Comparison of final Altiplano model with laboratory $V_p$ vs depth measurements

$V_p$ (km/s)

Depth (km)

Felsic

Mafic

high
ave
low

geothermal gradients
Crustal Thickness
10 km contour interval plus 45 km contour
Zircon: $\text{ZrSiO}_4$

- Common accessory mineral in igneous rocks, especially granitoids
- Rich in U, Th; poor in Pb
- Highly refractory (melts at high T) and retentive (holds in its U, Th, Pb)
- Therefore ideal for U-Pb geochronology
(A) Typical banded gneiss (bgn) consisting of older tonalite (>3.7 Ga, grey) and younger granite (3.65 Ga, white), Itsaq Gneiss Complex, Greenland. The gneiss was cut by a mid-Archean dyke, now an amphibolite (ad), which was strongly deformed at 2.7 Ga. (B) Cathodoluminescence images of typical zircons separated from banded gneiss. Zircons were embedded in epoxy resin and sectioned prior to imaging. 3.79 Ga oscillatory-zoned igneous zircons were partly replaced and overgrown during high-grade metamorphism and deformation over the following one billion years. Dates are expressed in millions of years, with 1σ analytical errors.
Canadian shield
Siberian shield

Elkins-Tanton, 2006
Archaean crust in red
The Earth during the Archaean?
Conflicting crustal growth curves

- periods of major crustal growth
- Fraction of crust produced per 200 Ma vs. time (Ma)
- Cumulative % age distribution vs. age (Byr)
Why is old continental crust preserved?

Look at the rocks at the back of the room. Determine the mineral proportions and use the information given in the handout to infer the density of the rocks.
If you add it all up, the continents have the composition of andesite

<table>
<thead>
<tr>
<th></th>
<th>Lower</th>
<th>Middle</th>
<th>Upper</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Major Elements</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO$_2$, wt. %</td>
<td>52.3</td>
<td>60.6</td>
<td>66.0</td>
<td>59.1</td>
</tr>
<tr>
<td>TiO$_2$, wt. %</td>
<td>0.8</td>
<td>0.7</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Al$_2$O$_3$, wt. %</td>
<td>16.6</td>
<td>15.5</td>
<td>15.2</td>
<td>15.8</td>
</tr>
<tr>
<td>FeO$_T$, wt. %</td>
<td>8.4</td>
<td>6.4</td>
<td>4.5</td>
<td>6.6</td>
</tr>
<tr>
<td>MnO, wt. %</td>
<td>0.1</td>
<td>0.10</td>
<td>0.08</td>
<td>0.11</td>
</tr>
<tr>
<td>MgO, wt. %</td>
<td>7.1</td>
<td>3.4</td>
<td>2.2</td>
<td>4.4</td>
</tr>
<tr>
<td>CaO, wt. %</td>
<td>9.4</td>
<td>5.1</td>
<td>4.2</td>
<td>6.4</td>
</tr>
<tr>
<td>Na$_2$O, wt. %</td>
<td>2.6</td>
<td>3.2</td>
<td>3.9</td>
<td>3.2</td>
</tr>
<tr>
<td>K$_2$O, wt. %</td>
<td>0.6</td>
<td>2.01</td>
<td>3.40</td>
<td>1.88</td>
</tr>
<tr>
<td>P$_2$O$_5$, wt. %</td>
<td>0.1</td>
<td>0.1</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Mg #, mol</td>
<td>60</td>
<td>48</td>
<td>47</td>
<td>54</td>
</tr>
</tbody>
</table>

*Upper*
Where is CC formed?
Comparing of the continental crust with the average andesite
Problems of continental crust formation:

- Bulk CC is andesitic
  (e.g. SiO$_2$ ~60 wt%; Mg$\#$ ~0.54)
- Mantle derived melts are (generally) basaltic
  (e.g. SiO$_2$ ~50 wt%; Mg$\#$ ~0.7)

- Two main problems of CC formation:
  - Silica enrichment
  - “Mg$\#$-gap” problem
How does it work?
Intra arc complexities

Kohistan arc  Talkeetna arc

Stern, 2002
Geology of Kohistan (NE Pakistan)

Kohistan Complex
- Yasin detrital series
- volcanosedimentary groups (Utor and Chalt)
- metasediments
- plutonic rocks (Kohistan Batholith)
- gabbro-norite with ultrabasites
- (Chilas Complex)
- norite plutons with ultrabasites
- Southern Amphibolites
- mantle ultrabasites
- imbricate thrust units

Indian Plate
- Precambrian to Mesozoic series
- Foreland Cenozoic deposits

MKT: Main Karakoram Thrust
PT: Panjali Thrust
MBT: Main Boundary Thrust

Jagoutz et al. 2006 EPSL
Dunite

Cr-diopside dykes

Cr-spinel trails

Scale
websterite

dunite
Seismic Moho

plag+grt+cpx+hbI

hbI+grt+cpx
Fe-Ti oxides
grt + cpx
+hbl+plag+qtz
Sarangar shearzone

hornblendite

SW

NE

pyx + plag + hbl

hornblendite
Courtesy of G. Zeilinger
The role of xtal fractionation vs partial melting

Muentener & Ulmer, 2006; Vielzeuf & Schmidt 2001
The characteristic of the delaminated crust:

$\rho > 3.3 \text{ g/cm}^3$

(Miller & Christensen 1994)
Midoceanic ridges
MOR's: Bildung und Extraktion

Plan

• Structure of MOR
• Adiabatic Melting of the mantle
• Effect of pressure and composition
• Extraction of melt from the mantle
The global ridge system, and spreading velocities
Distribution of earthquakes and plate boundaries
The global ridge system
Age of the ocean floor
Principal results from:

1968 - 1983

DSDP - Deep Sea Drilling Project

Glomar Challenger

96 cruises

624 sites

15 years - 1983
1983 - 2003

ODP

Ocean Drilling Project

Joides Resolution: 110 legs - 650 sites - 20 different countries
Future - IODP - Integrated Ocean Drilling Program (at least for the next 10 years)

2 ships: Joides Resolution- Chikyu (started 2002)

Possibility to drill into subduction zones

http://www.iodp.org
http://www.swissiodp.ethz.ch/
Cruises DSDP - ODP

DSDP Legs 1–96, Sites 1–624 (●) and ODP Legs 100–210, Sites 625–1277 (●)
ODP legs (note that Polar areas are missing!)
Classic mid-ocean ridge
Oceanic Crust and Upper Mantle Structure

Typical Ophiolite

Layer 1

A thin layer of pelagic sediment

# Oceanic Crust and Upper Mantle Structure

Layer 2 is basaltic

Subdivided into two sub-layers

Layer 2A & B = pillow basalts

Layer 2C = vertical sheeted dikes


## Lithology

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<th>Typical Ophiolite</th>
<th>Normal Ocean Crust</th>
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<tr>
<td>Deep-Sea Sediment</td>
<td>1</td>
<td>~ 0.3</td>
<td>0.5</td>
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<td>Basaltic Pillow Lavas</td>
<td>2A &amp; 2B</td>
<td>0.5</td>
<td>0.5</td>
</tr>
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<td>Sheeted dike complex</td>
<td>2C</td>
<td>1.0 - 1.5</td>
<td>1.5</td>
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<tr>
<td>Gabbro</td>
<td>3A</td>
<td>2 - 5</td>
<td>4.7</td>
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<tr>
<td>Layered Gabbro</td>
<td>3B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layered peridotite</td>
<td>4</td>
<td>up to 7</td>
<td></td>
</tr>
<tr>
<td>Unlayered tectonite peridotite</td>
<td>4</td>
<td></td>
<td></td>
</tr>
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**Layer 3** more complex and controversial
Believed to be mostly gabbros, crystallized from a shallow axial magma chamber (feeds the dikes and basalts)

Layer 3A = upper isotropic and lower, somewhat foliated ("transitional") gabbros
Layer 3B is more layered, & may exhibit cumulate textures

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Oceanic Crust and Upper Mantle Structure

Discontinuous diorite and tonalite ("plagiogranite") bodies = late differentiated liquids

Layer 4 = ultramafic rocks

Ophiolites: base of 3B grades into layered cumulate wehrlite & gabbro

Wehrlite intruded into layered gabbros

Below → cumulate dunite with harzburgite xenoliths

Below this is a tectonite harzburgite and dunite (unmelted residuum of the original mantle)
A new classification of mid-ocean ridges: Ultra-slow, slow, and fast: based on geophysical observations

Dick et al. 2003, Nature
Slow-Spreading Ridge models

'classic layer model'

- variable, low magma supply
- poorly developed melt zone (magmatic/amagmatic cycles)
- well developed axial rift valley, rugged topography
- thick crust (variable)
- segmented ridges
- faulting prevalent, may root in brittle-ductile transition
- large vent fields, fault-controlled

'e.g. MARK (Mid-Atlantic Ridge/Kane Fracture Zone)

'non-layered model'

- basaltic dikes & lavas
- gabbro
- gabbro & crystal mush (most recent intrusions)
- peridotite

(after Sinton & Detrick, 1992)

(Km)

(Cannat, 1993)
- slow ridge
- fast ridge

- cold mantle
- low degree of melting
- Thin crust

- hot mantle
- high degree of melting
- Thick crust

Langmuir et al. 1992
Possible explanations for melt supply:

- Cold mantle
- Hot mantle
- Deep thermal boundary layer
- Shallow thermal boundary layer
<table>
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<tr>
<th>MOR</th>
<th>Crystallization Pressures (GPa)</th>
<th>Possible Hotspot Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EPR</strong></td>
<td>$0.20 \pm 0.15$</td>
<td>Shona</td>
</tr>
<tr>
<td><strong>MAR</strong></td>
<td>$0.38 \pm 0.21$</td>
<td>Azores</td>
</tr>
<tr>
<td><strong>SWIR</strong></td>
<td>$0.52 \pm 0.28$</td>
<td>Bouvet</td>
</tr>
<tr>
<td><strong>(“normal” ridge segments)</strong></td>
<td>$0.47 \pm 0.17$</td>
<td>Reykjanes Ridge</td>
</tr>
<tr>
<td><strong>av. P (GPa)</strong></td>
<td></td>
<td>Marion</td>
</tr>
<tr>
<td><strong>av. P (GPa)</strong></td>
<td></td>
<td>Crozet</td>
</tr>
</tbody>
</table>
Segregation und emplacement of magmas

Porous flow

Diapiris

Magma fractures
What happens to a melt that is in equilibrium with a mantle assemblage at 10 kbar, if decompressed to 1 atm?

(1) Cristallisation of Olivine, until composition reaches the the Ol-CPx cotectic

(2) Cotectic xtal of Ol+Cpx

(3) Xtal of Ol+Cpx+Opx (again in eq with mantle)

Melt not in equilibrium with the mantle will react:

Pyx+liq$_1$ -> ol + liq$_2$ -> formation of DUNITE
Melt migration in the mantle ...

Mechanism:
- diffuse → porous flow
- focused
- porous flow
- dikes

Reaction rate with surrounding rocks:
- high
- less
- little
Impregnated Dunite (Oman)

Ozeanische Kruste

Bildung von Gängen (eventuell schon in den Schmelzkänen), Übergang von fokussiertem Porenfluss zu Gängen

Schmelzmigration via fokussiertem Porenfluss (in Duniten)

Mechanische Segregation (durch Deformation entstanden)

teilweises Aufschmelzen, relative geringe Produktivität, eventuell erhöht entlang mafischen Gesteinen

Schmelze | Dunit | Harzburgit | Lherzolit

mafische Gesteine

Transportgeschwindigkeit zunehmend

Impregnated Dunite (Oman)
Istostasy
Accretion 1

**Accretion of a buoyant fragment to a continent**

**TIME 1**
A buoyant oceanic or continental fragment is carried into a plate collision zone.

**TIME 2**
The fragment is more buoyant than the subducting lithosphere, and is not subducted.

**TIME 3**
The fragment becomes welded to the overriding plate.

**Accreted terrane**

**Accretion of an island arc to a continent**

**TIME 1**
A plate carrying a continent subducts beneath an oceanic island arc.

**TIME 2**
The continental crust is more buoyant than the subducting lithosphere and is not subducted with it.

**TIME 3**
The island arc crust becomes welded to the island continent.

**Accreted terrane**
**Accretion II**

**Accretion along a transform fault**

**TIME 1**
Two plates slide past each other along a transform fault.

**TIME 2**
A terrane fragment on plate B is carried along the margin of plate A.

**TIME 3**
When the fault becomes inactive, the fragment becomes welded to plate A in a position distant from its original position.

**Accretion by continental collision and rifting**

**TIME 1**
A plate carrying a continent subducts beneath another continental plate.

**TIME 2**
The continent is not subducted, so two continents are welded together along a set of thrust faults.

**TIME 3**
Later, rifting and seafloor spreading carry the continental plates apart, leaving a fragment of one continent welded to the other.
Two forms of subduction-related magmatism

Slab melting

Hot slabs; typical of the early earth?

Dehydration melting

Cool slabs; typical of today?
The logic:
Zircon = Granite = Melts of Hydrous Sediments = Aqueous Weathering = Ocean and Continents = Cool
The early Paleozoic western US
W. W. Norton. Adapted from Coney et al., 1980.
Cold cheese stands tall.

Cheese softens and spreads out.

Upper, brittle part of range undergoes normal faulting.

Not to scale

Deep, ductile part of range flows sideways.
Bedrock
Adapted from Geologic Map of the United States, U.S. Geological Survey
UCC and LCC are not complementary
Two different liquid lines of descent

Grove et al. 2002
Geological map of the Jijal-Dasu region

Zeilinger, PhD 2002
Jijal profile along the Indus Valley (magmatic activity ~118 - 75 Ma)

Black smoker video
Evolution d'un rift et changement des géothermes

(a) Profondeur (km)

Lithosphère
Asthensphère

(b) Température (°C)

(c) Température (°C)

after Philpotts 1990
Jijal-sequence: Evidence for post-magmatic tilting

Chilas-sequence: Evidence that the original orientation is preserved
Syn-magmatic extension
Geodynamic model for the emplacement of the Chilas Complex

- blueschists in accretionary prism
- Jijal crust section
- split volcanic-arc rollover rotation
- sealed remnant back-arc basin?
- extensional mantle diapirism and associated gabbro-norites (Chilas Complex)
- Chilas crust section
- rolling-back slab

~85 Ma

Burg & Jagoutz et al. 2006, Tectonics
Geology of Kohistan

Jagoutz et al. 2006 EPSL

Chilas Crust

Jijal Crust
Melt transport mechanisms: