes from slab to wedge. Field and experimental evidence from Mt. Shasta region, USA.

- Lavas are high-$\text{H}_2\text{O}$ mantle melts with a significant component added from the subducted slab.
- Where are these melts generated in the mantle wedge?
- What is contributed from the subducted slab?

*Mt. Shasta, N. Calif. – looking W from Med. Lake
Shasta produced $\sim 500\text{ km}^3$ magma in $\sim 250,000$ years.*
Major elements and \( \text{H}_2\text{O} \)

Wet, primitive andesites are in equilibrium with mantle residues = melts of depleted mantle
Estimates of Pre-eruptive H$_2$O

- H$_2$O solubility in silicate melts is P-dependent and goes to $\sim 0$ at P = 1 bar.

- So, H$_2$O is often lost as a gas phase

- Pre-eruptive H$_2$O contents are obtained using:
  - Thermodynamic models of mineral/melt equilibria.
  - Effect of H$_2$O on “freezing path” or melt composition produced during fractional crystallization.
  - Direct measurement of H$_2$O in melt inclusions.
Estimation of pre-eruptive $\text{H}_2\text{O}$ content

Sisson & Grove (1993)
Direct measurement of \( \text{H}_2\text{O} \) in Shasta melt inclusions (Anderson, 1979).

\( \text{H}_2\text{O} \)-contents of arc magmas seem to be too high to result from any batch melting process of any potential \( \text{H}_2\text{O} \)-bearing mantle source.

New experimental evidence changes this.
How do these new phase equilibrium constraints help us understand the processes of melting in subduction zones?
Cinder Cone
Basaltic Andesite –
85-44 and S-1
Primitive BA (S-1) and PMA (S-17) – Hydrous melts saturated with a harzburgite residue at top of mantle wedge > 25 % melting.
Topic 2: Estimating the chemical composition of the fluid-rich component.

- We will model this by assuming 2 components: 1) a silicate melt from a harzburgite residue (wedge) 2) a fluid-rich component from the subducted lithosphere (slab).
- Use mass balance. Calculate elemental contribution from mantle melting
- Use H$_2$O content of lava to estimate the composition of the H$_2$O-rich component.
Mass Balance Model

\[ C_{\text{fluid}} = \frac{(C_{\text{lava}} - X_{\text{melt}}C_{\text{melt}})}{(X_{\text{fluid}})} \]

- Substitute batch melting equation for \( C_{\text{melt}} \)
- \( F \) is fraction of mantle melt and
- \( D \) is bulk distribution coefficient
- \( C_0 \) element abundance in mantle source
- \( \alpha \) is a correction for other elements in fluid

\[ C_{\text{fluid}} = \frac{(C_{\text{lava}} - (1 - X_{\text{H2O}}/\alpha)C_0/[F+D(1-F)])}{(X_{\text{H2O}}/ \alpha)} \]
Estimated fluid component = gray
Lavas = solid black
Silicate melt of mantle = open square.
Note the dichotomy in La/Sm_N and Dy/Yb_N
H$_2$O-rich component a fluid? No…

Estimated fluid-rich component (black circles)

Least similar to a hydrous fluid saturated with eclogitic residue

Slfl = slab fluid
Ds from Ayers, Brenan, Kogiso, Stalder, etc.

Wdfl = wedge fluid

Kesel (2005) = fluid in MORB at 4 GPa
H$_2$O-rich component a silicate melt? Much closer….

Estimated fluid-rich component (black circles)

Most similar to a mix of hydrous low degree melt of eclogitic residue n-MORB (Hofmann) and Sediment (Ben Otham)

eclogite melt Ds from Green et al. (2000)
But the eclogite melt model of MORB & Sediment are not perfect fits.

Misfits:

Highly incompatible elements

& HFSE

& Fluid mobile
Any H$_2$O rich slab fluid/melt is likely to interact with the wedge

  Olivine + SiO$_2$(fluid) = orthopyroxene

- Bell et al (2005) characterize chemical interaction between wedge & subduction added component in Kaapvaal harzburgites. Metasomatic reaction is:

  1.25 Oliv + 1 liquid = 1.0 Opx + 0.08 Gar + 0.17 Phlog

Let’s further react the slab melt with the wedge. The result is Distilled Essence of Slab Melt.
Brown symbols show effect of wedge peridotite + slab melt interaction at base of wedge using reaction inferred by Bell et al. (2005).

- highly incompatible elements - better
- HFSE - worse
- Fluid mobile - better
So, what medium transfers elements from hot, young subducted lithosphere?

Is it a melt??  A fluid??

Looks most like a low degree melt of sediment/MORB eclogite.

Fluid – not a good match.

Mantle wedge / slab melt interaction improves model.
Signatures of both:
MORB
(High La/Sm)
and
Sediment Components

Juan de Fuca
MORB

Primitive Cascade Magmas
(Bacon et al., 1997)
Topic 3: New experimental constraints on subduction zone melting processes.

- Can the slab and the wedge BOTH melt?
- Can we understand the high pre-eruptive H$_2$O contents of arc magmas?
3) New experimental data from Grove et al. (2006) 
EPSL 249: 74-89 
Shows that hydrous phases are stable on the vapor-saturated mantle solidus. 
We will use this data to develop a model for melting in the mantle wedge.
Chlorite on the vapor-saturated solidus – a way to transport H$_2$O deep into the wedge

Also, Ilmenite, Rutile & Ti-clinohumite are stable.
Old & New Expts. Why the difference? – melting kinetics

Olivine melting rate is slower than that of pyroxene.
- Olivine also melts at a lower Temperature by about 200 °C.
- In the short run time expts pyroxene melted first.
Serpentine and chlorite dehydration as a source for $\text{H}_2\text{O}$.

We know that $\text{H}_2\text{O}$ is subducted in a variety of hydrous phases to substantial depths.

How do these phases interact with the wet peridotite solidus?

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Chlorite breakdown crosses the wet solidus above 3.5 GPa. Does this cut off wet melting?

Black is Martian mantle
Grey is Earth’s mantle
Where is water stored in the wedge? Thermal model of Kelemen et al. (2003)

Hydrous phases in the mantle wedge & subducted slab.

Chlorite provides a source of $\text{H}_2\text{O}$ for wet arc melting that is above the slab.

Produced by fluid released from the slab at shallow depths.

$\text{H}_2\text{O}$ is stored even when the slab is too hot.

Chlorite also stable below the slab-wedge interface in the cool core of the slab.
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Where is water stored in the wedge?

Chlorite breaks down as pressure increases. Thus, the H$_2$O supply through chlorite breakdown will stop at slab depths of 120 – 150 km.

Chlorite is stable below the slab-wedge interface in the cool core of the slab and this could supply H$_2$O.
Melting behavior of peridotite vs. sediment and basalt in presence of excess H$_2$O. The solidi converge as pressure increases.
The melting model:
Melting paths calculated wherever vapor-saturated melting could occur – no assumptions about melt connectivity Mibe et al. (1999).

Buoyant hydrous melts leave the base of wedge and ascend into the overlying mantle by porous flow.

Melt volume equilibrates with mantle at each step – both thermally and chemically – reactive porous flow

Assumptions: initial critical melt fraction – $F_{crit} = 2.5$ wt. % values range from $< 0.1$ (Kohlstedt, 1992) to 8 % Fujii et al. (1986)
Thermal model of Kelemen et al. (2003)

Subducted Lithosphere

Melt $H_2O$ content
- < 5%
- 5-10%
- 10-20%
- 20-28%

solidus

P1, T1

P2, T2

P3, T3
A cooling path is shown on the diagram, starting at P1, T1 (~28% H₂O) and ending at P3, T3. The path crosses the vapor-saturation solidus line and the vertical melting paths in the wedge.
Silver and Stolper (1985) speciation model for melting in simple two component systems mineral – H₂O

Includes molecular H₂O – OH speciation and leads to a planar T – P – X_{H₂O} solid – melt boundary

Note linearity of liquidus boundary.

This melting behavior is “adjusted” for perid.
Melt $\text{H}_2\text{O}$ content is strongly influenced by the lever rule effect – melt % increases rapidly as bulk composition approaches liquidus.

Reactive porous flow melting = melt volume must come into equilibrium with mantle at each step – both thermally and chemically.
The melting model:

We use our phase diagram & measured \( \text{H}_2\text{O} \) solubility vs. pressure in forsterite – \( \text{H}_2\text{O} \) to predict the peridotite – melt boundary in \( T – P – X\text{H}_2\text{O} \) space. The expression is:

\[
7290^\ast P - 810^\ast T - 24600^\ast \text{H}_2\text{O} + 1093500 = 0
\]

where \( T \) is in °C, \( P \) is in kilobars and \( \text{H}_2\text{O} \) content is in wt. %.

At \( P_2, T_2 \) the amount of melt \( (F_{P2,T2}) \) is given by:

\[
F_{P2,T2} = \left( \frac{X_{\text{init}} - X_{P2,T2}}{X_{\text{init}}} \right) \times F_{\text{init}} + F_{\text{init}}
\]
Highest melt fraction achieved in a very thin layer. Most of wedge contains < 5% melt (double arrows). Chlorite is transported down into the wedge ABOVE the slab and gives up its H₂O at solidus. Maximum melt % occurs in a thin layer in hot core of the wedge.
Melt H$_2$O content continuously decreases as melt ascends and reacts with hotter mantle.

Melt at top has lowest H$_2$O.

Thin layer of H$_2$O-rich melt – pinches out.
In this region temperature decreases in overlying mantle wedge. Melt amount decreases, melt crystallizes. Oliv + liquid react and form pyroxene. OR Diapiric flow?

$H_2O$ content increases – latent heat is released = increasing T. OR Diapiric flow?
When mantle peridotite is hydrated it contains 13 % chlorite. Bulk H$_2$O of solid is 2 wt. %.

Bulk perid. = 2 wt. % H$_2$O. H$_2$O content of melt could exceed 10 wt. %.

High H$_2$O contents are possible.
• Hydrous flux melting explains the shallow final equilibration depth of arc magmas AND provides a mechanism for creating SiO$_2$ – rich crust through arc magmatic inputs.

• Stable chlorite in the mantle wedge allows for high H$_2$O content in arc magmas.

• At the same time subducted sediment and basalt can melt and transfer key trace element signatures to melts of mantle wedge.
**Experimental Details**
Au capsules – Piston cylinder - 1.2 – 3.2 GPa
Hart & Zindler Primitive Mantle
Oxide starting mix
With MgO added as Mg(OH)$_2$ = 14 wt. % H$_2$O

**Run Duration**
96 – 140 hours (a few at 24 hrs)

**Experimental Products**
Homogeneous olivine, opx, cpx, spinel and/or garnet
Melt or vapor phase (supercritical fluid)

**Equilibrium**
QUILF used to check Temp. from Opx-Cpx – within 1 sigma of uncertainty
and f$_{O_2}$ from oliv-opx-spinel (Ballhaus et al., 1994) = QFM + 0.8
## PREVIOUS STUDIES

<table>
<thead>
<tr>
<th>Run Times</th>
<th>$H_2O$ added</th>
<th>Capsule</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High – T melting</strong></td>
<td></td>
<td></td>
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<tr>
<td>Kushiro et al. (1968)</td>
<td>5 – 30 min</td>
<td>30%</td>
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<tr>
<td>Millhollen et al. (1974)</td>
<td>0.5 – 3 hrs.</td>
<td>5.7 %</td>
</tr>
<tr>
<td>Green (1973)</td>
<td>1 – 6 hrs.</td>
<td>10 %</td>
</tr>
<tr>
<td><strong>Low – T melting</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mysen and Boettcher (1975)</td>
<td>24 – 64 hrs.</td>
<td>20- 30 %</td>
</tr>
<tr>
<td><strong>THIS STUDY</strong></td>
<td></td>
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<tr>
<td>48 – 120 hrs</td>
<td>14 –30 %</td>
<td>Au</td>
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Direct determination of liquidus mineral assemblage at high pressure and temperature = mantle conditions

“Dry” HAOT magmas record melting as convecting mantle is drawn into the wedge
Shallow, hot mantle melting beneath the Cascades

Inferred from Pressure of multiple saturation.

\[ T = 1300 - 1450 \, ^\circ C. \]

Elkins-Tanton et al. (2001)
Major element characteristics of the fluid-rich Mt. Shasta component

- $\text{Na}_2\text{O} = 25$ to $33$ wt.
- $\text{K}_2\text{O} = 5$ to $13$ wt.
- $\text{SiO}_2 = 0$ wt.
- $\text{H}_2\text{O} = 54$ to $70$ wt.
- Similar to finding of Stolper & Newman (1994).

So, what is it? A melt or a fluid?
Estimated Slab Contribution

Mt. Shasta primitive
BA
and
PMA
Mantle melting trend to high-SiO$_2$ - low FeO*/MgO is controlled by the reaction relation oliv + liq $\rightarrow$ opx.

\[ 1.0 \text{ Opx} = 0.5 \text{ Oliv} + 0.5 \text{ Liq} \]
Shasta H$_2$O-rich lavas have high SiO$_2$ and low FeO*,