Komatiites and the Early Evolution of the Earth

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Outline

• Earth Evolution: theories and constraints
• Komatiites: evidence for a subduction origin
• Komatiite mantle melting process: a new-old model
• Implications for the Early Earth
Heat Sources in the Early Earth

• Radiogenic Heat
• Core Segregation
• Giant Impact/Accretionary Heat
Heat Sources in the Early Earth

4–4 Mean mantle heat production rates due to the decay of the radioactive isotopes of U, Th, and K as functions of time measured back from the present.

Turcotte and Schubert, Geodynamics (2002)
Geodynamic Models - basic

![Graph showing temperature (°C) vs. time (Ga)](image)

- upper mantle temperature
  - Davies, GJI (1993)
- 130 kJ/mole
- 400 kJ/mole
Geodynamic Models

episodic cooling due to phase transitions

Davies, EPSL (1995)
Observational Constraints

- Metamorphic Gradients - inconclusive
- Tectonic Style (rigid vs gooey) - inconclusive

- Archean magmatic products - promising
  - Direct evidence of temperatures in the interior of the early Earth
  - Fundamental constraint on all **thermal and chemical** evolution models
Eastern Kaapvaal Craton
Not too different in the Archean

- Magmatic products in greenstone belts (to 3.5 Ga) and gneisses (to 4.0 Ga) are primarily **basalts and granites**. No suggestion of higher temperatures.

- 4.4 Ga zircons (Wilde et al., Nature, 2001) contain granitic inclusions and provide isotopic evidence for liquid surface water.

- Primary difference - presence of **komatiites** in many igneous sequences
1.7 m thick unit in Komati Fm.
~10% of stratigraphic thickness is komatiite

after J. Dann
Really, really, really high MgO
High MgO means high T

![Graph showing liquidus temperature vs. MgO content at 1 atm and 3.0 GPa.](image)
Plume model

Herzberg, JGR (1992)
Inklings of a Problem

- Much of upper mantle would be molten

- Many komatiites interlayered with subduction related magmas

- Mounting evidence for high H$_2$O contents
Not compatible with geophysical constraints

dull hot!  

Davies, GJI (1993)
Comes close to lower mantle temperatures for episodic models

But melts in the lower mantle would sink!

Davies, EPSL (1995)
Plume-Arc Interaction

Sproule et al., 2002
Evidence for H$_2$O in komatiite magmas

- Pyroxene compositions in Barberton and in Commondale komatiite
- Amphibole in komatiite and melt inclusions
- High Pressure Phase Equilibria
Experiments on komatiites - TZM-bomb experimental set-up
ZHM/MHC-bomb

- up to 3 kbar & 1350°C
- gas pressure media
- fO$_2$ buffered by Ni-NiO
ZHM/MHC-bomb and furnace
1-atm (dry) and 2-kbar (H₂O sat.) Experiments

**Commondale komatiite**
- 1-atm Liquidus: 1550°C
- 1-atm Low-Ca Px: 1345°C
- 2-kbar Low-Ca Px: 1135°C
- At 2-kbar Px suppression: 210°C
- 5 wt% H₂O

**Barberton komatiite**
- Parman et. al., 1997
- At 2-kbar Px suppression: ~200°C
Augite Wo contents in Barberton
Augite Al contents

![Graph showing Augite Al contents with data points for chill margin and interior augite.](image)
Preserved Igneous Pyroxenes

Orthoenstatite in Commondale

1 cm

Pyroxene Mg#: <92

From the center of a several meter-thick flow
Equilibrium Pyroxene Growth

H₂O Saturated (when first opx appeared) = ~4.5 wt% H₂O

Commondale Komatiites
Chemical Trends Caused By Undercooling

Graphs showing the chemical trends of CaO, Al2O3, and CaO with Mg# for different cooling rates (10 C/hr and 100 C/hr) and natural samples.
Undercooled, Hydrous Komatiites

Commondale komatiite

- Nat px
- H₂O Sat
- Anhy
- 10 °C/hr

Diagram showing the relationship between Cr₂O₃ wt% and Mg# with symbols indicating different conditions of undercooling and water saturation.

- More Undercooling
- Less Undercooling
- Undercooling + H₂O
- ~7 wt% H₂O
- ~4.5 wt% H₂O
Amphibole in Proterozoic komatiites

Hanski, 1992
High-P melting experiments deeper = wet
Other Potential Evidence for High H₂O

• Melt Inclusions

• Spinifex textures
Melt Inclusions

• 1.1-2.6 wt.% H₂O
• devolatilization?
• re-equilibration?

Shimizu et al., 2001
MI H₂O contents in modern magmas
Spinifex texture

olivine-spinifex
Komati Fm.
Subduction-like Geochemical Features

• Subduction-like characteristics
  – high SiO$_2$, MgO, CaO/Al$_2$O$_3$, low TiO$_2$
  – HFSE depletions
  – variable LREE

• Boninite-like characteristics
  – high MgO,
  – Ti/Zr and Nb/Th systematics
  – Positive Zr and Hf anomalies
High SiO$_2$
Low TiO$_2$
LILE variability, HFSE depletions
North Caribou, Superior Province

Hollings and Kerrich, 1999
U-shaped pattern
LILE depleted boninites
Mixing of fluid and dep. mantle
Bimodal trend

Nelson et al., 1984
Cameron et al., 1983
Sobolev&Danu., 1994
Bimodal trend

Nelson et al., 1984
Cameron et al., 1983
Sobolev & Danu., 1994

Cape Vogel
New Caledonia
New Zealand
Cyprus
Victoria

Bonin
Cyprus
New Zealand
N. Tonga trench
Weaknesses

- Differences in Ti, Fe, Nb/Th, Nd isotopes
- Distinguish chemical signature of slab fluid from crustal contamination
  - Zr anomalies, Nd isotopes?
- Correct for effects of alteration
  - high SiO$_2$
Ion Probe analyses of unaltered augite
Measured and Estimated Augite REE
Assessment of TE mobility

Barberton

gain

loss
Subduction summary

- Fits geochemistry
- Fits evidence for high $\text{H}_2\text{O}$
- Fits tectonic models of greenstone belt formation
- Requires a single, currently observed process = subduction

- What are implications for Earth Evolution?
Predicted melting conditions
Subduction initiation

Based on boninite model of Stern and Bloomer, 1992
Mature subduction zone

calc-alkaline magmas

komatiites tholeites
Experimental Estimates of Hydrous Melting Conditions

1-6 wt.% H$_2$O
Geodynamic Models - basic

upper mantle temperature
Davies, GJI (1993)

Temperature (°C)

Time (Ga)

130 kJ/mole
400 kJ/mole
Geodynamic Models

episodic cooling due to phase transitions

Davies, EPSL (1995)
Subduction zone model explains most observations with a single, currently active process.

- Suggests Archean sub-arc mantle ~100ºC hotter than present sub-arc mantle.
- Little evidence requires plume model.
Western Barberton Greenstone belt

after Byerly
Evidence that does not constrain \( \text{H}_2\text{O} \) contents

- Presence of vesicles (tuffs)
- Depletion of source (\( \epsilon \text{Nd}_{(t)}>0 \))
- Eruption on surface
High CaO/Al$_2$O$_3$
U-shaped pattern
majorite TE partitioning
majorite fractionation
Influence of H₂O on the Development of Spinifex Textures in Komatiites

Experimental and Field Constraints, Barberton Mountainland, South Africa

S. Parman, J. Dann, M. de Wit, J. Barr, A. Wilson

Conditions for formation of olivine spinifex in komatiites

- **Experimental Evidence** for spinifex formation
- Experimental Containers influence nucleation and growth
- H₂O changes nucleation and growth conditions

- **Field evidence** of initial conditions
  - Melt arrives undercooled (supersaturated)
  - Cooling rate is slow, but variable chill geometry influences cooling rate
  - H₂O in melt is important
Hopper–like surface texture of olivine blade in coarse, bladed spinifex zone. Individual crystals ~30–40 cm length, grow 1 to 4 meters from heat loss boundary.
Petrologic Evidence suggest 4 – 6 wt. % H$_2$O pre-emplacement for Barberton komatiites (Parman et al., 1997)

H$_2$O can promote development of spinifex textures
1) Changes in melt physical properties
   Lowers nucleation rate
   Increases growth rate
2) Undercooling by decompression of hydrous magma

Compositions of igneous pyroxene in spinifex record evidence of 4 – 6 wt.% pre-eruptive H$_2$O
Augite Wo contents

Experimental Evidence on Spinifex formation

Container size controls on spinifex development
- 1 Larger container = lower nucleation rate
- 2 Leads to more dominant control of growth rate on crystal morphology

- H$_2$O lowers melt viscosity, lowers
- Lowers nucleation rate
- Speeds up growth rate
- Leads to growth of a few BIG crystals
- Ultramafic Pegmatites
Donaldson (1976) Olivine morphology vs cooling rate & undercooling

Micro-spinifex develops at rapid cooling rates

No spinifex textures were produced at slow cooling rates

Experimental Approach

Munro township komatiite SSK 17 % MgO

$T_{\text{initial}}$ 1370 °C @ 0.1 MPa “DRY”

1300 °C @ 200 MPa H$_2$O-saturated “WET”

Variable cooling rate 3 to 100 °C/hr

Variable container composition - volume (ml) - texture

MgO 0.4 granular-hopper

Al$_2$O$_3$ 0.7 – 60 hopper-chain

SanCarlos 0.3 chain-euhedral

Pt-Fe loops 0.03 chain-euhedral

AuPd (200 MPa) 0.27 hopper-chain
Large container dry ~ 5 times larger
Small container “wet” ~ 7 times larger

Possible to get a complete transition in crystal morphology at constant cooling rate

From many equant small crystals - shown here in a cooling rate experiment performed in an MgO capsule

To spinifex – just by lowering the surface area to volume ratio

- reducing heterogeneous nucleation sites
- grow fewer longer crystals

250 microns
Both equant and spinifex crystal forms

Large container – 60 ml crystals extend to edges
Large container dry ～ 5 times larger
Small container “wet” ～ 7 times larger

Adding H₂O increases crystal size and decreases nucleation density dramatically. 3 °C/hr expt. 200 MPa
$10^\circ$C/hr, 6 wt.% H$_2$O

1 mm

$10^\circ$C/hr, 6 wt.% H$_2$O
$\Delta T = \text{undercooling}$

$U = \text{Growth rate}$

Influence of $H_2O$ is to put peak in growth rate at LOWER undercooling

$N = \text{Nucleation density}$

At the same time $H_2O$ addition reduces nucleation rate.

Result is fewer, bigger, faster growing crystals.

Fenn, 1976

Here are predicted cooling rate vs distance and growth rate vs cooling rate for conductive cooling.

Cooling rate and crystal size are related, slow cooling bigger crystals.

Predicted from wet cooling expts.
**Field evidence in Barberton komatiites**

- Equant olivine present in chill margins
- Close spatial association of spinifex with granular-textured olivine
- Largest bladed spinifex forms at slowest cooling rates

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**Equant olivine in chill margins = Emplacement at undercooled conditions**

![Ternary diagram showing the relationship between temperature, pressure, and water content during emplacement](diagram.png)

- **Liq**: Liquid phase
- **Ol**: Olivine
- **V**: Water

Temperature (°C) vs. Pressure (MPa) diagram with the following phases:
- **Ol + Liq**: Solid and liquid phases
- **Ol + Liq + V**: Solid, liquid, and water phases

**Pre-emplacement conditions**

- **H₂O dissolved in melt**

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**Legend**

- **ΔT**: Temperature difference

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**Notes**

- Emplacement at undercooled conditions
- Influence of H₂O on phase transitions
NO olivine in chill margins = Emplacement at superheated conditions

Pre-emplacement conditions

<table>
<thead>
<tr>
<th>Temp °C</th>
<th>Pressure MPa</th>
</tr>
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<tbody>
<tr>
<td>1750</td>
<td></td>
</tr>
<tr>
<td>1350</td>
<td></td>
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</tbody>
</table>

Liq

Ol + Liq

Ol + Liq + V

DRY melt

Equant Olivine

Chill Margin

50 microns
More equant olivine ~ 1 cm from chill – consistent with emplacement at undercooled conditions

Inflation features - Spinifex veins intruding granular, equant olivine cumulate
Thin pillows – no spinifex

Thicker – only radiate texture

Grove et al., 1996
Examples of spinifex in 4 to 10 m thick inflated flows

Grove et al., 1996

Note variable thickness of zones & discontinuities
Inflation features imply conductive cooling conditions and overpressures that allow for slow cooling and development of spinifex textures.

Spinifex blade maximum length vs distance from upper chill margin in Barberton komatiites.
Conclusions

H$_2$O controls on development of spinifex textures

1) Undercooling by decompression/devolatilization of hydrous magma

2) H$_2$O changes melt physical properties
   • Lowers nucleation rate – destroys nuclei
   • Decreases melt viscosity – increases growth rate at undercooled conditions

3) Injection of melt into cumulates and Flow inflation processes modify thermal conditions leading to spinifex growth at slow cooling rates

Spinifex flows = Ultramafic pegmatites
Crystal size vs. cooling rate calculated with dry small volume data

Grove et al., 1996

High-P melting experiments

Phase diagram for BK
Experimental Estimates of Hydrous Melting Conditions

![Graph showing the relationship between MgO and temperature for majorite fractionation.]

- Falloon & Danu, 1999
- Parman, unpub. (model)
- komatiites
- boninites
- 1-6 wt.% H$_2$O

majorite fractionation

![Graph showing Ti/Zr vs. La/Sm for komatiites and boninites.]

- komatiites
- melting in majorite stability field
- MORB & OIB
- basaltic komatiites
- boninites

CC
Mixing of fluid and depleted mantle