Mapping the Water Content in the Mantle from Seismological Measurements

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1. Introduction
    1.1 Water circulation in the mantle
    1.2 Importance of water in nominally anhydrous minerals
    1.3 Partial melting and water distribution

2. Basic physics of seismic properties of rocks
    2.1 Direct effects vs. indirect effects

3. Effects of water through direct mechanisms
    3.1 Hydrous minerals
    3.2 Effects of water-related defects on elastic properties

4. Effects of water through indirect mechanisms
    4.1 Anelasticity
        4.1.1 Basics of anelastic relaxation
        4.1.2 Some mineral physics observations on anelasticity
    4.2 Anisotropy
        4.2.1 The role of water on preferred orientation in olivine
        4.2.2 New results: microscopic interpretation

5. Applications
    5.1 interpretation of seismic anisotropy in terms of water circulation

Thermal Structure and Metamorphic Evolution of Subducting Slabs

Simon M. Peacock, Dept. of Geological Sciences, Arizona State University, Tempe, AZ

1. Overview
   - 1.1 Subducting slabs power the subduction factory
   - 1.2 Subduction zones are (way) cool
   - 1.3 Subducted material undergoes metamorphism and releases H_2O

2. Constraints on the thermal structure and metamorphic evolution of subducting slabs
   - 2.1 Surface heat flow measurements
   - 2.2 Seismic observations
   - 2.3 High-pressure, low-temperature metamorphic terranes
   - 2.4 Arc volcanism

3. Parameters controlling the thermal structure of subducting slabs
   - 3.1 Convergence rate
   - 3.2 Thermal structure (age) of incoming lithosphere
   - 3.3 Slab geometry
   - 3.4 Rate of shear heating
   - 3.5 Vigor and geometry of flow in the mantle wedge
   - 3.6 Differences between thermal models

4. Thermal models of specific subduction zones
   - 4.1 Cool – NE Japan, Aleutians
   - 4.2 Warm – Nankai, Cascadia

5. Metamorphic evolution of subducting slabs
   - 5.1 Inputs
     - 5.1.1 Pelagic ± terrigenous sediments
     - 5.1.2 Altered oceanic crust (metabasalt and metagabbro)
     - 5.1.3 Altered (?) mantle (depleted ultramafic rocks, serpentinite?)
   - 5.2 Cool subduction zones: high-pressure, low-temperature metamorphism
     - 5.2.1 Sediments: opal quartz coesite, clay mica melt
     - 5.2.2 Metabasalt, metagabbro blueschist eclogite
     - 5.2.3 Ultramafic: olivine spinel, Serpentine phase-A ?
   - 5.3 Warm subduction zones + possible partial melting of subducted materials
   - 5.4 H_2O released from subducting slabs

6. Testing thermal-petrologic models against seismic + magmatic observations
   - 6.1 Dipping low-velocity layer
   - 6.2 Subduction-zone seismicity
     - 6.2.1 Downdip limit of subduction thrust earthquakes
     - 6.2.2 Intermediate-depth earthquakes
     - 6.2.3 Deep-focus earthquakes

7. Critical uncertainties in thermal-petrologic models of subducting slabs
   - 7.1 Mantle wedge flow model
   - 7.2 Thermal parameters as a function of (P,T,X)
   - 7.3 Phase equilibria and kinetics at low T and high P

Three Tectono-Magmatic Systems Interact in Central America

Michael Carr, Department of Geological Sciences, Rutgers University, Piscataway, NJ.

1. Volcanic front
   Lines of composite volcanoes in strike-slip settings, composed of magmas with strong slab signature, high water abundances, and plagioclase and pyroxene phenocrysts. Formed by flux-decompression melting. Very active today.

2. Secondary front
   Rare composite volcanoes 10-30 km behind the volcanic front, composed of magmas with moderate slab signatures and plagioclase and pyroxene phenocrysts. Rare during the Holocene

3. Back-arc volcanism
   Clusters of cinder cones and shields in extensional settings, composed of magmas with low to negligible slab signatures and rare olivine phenocrysts. Form by decompression melting. Moderate Holocene activity.

4. Magma migration is commonplace
   Composite cones can erupt all nearby magmas, commonly creating mixtures of volcanic front and back-arc magmas. Large cones are more extensively mixed, so smaller cones are best for revealing the end member magmas.

5. Geographic-geochemical zoning
   Geochemical zoning along and across the arc results from changes in the mantle, changes in the strength of the slab signature and variations in the hemipelagic sediment component.

6. Mantle zoning
   The first-order mantle zoning is the presence of ‘Galapagos-like’ isotopic signatures in basalts from central Costa Rica to northern Panama. Data from recent lavas define a field extending toward the ‘HIMU’ end member of ocean-island basalt compositions. Northwest and southeast of this region, the mantle is inferred to be more depleted, typical of asthenosphere and close to EMORB mantle composition. The second-order mantle zoning consists of variations in the MORB-like mantle. Very little is known except that the most depleted region is near Lake Yohoa, Honduras. The back-arc lavas in western Nicaragua erupt at the volcanic front and are LREE depleted, indicating an earlier episode of low degree melting.

7. Slab signature

   Several unusual aspects of Cocos Plate stratigraphy make the slab signature complex and separable into components:

   7.1 From Guatemala through Nicaragua, the age and source of the subducted slab is nearly identical, suggesting a uniform supply into the trench.

   7.2 The sediments consist of a lower carbonate and an upper hemipelagic mud. The Ba/La and U/Th ratios change by only a factor of 2 to 5 through these very different sediments.

   7.3 The high Sr/Nd of the carbonate creates a horizontal (constant Nd isotope ratio) mantle-sediment mixing line rather than a mix that extends down the mantle array.

   7.4 The hemipelagic sediments are rich in carbon and U, creating U/Th ratios greater than 2, rather than less than 0.35; thus the hemipelagic sediments are easily fingerprinted. The fingerprint for the carbonates is extremely high Ba/Th.

8. Zoning of the subduction signature (Ba/La, U/Th, ^{10}Be/^{9}Be)

   Across the arc: Cross-arc transects more than 100 km in length occur across southeast Guatemala and central Honduras, both the result of extensive graben formation. In southeast Guatemala the slab signature ends abruptly just 10 to 30 km behind the volcanic front. In Honduras the slab signature decreases with distance across the arc in a more or less progressive manner.

The Izu-Bonin-Mariana Subduction Factory

Robert Stern, Department of Geosciences, University of Texas at Dallas, Richardson, TX.

1. Definition and Geography.
    - 1.1 Location, dimensions, areal extent, deepest and highest points.
    - 1.2 Active vs. Fossil constituents
    - 1.3 Active constituents
        - 1.3.1 Forearc
        - 1.3.2 Active arc
        - 1.3.3 Back-arc basin

2. History
    - 2.1 Subduction Initiation
    - 2.2 Evolution of the arc system

3. Geophysics
    - 3.1 Seismicity
    - 3.2 Tomography
    - 3.3 Crustal Structure
    - 3.4 Gravity
    - 3.5 Magnetics
    - 3.6 Heatflow
    - 3.7 Plate motions of the Philippine Sea Plate

4. Inputs
    - 4.1 Plate convergence
    - 4.2 Crust and Lithosphere
    - 4.3 Off-ridge volcanism
    - 4.4 Sediments

5. Forearc
    - 5.1 Structure of the Inner Trench Wall
    - 5.2 Serpentine mud volcanoes & vents
        - 5.2.1 Distribution and dimensions
        - 5.2.2 Geology of mud volcanoes
        - 5.2.3 Entrained mantle materials (peridotite & blueschists)
        - 5.2.4 Vent fluids
    - 5.3 Forearc basin
        - 5.3.1 Sedimentary sequence

        - 5.3.2 Structure
        - 5.3.3 Young igneous rocks

6. Frontal Arc
    - 6.1 Guam-saipan-Tinian
    - 6.2 Ogasawara Islands

7. Active Arc
    - 7.1 Along-arc subdivisions
    - 7.2 Subaerial volcanoes
    - 7.3 Submarine volcanoes
    - 7.4 Eruption History
    - 7.5 Petrography
        - 7.5.1 The problem of liquid compositions vs. whole-rock analyses.
        - 7.5.2 The importance of quantitative petrography
    - 7.6 Mineral chemistry
    - 7.7 Geochemistry
        - 7.7.1 Major Elements
        - 7.7.2 Trace elements
        - 7.7.3 Isotopic compositions
            - 7.7.3.1 Sr - Nd - Pb - Hf
            - 7.7.3.2 O - C
            - 7.7.3.3 S
            - 7.7.3.4 Be, B
            - 7.7.3.5 Rare gasses
            - 7.7.3.6 U-series

8. Mariana Trough back-arc basin
    - 8.1 Along-rift subdivisions
    - 8.2 Petrography
    - 8.3 Mineral chemistry
    - 8.4 Geochemistry
        - 8.4.1 Major Elements
        - 8.4.2 Trace elements
        - 8.4.3 Isotopic compositions
            - 8.4.3.1 Sr - Nd - Pb - Hf
            - 8.4.3.2 O - C
            - 8.4.3.3 S
            - 8.4.3.4 Be, B
            - 8.4.3.5 Rare gasses
            - 8.4.3.6 U-series

9. Subduction Factory Processes
    - 9.1 Slab processes
    - 9.2 Mantle processes
    - 9.3 Crustal processes
        - 9.3.1 Izu Collision zone

Outline for MARGINS SubFac – Izu-Bonin-Marianas (IBM) focus region

Matthew J. Fouch, Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington D.C.

1. The subducting slab
    a. Regional seismicity – locations, focal mechanisms, rates
    b. Slab morphology
        i. General seismic structure
        ii. Variations across the IBM system
    c. Anisotropy/strain
        i. Current strain regime
        ii. Fossil anisotropy in plate
    d. Deep earthquakes in the IBM – how low do they go?
    e. How deep does the plate penetrate?
2. The mantle wedge
    a. Shape
    b. Mantle flow - anisotropy/strain
3. Current seismic networks
    a. IRIS/GSN
    b. FREESIA
    c. Pacific-21 (old POSEIDON)
4. Issues to discuss / future directions
    a. What is the detailed 3-D seismic structure at depth?
        i. Imaging melt?
        ii. Determining thermal/chemical/compositional variations?
        iii. Imaging phase transitions?
    b. What is the shape of the wedge?
    c. Can we image patterns of flow in the mantle (i.e., slab coupling)?
    d. Characteristics of deep earthquakes in the IBM
    e. Current projects in the Marianas
        i. NSF-MARGINS experiment (Taylor/Klemperer/Wiens/Hildebrand/Suyehiro et al.)

Slab Geochemical Tracers

Tim Elliott, Department of Earth Sciences, University of Bristol, Bristol, UK
Terry Plank, Department of Earth Sciences, Boston University, Boston, MA.

1. The bag of tracers and their key features:
    1.1 Light stable isotopes (Li, B, O, C)
    1.2 ^{10}Be
    1.3 Incompatible elements stressing
        1.3.1 Different behaviours (fluid mobile vs non-mobile
        1.3.2 Key ratios (Ce/Ce*, La/Nb, Ce/Pb)
        1.3.3 Relative leverage on mantle
    1.4 Long-lived radiogenic isotopes (Pb, Sr, Nd, Hf, Os, He) with reference to elemental behavior
    1.5 U-series nuclides, basic behavior during melting a slab addition processes

2. General observations:
    2.1 Compositions of inputs to the arc
    2.2 Ubiquitous two slab derived components (and how this may be disguised)
    2.3 Constraints on mass-balance
    2.4 Timing of additions from ^{10}Be and U-series

3. Case study of the Marianas
    3.1 Importance of multi-element constraints
    3.2 A quantitative model
    3.3 Implications for composition of subduction processed slab
    3.4 Comparison with proposed deep recycled components

Experimental Constraints on Slab Mineralogy and Dehydration

John R. Holloway, Depts. of Geological Sciences, and Chemistry & Biochemistry,
Arizona State University, Tempe, AZ

1. Historical perspective on experiments
    - 1.1 Hydrous basalt/sediment melting experiments
        - 1.1.1 Barely subsolidus, 700°C minimum temperature
        - 1.1.2 Hornblende stability only determined in melting range (basalts)
        - 1.1.3 Short (hours) run duration

2. "Modern" Experiments: Hydrous basaltic compositions
    - 2.1 Experimental difficulties
        - 2.1.1 Low temperatures
        - 2.1.2 Lack of equilibrium
        - 2.1.3 Fine grain size
        - 2.1.4 Uncertain oxidation state control
    - 2.2 Experimental solutions
        - 2.2.1 Long run duration (days – weeks)
        - 2.2.2 Starting materials "seeded" with possible minerals
        - 2.2.3 Modern techniques for phase identification and analysis
    - 2.3 Three groups with results on approximately the same compositions
        - 2.3.1 Liu, Ernst and Bohlen (L-E-B)
            - 2.3.1.1 Amphibole out results in total dehydration
            - 2.3.1.2 Lawsonite only other stable hydrous phase
        - 2.3.2 Pawley and Holloway (P-H)
            - 2.3.2.1 Amphibole reacts to chloritoid and aqueous fluid
            - 2.3.2.2 Chloritoid reacts to lawsonite
            - 2.3.2.3 Epidote (zoisite) stable
        - 2.3.3 Poli and Schmidt (P-S)
            - 2.3.3.1 Amphibole reacts to chloritoid and aqueoud fluid
            - 2.3.3.2 Chloritoid reacts to lawsonite
            - 2.3.3.3 Zoisite (epidote) stable

- 2.3.4 Important differences
  - 2.3.4.1 "Pressure Gap" in hydrous minerals (L-E-B): No transport of H_2O below 65 kilometers
  - 2.3.4.2 Amphibole-Chloritoid-lawsonite (P-H, P-S): Transport of about 0.5 wt. % H_2O to almost 300 kilometers
- 2.3.5 Explanation(s):
  - 2.3.5.1 Lack of equilibrium in P-H and P-S experiments.
  - 2.3.5.2 Differences in bulk composition and/or oxidation state
  - 2.3.5.3 Lack of experiments by L-E-B in critical P-T region.

3. "Modern" Experiments: Hydrous metasediment composition
   - 3.1 Results show hydrous mineral stability to 300 kilometers: Nichols at al. (1994), Domanik and Holloway (1996), Johnson & Plank (1999)
   - 3.2 Metasediments probably do not dehydrate much at subsolidus T's.

4. Implications for subduction-zone magma generation
   - 4.1 We don't know phase relations for metabasalts for T<650°C at P>3 Gpa
   - 4.2 Single-phase dehydration boundaries usually do not match volcanic front positions (Schmidt & Poli, 1998)
   - 4.3 Subduction-zone magmatism must result from complex interplay between subducting slab and the mantle wedge

Seismological Constraints on Structure and Flow Patterns Within the Mantle Wedge.

Douglas A. Wiens, Department of Earth and Planetary Sciences, Washington University, St Louis, MO.

1. Seismological observables and methods
    - 1.1 Seismic velocity
    - 1.2 Velocity anisotropy
    - 1.3 Seismic attenuation
    - 1.4 Methods
        - 1.4.1 1-D structure inversion
        - 1.4.2 Surface wave tomography
        - 1.4.3 Body wave tomography
        - 1.4.4 Shear wave splitting

2. Seismic velocity and attenuation results for arc-backarc systems: Constraints on mantle temperature and melt production
    - 2.1 Seismic evidence on the distribution of volatiles and magma beneath the volcanic front
    - 2.2 Seismic structure of backarc spreading centers and relationship to arc structure
    - 2.3 Deep seismic anomalies beneath arcs – evidence for deep volatile release?

3. Seismic anisotropy results: Constraints on mantle flow patterns
    - 3.1 A review of anisotropy observations in arcs
    - 3.2 The Tonga-Lau system: a complex pattern of anisotropic orientations
    - 3.3 Models for arc flow patterns and relationship to observations
        - 3.3.1 Flow determined by regional and global flow patterns
        - 3.3.2 Backarc flow driven by coupling to the downgoing plate
        - 3.3.3 Slab roll-back and along-arc flow
        - 3.3.4 Other possible interpretations

4. Future directions
    - 4.1 Large datasets, higher resolution, and mega-experiments
    - 4.2 Better experimental linkage between observations and physical conditions
    - 4.3 Use of geodynamic models for hypothesis testing

Melt Generation in the Mantle Wedge

Glenn A. Gaetani, Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, Troy, NY.

1. Introduction
    1.1 Geophysical and geochemical constraints on the nature of melt generation in the mantle wedge

2. Phase equilibria
    2.1 Simple system constraints on hydrous peridotite melting
    2.2 Experimental results in natural systems

3. Physical properties and melt segregation
    3.1 Effects of H_2O on melt density and viscosity
    3.2 Effects of H_2O on melt distribution

4. Melting rates
    4.1 Relationship between isobaric and polybaric melt productivity
    4.2 Anhydrous melt productivity
    4.3 Effect of H_2O on melt productivity

The Rheology of the Mantle Wedge

Greg Hirth, Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA.

1. Introduction
    - 1.1 A geodynamic model of an arc
        - 1.1.1 Viscous deformation mechanisms
        - 1.1.2 Effects of temperature, pressure and grain size
        - 1.1.3 Effects of water and melt fraction
    - 1.2 The importance of rheology on melt migration processes

      Porous flow requires both permeability and compaction of the matrix (introduce possibility that melt migration can be controlled by either permeability or rheology)
    - 1.3 The problem

      Melt needs to get from the melting region, through the lithosphere, and to the base of the volcanic arc. This presumably involves a transition from porous flow to focussed flow of melt in conduits or dikes.

2. Introduction to deformation mechanisms
    - 2.1 Overview of lab experiments, flow laws and viscosity
    - 2.2 Dislocation creep of olivine aggregates and extrapolation to upper mantle conditions
    - 2.3 Effect of temperature on dislocation creep
    - 2.4 Transition to diffusion creep in the laboratory with an emphasis on the effect of grain size
    - 2.5 Effect of pressure on viscosity in the dislocation and diffusion creep regimes.
    - 2.6 Importance of stress and grain size for determining dominant deformation mechanism

3. Role of melt on the rheology of the mantle wedge
    - 3.1 Overview of the nfluence of melt on rheology
    - 3.2 The Cooper and Kohlstedt model
    - 3.3 The effect of melt on strain rate/viscosity in the diffusion creep regime
    - 3.4 Microstructure and melt topology
    - 3.5 Effect of melt on strain rate in the dislocation creep regime
    - 3.6 Decreases in viscosity as a result of a transition to grain boundary sliding in the presence of melt
    - 3.7 Effects of melt on grain size and grain growth

Melt inhibits grain growth; therefore, the onset of melting can result in a decrease in grain size leading to both a decrease in viscosity and permeability.

- 3.8 Potential for the presence of melt to lead to a transition to grain boundary sliding
- 3.9 Compaction and constraints on "Bulk Viscosity" versus "Shear Viscosity" Comparison of the effects of melt in compaction experiments to that determined in distortional strain experiments; the role of differential stress on melt topology.
- 3.10 Exponential relationship between melt fraction and viscosity

4. Role of Water on Viscosity
   - 4.1 Influence of water on viscosity in both the dislocation and diffusion creep regimes
   - 4.2 Solubility of water as a function of pressure and the maximum possible viscosity reduction caused by the presence of water
   - 4.3 Trade-off in the effects of melt and water caused by partitioning of water into melt phase

5. Putting it all together: A first cut on the rheology of the wedge
   - 5.1 Extrapolation of flow laws to wedge conditions to give constraint on magnitude of viscosity; uses of the water content of arc magmas as a constraint on the water content in the wedge

6. Complications
   - 6.1 Might melt promote brittle behavior of aggregates through a decrease in the effective pressure?
   - 6.2 Dilatancy hardening in partially molten rocks using data on granitic systems
   - 6.3 Rheology of olivine+melt system with different melt viscosities and the possible effects of melt pressure on physical properties
   - 6.4 Influences of deformation on melt topology
   - 6.5 The transition to "dike-like" behavior, with an emphasis on the role of permeability

7. Constraints on permeability
   - 7.1 Constraints from melt topology (e.g., von Bargen and Waff, Faul)
   - 7.2 Constraints from analog system (e.g., Wark and Watson)
   - 7.3 Constraints from compaction experiments (e.g, Viskupic)
   - 7.4 Effects of deformation (melt topology) and second phases (e.g., pyroxenes)

8. Independent constraints on wedge rheology
   - 8.1 Effect of rheology on seismic velocity (attenuation)
   - 8.2 Seismic anisotropy (role of melt and lattic-preferred orientation of olivine)
   - 8.3 Geochemistry/Petrology: Where do melts equilibrate?, how fast do they get out?, where does the water come from?