AGU Chapman Conference
The Great Plume Debate:
The Origin and Impact of LIPS and Hot Spots

Ben Nevis Hotel, Fort William, Scotland, United Kingdom
28 August – 1 September 2005

Conveners

- **Ian Campbell**, Research School of Earth Sciences, The Australian National University, Canberra, A.C.T. 0200, Australia, email: Ian.Campbell@anu.edu.au
- **Gillian R. Foulger**, Dept. Earth Sciences, Science Laboratories, University of Durham, South Rd., Durham, DH1 3LE, U.K., email: g.r.foulger@durham.ac.uk
- **James H. Natland**, Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker, Causeway, Miami, FL 33149, email: jnatland@msn.com
- **Dean C. Presnall**, Geophysical Laboratory, 5251 Broad Branch Rd., NW, Washington, DC 20015, e-mail presnall@gl.ciw.edu
- **W. Jason Morgan**, Dept. Earth Planet. Sci., Harvard Univ., 20 Oxford St., Cambridge, MA 02138, email: wjmorgan@princeton.edu

Program Committee

- **J. Godfrey Fitton**, University of Edinburgh, Godfrey.Fitton@ed.ac.uk
- **Brian Bell**, University of Glasgow, b.bell@earthsci.gla.ac.uk
- **C. Henry Emeleus**, University of Durham, c.h.emeleus@durham.ac.uk

Sponsors

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Cover Image: View looking north-west from Bidean nam Bian, in the Devonian Glen Coe volcanic complex, toward Loch Leven and Ballachulish. The Ballachulish intrusive complex forms the high ground in the left middle distance (south of the Ballachulish Bridge); the lower ground to the north of the bridge is composed of Dalradian metamorphic rocks. Loch Linnhe and the Great Glen Fault run across the middle of the photograph (SW-NE). Moine metamorphic rocks form the mountains in the distance. Fieldtrip 2, the “Road to the Isles” half-day excursion, will comprise a transect of this part of the Caledonian orogenic belt.

Great Plume Debate Chapman Conference: Agenda at a Glance

	Sunday 28 Aug	Monday 29 Aug	Tuesday 30 Aug	Wednesday 31 Aug	Thursday 1 Sept
8:00 - 8:30	*Welcome and introduction*				
8:30 - 10:00	*Plume theory & predictions*	*Temperature I*	*Geochronology I*	*Field evidence I*	*Petrology & Geochemistry I*
10:00-10:30	coffee	coffee	coffee	coffee	coffee
10:30-12:00	*Alternative theories & predictions*	*Temperature II*	*Geochronology II*	*Field evidence II*	*Petrology & Geochemistry II*
12:00 - 13:30	lunch & posters	lunch & posters	lunch & posters	lunch & posters	lunch & posters
13:30-15:00	*Lithosphere & mantle physics & dynamics I*	Fieldtrip I: *Ballachulish and Glen Coe*	*Seismology I*	Fieldtrip II: *The Road to the Isles*	*Discussion I*
15:00-15:30	tea		tea		tea
15:30-17:00	*Lithosphere & mantle physics & dynamics II*		*Seismology II*		*Discussion II & Synthesis*
17:00-18:00	posters		posters		posters
18:00-19:00		posters		posters	
19:00-20:00	dinner	dinner	dinner	dinner	dinner
20:00 onwards	posters	posters	posters	posters	posters
20:30-21:00		Lecture: *Scottish Highlands geology in a global context* Ian Dalziel	*Planetary*		
21:00-21:30				Scottish evening entertainment	
21:30-22:00					

Preliminary Schedule
AGU Chapman Conference on the Great Plume Debate:
The Origin and Impact of LIPs and Hot Spots
28 August - 01 September 2005
Fort William, Scotland, United Kingdom

Sunday 28 August 2005

Time	Speaker	Title
8:00 – 8:30h	I. Campbell & G. Foulger	Welcome and Introductions
Plume theory & predictions *Conveners: Ian Campbell & W. Jason Morgan*		
8:30 – 10:00h	I. Campbell	Testing the Plume Hypothesis
	J. Morgan	The Deep Mantle Plume Hypothesis
	Discussion	
10:00 – 10:30h	Coffee	
Alternative theories & predictions *Conveners: Gillian Foulger & Dean Presnall*		
10:30 – 12:00h	G. Foulger	The Generation of Melting Anomalies by Plate Tectonic Processes
	L. Elkins-Tanton	Continental Magmatism Caused by Lithospheric Rayleigh-Taylor Instabilities
	D. Sandwell	Cracks and Warps in the Lithosphere from Thermal Contraction
	Discussion	
12:00h-13:30h	Lunch and Posters	
Lithosphere & mantle physics & dynamics I *Conveners: John Tarduno & Erin Beutel*		
13:30 – 15:00h	J. Davies	Mantle Convection – An Overview
	U. Hansen	Generation and Evolution of Plumes in Mantle-Relevant Scenarios
	J. A. Tarduno	On the Motion of Hawaii and Other Mantle Plumes
	Discussion	
15:00 – 15:30h	Tea	
Lithosphere & mantle physics & dynamics II *Conveners: Erin Beutel & John Tarduno*		
15:30 – 17:00h	E. Burov	The Plume Head - Continental Lithosphere Interaction Using a Tectonically Realistic Formulation for the Lithosphere
	S. King	How Many Hotspots Can be Explained by Edge Driven Convection?
	J. Van Wijk	Formation of Volcanic Rifted Margins: Influence of the Pre-Rift Lithosphere Architecture
	W. Stuart	Hawaii Volcano Chain as a Thermoelastically-Driven Propagating Crack
	Discussion	
17:00 – 19:00h	Posters	
19:00 – 20:00h	Dinner	
20:00h +	Posters	

Monday 29 August 2005

Temperature I *Conveners: Nick Arndt & Carol Stein*		
8:30 – 10:00h	N. Arndt	The Temperatures of Mantle Plumes
	M. Cheadle	Komatiites and the Temperature of the Mantle: “Some Like It Hot”.
	C. M. Lesher	High-Mg Magmatism Through Time: Implications for Mantle Plumes
	Discussion	
10:00 – 10:30h	Coffee	
Temperature II *Conveners: Carol Stein & Nick Arndt*		
10:30 – 12:00h	R. Harris	Observations of Heat Flow on Hotspot Swells
	D. Presnall	MORB Major-Element Systematics: Implications for Melting Models and Mantle Temperatures
	T. Falloon	Magmatic Crystallization Temperatures of Tholeiite Magmas: Implications for the Existence of Thermally Driven Mantle Plumes
	Discussion	
12:00 – 13:30h	Lunch and Posters	
13:30 – 18:00h	**Field Trip I:** Ballachulish and Glen Coe	
19:00 – 20:00h	Dinner	
20:00h +	Posters	
20:30 – 21:30h	Lecture: Where on Earth was Fort William during Neoproterozoic and Paleozoic times? Scottish Highlands geology in a global context. *Ian Dalziel*	

Tuesday 30 August 2005

Geochronology I *Conveners: Bob Duncan & Ajoy Baksi*		
8:30 – 10:00h	R. Duncan	Timing and Duration of Volcanism at Large Igneous Provinces: Implications for Geodynamics and Links to Hotspots
	K. Hoernle	Origin of Long-term Intraplate Volcanism in the Canaries, Madeira, Galapagos and New Zealand: Which are Consistent with the Plume Hypotheses?
	A. Koppers	The Geochronology of Hotspot Trails and the Timing of the Hawaii-Emperor Bend
	Discussion	
10:00 – 10:30h	Coffee	
Geochronology II *Conveners: Ajoy Baksi & Bob Duncan*		
10:30 – 12:00h	A. Baksi	Critical Assessment of Radiometric Ages for Oceanic Hotspot Tracks, Based on Statistical Analysis of Individual Ages, and Evaluation of the Alteration State of the Material Dated
	J. O'Connor	Volcanic Imprint of Oceanic Hot Spots and LIPs: Shallow/Local versus Deep/Global?
	D. Praeg	Cenozoic Vertical Movements on the NW European 'Passive' Margin: Responses to Upper Mantle Convection?
	Discussion	
12:00 – 13:30h	Lunch and Posters	
Seismology I *Conveners: Guust Nolet & Thorne Lay*		
13:30 – 15:00h	R. Allen	Constraining the Geometry and Flow of the Iceland Mantle Upwelling
	D. Zhao	Multiscale Seismic Tomography of Mantle Plumes and Subducting Slabs
	G. Nolet	The Role of Mantle Plumes in the Earth's Heat Budget
	Discussion	
15:00 – 15:30h	Tea	
Seismology II *Conveners: Thorne Lay & Guust Nolet*		
15:30 – 17:00h	A. Deuss	Constraints on the Observation of Mantle Plumes Using Global Seismology
	B. Julian	Guided Seismic Waves: Possible Mantle-Plume Diagnostics
	T. Lay	Is the "D" Region the Source of Mantle Plumes?
	Discussion	
17:00 – 19:00h	Posters	
19:00 – 20:00h	Dinner	
Planetary *Convener: Donna Jurdy*		
20:30 – 22:00h	W. Hamilton	The Surface of Venus Records Ancient Impacts, Not Young Plumes
	V. Hansen	Venus' Many Circles: Extraterrestrial Clues for the Great Plume Debate
	A. Jones	Meteorite Impacts as Triggers to LIPs and Hotspots
	C. Reese	Impact Induced Martian Mantle Plumes: Implications for Tharsis
	Discussion	

Wednesday 31 August 2005

Field evidence I *Conveners: Andy Saunders & David Sandwell*		
8:30 – 10:00h	A. Saunders	Plumes and Uplift
	S. Jones	Uplift Associated with the North Atlantic Igneous Province
	Y. Xu	Surface Responses to Mantle Plume: Sedimentation and Lithofacies Paleogeography in SW China Before and After the Emeishan Flood Volcanism
	Discussion	
10:00 – 10:30h	Coffee	
Field evidence II *Conveners: David Sandwell & Andy Saunders*		
10:30 – 12:00h	H. Sheth	The Deccan Beyond the Plume Hypothesis
	V. Sallarès	Crustal Seismology Helps Constrain the Nature of Mantle Melting Anomalies. Galápagos Volcanic Province: A Case Study
	J. Winterer	Midplate Volcanic Overprinting: New Wine in Old Bottles
	Discussion	
12:00 – 13:30h	Lunch and Posters	
13:30 – 18:00h	**Field Trip II:** The Road to the Isles	
19:00 – 20:00h	Dinner	
20:00h +	Posters	

Thursday 01 September 2005

Petrology & Geochemistry I *Conveners: Eiichi Takahashi & Dean Presnall*		
8:30 – 10:00h	C. Hawkesworth	Geochemistry and Mantle Plumes
	J. M. Rhodes	Magmatic Evolution of Mauna Loa Volcano: Implications for a Chemically and Thermally Zoned Mantle Plume
	E. Takahashi	Magma Genesis in a Mantle Plume: Based on High-pressure Melting Experiments and Growth History of Some Hawaiian Volcanoes
	Discussion	
10:00 – 10:30h	Coffee	
Petrology & Geochemistry II *Conveners: Dean Presnall & Eiichi Takahashi*		
10:30 – 12:00h	G. Fitton	Do Hotspot Basalts Share a Common Mantle Source?
	M. Keskin	Eastern Anatolia: A Hot Spot in a Collision Zone Without a Mantle Plume
	A. Schersten	The Hf-W Perspective on Whether a Trace of the Earth's Core Exists in Hot Spot Volcanic Rocks
	Discussion	
12:00 – 13:30h	Lunch and Posters	
13:30 – 15:00h	**Discussion I**	
15:00 – 15:30h	Tea	
15:30 – 17:00h	**Discussion II and Synthesis**	
17:00 – 19:00h	Posters	
19:00 – 20:00h	Dinner	
20:00h +	Posters	

Poster Session: Sunday, 28 August 2005

First Author	Title
S. Goes	Testing Thermal Whole Mantle Plumes Seismically
Withdrawn	How Geometry and Ages of Global Hotspots are Explained by Classical Hypotheses of Rigid Plate and Fixed Hotspot
M. Yamamoto	Plume-fed Asthenosphere Flow Model: Evidence from Isotopic Variation Along Mid-ocean Ridges
Y. Niu	Slab Dehydration, Subcontinental Lithosphere Thinning and Widespread Mesozoic/Cenozoic Volcanism in Eastern China: A Special Consequence of Plate Tectonics
S. V. Rasskazov	Late Mesozoic Through Cenozoic Magmatism in East Asia: Effect of Directly and Obliquely Subducted Slab Flexures
J. W. Sears	Fracture Propagation on a Sphere: Implications for Non-Plume Origin of Large Igneous Provinces on Fragmenting Supercontinents
K. K. Sharma	Neoproterozoic Anorogenic Magmatism Associated with Rodinia Breakup: Not a Result of Mantle Superplume
A. Tiwary	Are the Precambrian Magma Chambers Responsible for the Cretaceous Deccan Trap Volcanism of India?
E. K. Beutel	Large LIPs and the Mantle Squeeze: A Mass Balance Approach to Hotspots
J. H. Davies	Mantle Convection - Plumes Rooted in Mid-Mantle
*A. Harris	The Many Potential Faces of Buoyant Mantle Upwellings: Diversity Within the Plume Family
V. C. Manea	Thermal Structure Beneath Kamchatka and Plume to Arc Magmatism Transition
M. Manea	Thermal Structure of the Cocos Slab Beneath Southern Mexico and its Relationship with the Arc Volcanism
Withdrawn	Small-scale Convective Instabilities in the Upper Mantle– A Generic Class of Hotspots Linked to Recent Continental Collision in Europe and the Circum-Mediterranean Region

* Student

Poster Session: Monday, 29 August 2005

G. R. Foulger	How Hot is Iceland?
R. R Keays	Why the High PGE Contents of Komatiites, Picrites and Allied Rocks Require Mantle Plumes
H. Mashima	Thermal State of NW Kyushu Mantle Suggested by Petrochemistry of Primitive Basalts
J. H. Natland	Influence of Eclogite in Mantle Sources on ‘Hot-spot’ Temperatures
K. D. Putirka	Evidence for High Temperature Mantle Plumes Based on Olivine-Liquid Thermometry
C. A. Stein	Does Hydrothermal Circulation Mask Anomalously High Heat Flow at Hot Spots?

Poster Session: Tuesday, 30 August 2005

L. A. Morgan	Patterns of Rhyolitic Volcanism in the Path of the Yellowstone Hot Spot
C. Tegner	Timescales of Flood Volcanism Recorded by Pressure Variations in Coeval Mafic Intrusions: A Fluid Inclusion Study of the Skaergaard Intrusion, East Greenland
A. B. Watts	Global Gravity, Bathymetry, and the Distribution of Submarine Volcanism through Space and Time
M. Widdowson	Duration and Timing of the Deccan CFBP
G. Laske	The SWELL Pilot Experiment off Hawaii - What Can We Learn About the Hawaiian Hotspot from Surface Waves?
J. R. R. Ritter	Comprehensive Imaging of the Eifel Plume, Central Europe
Withdrawn	Seismic Evidence for a Lower Mantle Origin of the Tanzania Hotspot
*M. Xue	Identifying the Origin of the Newberry Hotspot Track
*Withdrawn	Upper Mantle Structure Beneath the Azores Hotspot From Finite Frequency Seismic Tomography
D. M. Jurdy	Uplift and Rifting on Venus: Role of Plumes

* Student

Poster Session: Wednesday, 31 August 2005

*D. L. Abt	Delamination Origin for Columbia River Flood Basalts and Wallowa Mountains Uplift in NE Oregon, USA
A. J. Breivik	Continental Breakup Magmatism and Transition to Hot-Spot Influenced Seafloor Spreading From the Moere Margin to the Norway Basin
R. G. Cawthorn	Kaapvaal Craton, South Africa: Repeated Basic Magmatism, Diamonds and Plumes
I. W. D. Dalziel	The Setting of LIPS in the Lithosphere Through Time: One Test of the Plume Hypothesis
B. T. Jordan	Testing a Propagating Shear-Zone Hypothesis for Age-Progressive Magmatism in a Continental Setting: The Oregon High Lava Plains
M. Khodayar	Compressional Structures Do Not Show Regional Horizontal Compression Near the Iceland Hotspot
M. Khodayar	Overview of Tectonic Deformation in Past and Present Rift-Jump Blocks, West and South Iceland
Withdrawn	Paleogene North Atlantic Igneous Province and the Iapetus Connection
K. Pierce	Geologic Evidence for a Mantle Plume Origin for Yellowstone: The Pattern and Scale of Volcanism, Faulting, and Uplift Along the Yellowstone Hotspot Track
I. Norton	Passive Margin Evolution: Are Plumes an Integral Part of Continental Breakup?
W. W. Sager	Does a Fault in the Plate Circuit Ruin Intra-ocean Comparison of Hotspot Tracks?
A. V. Smirnov	Co-location of Eruption Sites of the Siberian Traps and North Atlantic Igneous Province: Implications for the Nature of Hotspots and Mantle Plumes
F. Tsikalas	NE Atlantic Breakup and Evolution of the Norwegian-Greenland Conjugate Volcanic Margins: Field Evidence to the Great Plume Debate
P. R. Vogt	Bermuda: Lava-lamp Plume, Edge-driven Convection, or/and Response to Distant Plate Reorganization?
M. Widdowson	The Deccan Basalt–Basement Contact: Evidence for a Plume-Head Generated CFBP?

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Poster Session: Thursday, 01 September 2005

*B. C. Christensen	The Evolution of Floreana Island, Galápagos Archipelago II: The Result of a Contaminated Mantle Plume
C. Class	Evolution of Helium Isotopes in the Earth's Mantle
E. I. Demonterova	Inverse Trace Element Modeling of Mantle Components from Late Cenozoic Basalts in Central Asia
M. L. Frezzotti	Fluid Inclusion Evidence for Water in the Mantle Beneath Hawaii
*W. R. Griffin	Testing Magmatic Emplacement Mechanisms in the Balcones Igneous Province of Texas
Withdrawn	The Evolution of Floreana Island, Galápagos Archipelago I: The Result of Upper Mantle Heterogeneities
*Withdrawn	Mantle Redox Conditions in LIPs: Constraints from the North Atlantic Igneous Province
M. J. Hole	Plumes or Rifting?: The Mesozoic Dykes of the Falkland Islands and Their Relationship to the Break-up of Gondwana.
A. V. Ivanov	Pliocene-Quaternary Alkaline Basalts of the Sredinny Ridge of Kamchatka: Evidence for Melting of Recycled Oceanic Crust in Tectonic Setting of a Modern Island Arc System
B. T. Jordan	Communicating the Plume Debate to Undergraduate Geoscience Students
S. Keshav	Re-Os-Pt Partitioning in Sulfur-bearing Solid/Molten Iron Metal at 3-22 GPa and 1300-1775 C: Is the Earth's Outer Core So Giving?
H. Mashima	Recycling of Archean Peridotitic Komatiite in the NW Kyushu Source
*R. Meyer	The Vøring Plateau Volcanic Margin: A Key Rock Succession to Understand Continental Breakup During the Initial Stages of the Opening of the NE-Atlantic
J. Natland	Layered Mantle Alternative to Mantle Plumes: Evidence from the Pacific Plate
S. Sensarma	The Dongargarh Group: A Large Igneous Province at the Archean-Proterozoic Transition in India
F. M. Stuart	Statistical Comparison of 3He/4He Distributions in Mid-Ocean Ridge and Ocean Island Basalts
D. Pandey	Applicability of Large Magma Chambers to Deccan Volcanism: A Numerical Study
J. Tuff	Experimental Constraints on the Role of Garnet Pyroxenite in the Genesis of High-Fe Mantle Plume Derived Melts

* Student

Testing the Plume Hypothesis

I. H. Campbell (Research School of Earth Sciences, The Australian National Univ., Canberra, ACT 0200, Australia; Tel: +61-2-6125-4366; Fax +61-2-61258253; E-mail: Ian.Campbell@anu.edu.au)

The physics of low Reynolds number plumes is well understood, which allows a number of testable predictions to be made about mantle plumes. They are predicted to originate from the core-mantle boundary and consist of a large head, with a diameter of ~1000km, followed by a narrower tail. When the head reaches the top of the mantle it flattens to form a disk with a diameter that is predicted to lie within the range 2000 to 2500km. Initial eruption from a plume head should be preceded by ~1000m of domal uplift. Picrites are expected to dominate the first melting products of a new plume and they should be concentrated near the centre of the volcanic province. All of these predictions are confirmed by observations, which provide strong support for the validity of the mantle plume hypothesis.

The Deep Mantle Plume Hypothesis

W. Jason Morgan (Dept. Earth Planet. Sci., Harvard Univ., 20 Oxford St., Cambridge, MA 02138, USA; Tel: +1-508-720-1509; E-mail: wjmorgan@princeton.edu)

In this talk I present the basic ideas of the plume model. There is not time to back each of these ideas with the supporting evidence -- that should hopefully be given in subsequent talks at this meeting.

(1) Near surface, near the 'rigid' top boundary layer, flow in the mantle has a large-scale 2-D character (mid-ocean ridges, subducting slabs). But away from this rigid layer the flow pattern is more fluid-like; rising columns are dynamically preferred to rising sheets.

(2) Stacey & Loper (1984) presented a model of how a low-density, low-viscosity layer at the base of the mantle would grow instabilities that would lead to a rising plume in the mantle. A consequence of the model is a large burst of rising material when the column reaches the surface (a flood basalt) and the eventual 'death' of a plume when the source layer is 'drained'.

(3) There is large-scale horizontal flow in the asthenosphere, moving material away from 'excesses' of asthenosphere (where a plume impinges) toward deficiencies where lots of lithosphere is made (especially at mid-ocean ridges).

(4) We know the rate asthenosphere is being 'destroyed' (by cooling and attaching itself to lithospheric plates); it equals the rate that lithosphere is being 'destroyed' by subduction at trenches into the deep mantle (~ 250 km3/yr.) How is the asthenosphere replenished at this rate?

(a) Heat conduction upward from deeper mantle, softening the mantle just below? (1/50th too small)

(b) Roll-like (2-D) upwelling of mantle from just below mid-ocean rises?

(c) Brought up by mantle plumes, and spreading out in the asthenosphere?

If (c) occurs, and asthenosphere can easily spread out horizontally beneath the lithosphere, it can 'turn off' the other two modes. The mantle does not have an adiabatic thermal temperature gradient everywhere, the hot material from CMB depths can make the asthenosphere hotter (in a potential temperature sense) than what's below, i.e. make the asthenosphere stable against 'upwelling' beneath the EPR, etc.

(5) The downgoing slabs are continually carrying chemical heterogeneities into the deep mantle (seds, oceanic crust, old oceanic islands, depleted mantle produced when making oceanic crust) on scales of 10 m to 10 km. Mantle convection doesn't completely homogenize these heterogeneities -- the mantle is 'lumpy' on scales of 10 cm to 10 km.

(6) This 'lumpiness' leads to the distinction between OIB and MORB chemistry. The 'easy to melt' lumps, with more of the large-ion incompatible elements in them, melt first as a plume nears the surface. At depths of 150 km to 70 km, these 'plums' are preferentially extracted beneath the hotspots, leaving a residue lacking these 'plums'. This residue

is then the 'Depleted Mantle Material', that after a long horizontal journey becomes the source of MORB's. (The more extensive, shallower melting at mid-ocean rises can melt the remainder left behind after the first-stage of melting.)

The key data supporting this hypothesis are: (1) the predictability in direction and rate of hotspot tracks, (2) the fact flood basalts have similar chemistry to OIB's and the observable ones have age progressive 'tracks' leading away from them, (3) the basic 'age' of OIB's (~1.8 Ga) agrees with the high overturn rate of plume material at ~250 km3/yr, and (4) many specifics of OIB and MORB chemistry are in accord with this model.

The Generation of Melting Anomalies by Plate Tectonic Processes

G. R. Foulger (Dept. Earth Sciences, Univ. of Durham, Durham DH1 3LE, U.K.; Tel: +44-191-386-4533; Fax: +44-191-334-2301; E-mail: g.r.foulger@durham.ac.uk)

Intraplate and on-ridge melting anomalies may result from processes associated with plate tectonics. The key elements of this general theory are:

1. Dehomogenising processes: Fusible components are removed from the mantle at ridges and re-introduced at subduction zones as oceanic crust, which transforms to eclogite at depth. Oceanic and continental lithosphere are metasomatised over time. Thickened continental lithosphere in collision zones may delaminate, and continental lithosphere may erode at the time of continental breakup and be recycled into the convecting upper mantle. These processes result in lateral variations in fusibility, chemistry and temperature in the upper mantle.
2. Processes that cause stress and lithosphere strength to vary: Lithosphere cooling and spatial and temporal variations in plate boundary type, tectonics and configuration result in stress fields that may be extensional in some intraplate regions. The history of continental breakup and re-suturing results in variable lithosphere structure, composition and strength.

In its simplest form, the theory proposes that variability in mantle source fusibility and composition result in variable magmatic productivity. Variations in stress and lithosphere strength control the location of volcanism. The theory predicts that melting anomalies will tend to occur in regions of extensional stress and that where fusible source material is available, melt volumes will tend to be large. The heat needed is, in the first instance, drawn from the upper mantle reservoir, which redistributes its heat through conduction, convection and the advection of melt. Fusible material residing in the upper mantle may melt to a high degree as it approaches ambient upper mantle temperatures. For example, the liquidus of eclogite may be lower than the solidus of peridotite.

There is considerable support for this theory. One third of all "hot spots" lie at or close to spreading plate boundaries and many lie in extensional intraplate regions such as the East African Rift, the Basin & Range Province, and back-arc regions. Many large igneous provinces (LIPs) are formed where continents break up along old suture zones, in particular where three or more branches meet. Much geochemical evidence is consistent with the presence of recycled fusible material in "hot spot" and LIP lavas, including continental crust, subducted oceanic crust, and metasomatised lithosphere.

Predictions of the theory include:

a) the melt volumes observed at "hot spots" and LIPs can be quantitatively modeled by lithosphere extension and source fertility without the need for very high temperatures,
b) the pattern of vertical motion accompanying LIP emplacement may be explained by relatively shallow tectonic processes,
c) the physics of the Earth permits the survival of inhomogeneities in the upper mantle and continental lithosphere that

correspond to the ages of the recycled components found in "hot spot" and LIP lavas,
d) the chronology of volcanism reflects the migration of the locus of extension and the lateral variation in fertility of the source tapped.
e) LIPs are not necessarily associated with time-progressive volcanic chains, and vice versa,
f) seismic tomography images reflect lateral compositional variations and do not indicate temperature variations alone,
g) "hot spot" lavas do not come from sources that are very hot compared with the regional,
h) geochemical observations be reconciled with fertile sources at relatively normal temperatures,
i) high 3He/4He ratios do not require a lower-mantle source,
j) components required to come from the Earth's core do not occur in "hot spot" and LIP lavas.

Continental Magmatism Caused by Lithospheric Rayleigh-Taylor Instabilities

Linda T. Elkins-Tanton (Dept. of Geological Sciences, Brown Univ. 324 Brook St., Providence RI, USA; Tel: +1-401-863-3185; E-mail: Linda_Elkins_Tanton@brown.edu)

Ductile removal of the lithosphere via gravitational Rayleigh-Taylor instability, often referred to as delamination, can produce continental magmatism over a range of eruptive volumes, major and trace element compositions, volatile contents, and accompanying topographic expressions. We investigate the process of gravitational instability using numerical experiments, and find that the process can produce a heterogeneous, locally hydrous upper mantle, as well as short-duration eruptive episodes of hydrous, alkali-rich magmas in the absence of subduction, subsidence during eruption, and shallow, dry melting under cratonic lithosphere. Within certain ranges of lithospheric thicknesses, instability sizes, and mantle potential temperatures, magmatic production can reach the scale of a large igneous province.

Loss of the lower lithosphere has been inferred from increases in crustal heat flow and seismic tomography in specific regions, from rapid regional uplift, and from the appearance of signature high-potassium magmas. A dense lower-lithospheric region may develop through melt injection and transformation into eclogitic phase assemblages, or through thickening and cooling of a lithospheric root, or through accumulation of mafic phases in magma chambers. Lower crustal and mantle compositions that result from arc magmatism are likely to exceed the mantle density by 50 to 250 kg/m3, which corresponds to about 1 to 5% density contrast. Given low enough viscosity, a density contrast as small as 1% is sufficient to drive a gravitational Rayleigh-Taylor instability.

When the Rayleigh-Taylor instability beings to sink it can pull the lithosphere downward through viscous traction as asthenosphere flows inward along the base of the lithosphere and down along the sides of the instability. In this phase asthenosphere may melt adiabatically as it rises into the space previously occupied by the unstable lithospheric material. If the instability contains volatiles, it may lose them as it sinks to higher pressures and acquires higher temperatures through conductive heating, much as a subducting slab does. Volatile content may this trigger melting in the surrounding mantle asthenosphere, or in the instability itself.
Lithospheric instabilities may be an important process for recycling crustal material and volatiles into the mantle, second only to arcs on Earth, and potentially the most important lithospheric process on other terrestrial planets for recycling. Loss of the lower lithosphere, possibly including crustal material, has been suggested by other researchers as the trigger for magmatism in many terrestrial settings, including the southern Sierra Nevada, the Tibetan Plateau, the Altiplano/Puna region, the Leucite Hills in Wyoming, Central Italy, eastern Anatolia, and the Dabie Shan. We further apply this

model to the Siberian flood basalts, to explain both the initial subsidence during the first kilometer of eruption and the volatile content of the final lavas, though we also present results from experimental petrology that the final magmas were formed from mantle material hotter than the range commonly cited for oceanic mantle.

Cracks and Warps in the Lithosphere From Thermal Contraction

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New marine gravity maps, based on retracked radar waveforms of ERS-1 and Geosat, show that linear volcanic ridges are widespread in the deep ocean basins, especially on seafloor that formed at higher spreading rate (full rate > 60 mm/yr). In the eastern Pacific, the ridges are geometrically associated with the development of 150-km wavelength lineaments in the gravity field. Proposed models for both the ridges and gravity lineaments include small-scale convective rolls, extension of the lithosphere, thermal contraction, and asthenospheric return flow in channels. Small-scale convection predicts ridges on the crests of the gravity lineaments, which is in conflict with observations. Plate tectonic models show that extension of the Pacific plate is insufficient to produce gravity lineaments by a boudinage mechanism although the morphology of the ridges seems to require extension. Cooling and contraction of the lithosphere can explain both the origin of the ridges and the gravity lineaments. Top-down cooling of the lithosphere produces two modes of thermoelastic stress - extension parallel to the ridge axis and concave - down thermal bending stress. The thermal bending stress is optimally released by lithospheric flexure between regularly spaced parallel cracks. The pull of subducting slabs around the Pacific plate may trigger the cracking which is amplified by thermoelastic flexure. These cracks provide conduits for the generation of volcanic ridges.

Mantle Convection - An Overview

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I will present an overview of mantle convection, trying to emphasise aspects that have a bearing on the plume debate. I will start by presenting the general physics that controls mantle convection and mention some simplifying assumptions that are sometimes made. I will follow that by briefly discussing the mantle's structure, and how the values of critical parameters are likely to vary with temperature and through the depth of the mantle, and their uncertainties.

With this background we will go to through a sequence of models, starting with the simplest model of mantle convection to explain the concept of thermal boundary layers, before advancing through more complex examples that show the importance of various properties. Some properties I hope to consider include the effect of the geometry of models (2D v 3D; spherical v Cartesian), the vigour of convection, surface velocity boundary conditions and the importance of plates, the mode of heating (internal v bottom), the introduction of chemical heterogeneity, the effect of phase transitions, compressibility, and temperature and depth dependent viscosity, thermal expansivity and thermal conductivity.

We will briefly touch upon simple plume theory, plume heads and 'non-lower boundary layer' convection means of producing 'plumes', e.g. lithosphere instabilities, edge convection, splash plumes, slab breakoff etc.

I will then consider what mantle properties might be required to prevent the formation of deep plumes. I will emphasise the uncertainty in many parameter values, and that Earth is a Heat Engine outputting ~ 44TW heat. There are two issues regarding this - (i) the mantle needs to produce a large amount of heat internally (and we know that the MORB source region's contribution is very low) (ii) how is this heat transported from the interior to the surface? The obvious means to prevent the generation of deep plumes is to have a very viscous lower mantle, with high thermal conductivity and low thermal expansivity – current work suggests that mantle properties have these trends. Whether the likely values can prevent plume formation though is unknown. If the lower mantle or core is a significant source of the surface heat flow it is likely that such a lower mantle could not transport heat sufficiently quickly by conduction or sluggish flow to (a) stay sufficiently cool to maintain its high viscosity etc, and prevent melting; and (b) to provide the heat flow observed at the surface. Therefore it is likely that a deep layer that would not produce plumes would probably need to also have a low level of heat generation and a cool core. It would also be important that the subducting surface layer does not enter the lower layer in any significant way, since this is also likely to lead to the formation of upwellings.

We will conclude by emphasising that - (i) the mantle is a heat engine that needs to transport a lot of heat, (ii) some of this flow must be by upwellings which in most models to date assume a cylindrical form, (iii) but there is still a lot of uncertainty regarding parameters, and limitations with modelling (numerical and laboratory).

Generation and Evolution of Plumes in Mantle-Relevant Scenarios

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Plumes originate as convective instabilities from thermal boundary layers within the Earth's mantle. The most prominent boundary layers are the 670km discontinuity and the Core-mantle boundary at 2900 km depth. The fluid dynamics of plumes, i.e. their spatiotemporal evolution and their transport properties are only understood under conditions which are oversimplified, as compared to the mantle. Laboratory experiments can hardly take into account features which can critically influence the formation and evolution of plumes. Mantle convection is likely to be partially powered by internal radioactive heat sources. Further, the viscosity of the mantle material is known to strongly depend on temperature and pressure. Also there is clear evidence for a decrease of the coefficient of thermal expansivity with increasing pressure throughout the mantle. All those effects have an effect on the generation and the evolution of plumes. By means of numerical experiments we investigate the plume evolution in different mantle-relevant scenarios. It is demonstrated that plumes do not exist in purely internally heated convection.as long as constant material properties are assumed. A viscosity, increasing with pressure and/or a coefficient of thermal expansion decreasing with pressure leads to a focusing of buoyancy into a few strong plumes. Such, even in internally heated systems, plume instabilities do evolve. A strong temperature dependence of the viscosity leads to episodic plumes. Initially a massive plume heads develops and travels upwards. Subsequentla,y pulses of hot material can rise through the established low viscosity channel. Plumes evolving selfconsistenly from a thermal boundary layer, do hardly entrain material during their ascent. Instead they transport mostly material from the boundary layer.

On the Motion of Hawaii and Other Mantle Plumes

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Paleomagnetic analyses conducted during Ocean Drilling Program (ODP) Leg 197 (Tarduno et al., 2003), studies of plate circuits (e.g. Cande et al., 1995) and geodynamic modeling results (e.g. Steinberger and O'Connell, 1998) have all pointed toward motion of the Hawaiian hotspot during formation of the Emperor Seamounts, between 81 and 47 Ma. The recognition of hotspot motion from paleomagnetic data follows work that has demonstrated that prior Pacific apparent polar wander paths fail internal consistency tests and that the physical processes derived from these paths, including rates of true polar wander, are untenable. The failure of prior Pacific APWPs can be traced to an over-reliance on remote sensing data (modeling of seamount anomalies and marine magnetic anomaly skewness), and an under-appreciation of the inherent limitations of such data. Recent attempts to systematically change the age of hotspots, their positions and the data used to compare the Pacific and Indo-Atlantic realms (Gordon, 2005) are ad hoc extensions of the fixed hotspot model. The relevant questions today include the scale of mantle flow recorded by hotspot track segments, the underlying processes that cause track segments to be dominated by mantle flow rather than plate motion for given time intervals, and what these factors tell us about the nature of plumes. A first-order consistency between the Hawaiian-Emperor and Louisville tracks argues for a Pacific-basin wide component of mantle flow. However the mismatch between these two tracks and central Pacific hotspot tracks indicates that smaller scale shallow processes must also be at work. Some efforts to model the observational constraints indicating motion of the Hawaiian hotspot highlight the early history of the plume, and its rise through the mantle. Although the initiation age of the Hawaiian hotspot is unknown, rapid motion followed the dated initiation of the New England and Tristan hotspots. This lends some support to the idea that hotspots can move rapidly while new plume conduits adjust to the convecting mantle.

The Plume Head - Continental Lithosphere Interaction Using a Tectonically Realistic Formulation for the Lithosphere

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Debates on the existence of mantle plumes largely originate from interpretations of supposed signatures of plume-induced surface topography that are compared with predictions of hydrodynamic models of plume-lithosphere interactions. Yet, these models are not really well suited for prediction of surface evolution: in general, they assume a fixed upper surface and a single layer viscous lithosphere. In nature, the surface evolution is conditioned by elastic - brittle - ductile deformation, by free upper surface and by layered structure of the lithosphere. We attempt to reconcile mantle- and tectonic-scale studies by introducing a tectonically realistic continental plate model in large-scale plume-lithosphere interaction. The model includes (1) a free surface boundary condition, (2) an explicit elastic-viscous (ductile)-plastic (brittle) rheology and (3) a stratified structure of continental lithosphere. The numerical experiments demonstrate important differences from predictions of conventional models. In particular, this relates to plate bending, mechanical decoupling of crustal and mantle layers (followed by lateral crustal flow) and tension-compression instabilities, which produce transient topographic signatures such as uplift and subsidence at large (> 500 km) and small horizontal scale (300-400 km, 200-300 km and 50-100 km). The mantle plumes do not necessarily produce detectable long-wavelength topographic highs but often generate alternating smaller-scale surface features that could be otherwise attributed to regional tectonics. A single long-wavelength domal uplift, predicted by conventional models, develops only for a very cold and thick lithospheres. Distinct topographic wavelengths or temporarily spaced events observed in the East African Rift system, as well as over French Massif Central, can be explained by a single plume impinging at the base of the continental lithosphere, without evoking complex asthenospheric upwelling.

How Many Hotspots Can be Explained by Edge Driven Convection?

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Fluid near a vertical wall of uniform temperature is dynamically unstable and this geometry will drive small-scale convection near the wall. This is the key element of the edge driven convection mechanism. Continent-ocean and craton boundaries are ideal locations for this form of small scale convection. Because the 660-km discontinuity is an effective barrier to short-wavelength flow; and because convective instabilities form nearly unit aspect ratio cells, hotspots within 600-1,000 km of a continent-ocean or craton boundary are prime candidates for edge driven convection. The lifetime of edge driven instabilities depends on the stability of the cratonic root. The most unique diagnostic for edge driven convection is imaging the downwelling limb of the edge driven convection cell. Because this is an upper mantle instability edge-driven convection would more strongly impact the 410-km discontinuity and may have little impact on the 660-km discontinuity. Edge driven convection does not explain long linear island chains or oceanic hotspots thousands of kilometers from a continent.

Formation of Volcanic Rifted Margins: Influence of the Pre-Rift Lithosphere Architecture

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It is known that continental rifting tends to follow weak zones in the lithosphere, such as orogenic belts, while stronger cratonic regions are usually not significantly deformed. For example, in the northern North Atlantic, rifting occurred along the Caledonian belt, and in eastern Africa, the East African Rift System is located within a Late Proterozoic belt. We think that such a pre-structured lithopshere not only influences the location of rifting, but that the inherited lithosphere architecture plays a role in the rifting process itself. To study the role of a pre-structured lithosphere in rifting and (volcanic) passive margin formation we use a numerical modeling approach. Our models are designed to simulate Atlantic-type passive margin formation.

Results from numerical experiments suggest that the old structures not only influence the location of rifting, but also lithosphere deformation during rifting, the thermal evolution of the lithosphere, and thus decompressional melting. The amount, timing and distribution of decompressional melting are influenced by factors such as pre-rift crustal or lithosphere thickness, orientation of inherited structures, and lithosphere composition. The modeling results suggest that a mantle plume is not a pre-requisite to form a volcanic rifted margin; dynamic processes related to lithosphere extension can explain the sometimes enigmatic amounts of melt observed at Atlantic-type passive margins.

Hawaii Volcano Chain as a Thermoelastically-driven Propagating Crack

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Lithosphere crack models for the Hawaii-Emperor volcano chain require a horizontal extensional stress normal to the volcano chain for the crack tip (Hawaii) to propagate to the southeast. We calculate the 3D thermoelastic stress rate field for a model Pacific plate lithosphere and find that horizontal tensional stress occurs normal to the entire Hawaii chain, but not beyond Hawaii to the southeast. In the model, the actual Pacific plate geometry is represented by a fragment of a spherical elastic shell with simplified lateral boundaries. The stress field is a consequence of cooling of Pacific plate material accreted at the East Pacific Rise and its precedents, and the current 3D temperature field is inferred from the seafloor age (Mueller et el., JGR, 1997).

The general horizontal stress pattern across the plate from the East Pacific Rise spreading boundary (southeast) to the Aleutian-Japan subduction boundary (northwest) is tension near the rise, then compression to midplate, and extension throughout the rest. Strong extension also occurs near Samoa where the plate boundary is a stress-concentrating notch. The thermoelastic model implies that the plate stress field and a feature dependent on it are approximately stationary with respect to the plate boundary reference frame. Thus, if part of the Hawaii section of the Hawaii-Emperor chain is equivalent to a vertical tensile crack, the southeast crack tip holds a fixed position with respect to the plate boundary. As the Pacific plate moves northwest through the stress field, the crack extends an equal distance to the southeast. In short, a nearly circular oceanic plate with spreading at one edge and subduction at the opposite edge will have a stress field favorable to tension cracks located near midplate and oriented in the plate velocity direction.

Sunday Poster Session

Testing Thermal Whole Mantle Plumes Seismically

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To prove or disprove the existence of plumes, clearly formulated hypotheses that can be tested against data are required. We set up two seismic tests for the simplest hypothesis of thermal, whole mantle plumes. If a thermal boundary layer exists at the base of the mantle and is not completely stabilized chemically, such upwellings should form.

Our first test checks whether the 1D structure of single layer thermally convecting mantle (pyrolitic with phase transitions, following a mantle adiabat between 300 and 2500 km depth) is compatible with global travel-time and mode-frequency data. We find that, in spite of the large uncertainties in the elastic and anelastic mineral physics data required to convert physical into seismic structure, the single-layer convection structure is difficult to reconcile with the seismic data. The seismic data prefer a slower transition zone and a slower deep mantle. This could be an indication of compositional heterogeneity in the deep mantle, which would also affect plume generation.

For the second test, we made a set of dynamically self-consistent thermal plume models with parameters that are Earthlike and compatible with observations. The temperature contrast of the basal boundary layer is chosen to yield sublithospheric plume temperature anomalies between 100 and 300K. The resulting plumes are weak and slow to form, yet they all have buoyancy fluxes larger than the the strongest hotspots. Their seismic anomaly amplitudes (strong in upper mantle, but only 1-1.5% in Vs in lower mantle) and widths (500-800 km wide in the lower mantle) are compatible with surface and seismic observations. Very strongly temperature-, and depth-dependent viscosity yields the narrowest and lowest buoyancy flux plumes, but induces sublithospheric small-scale convection which may complicate the plume's surface signature.

How Geometry and Ages of Global Hotspots are Explained by Classical Hypotheses of Rigid Plate and Fixed Hotspot

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Since J. Tuzo Wilson and W. Jason Morgan's hypothesis of moving rigid plate over fixed hotspots, quite a few geological and geophysical observations were well explained by the theory for more than thirty years. But over the last decade, there are increasing arguments on discrepancies between the classical theory and observations, and those are, they say, caused by intra-plate deformations and/or plume drift. Here we would like to point out that those discrepancies will disappear for the most part if we apply accurate models of absolute plate motions. We show new technique of constructing models of absolute plate motions, and how geometrical positions and radiometric ages of global hotspots are consistent with the two conventional assumptions. Also we analyzed global paleomagnetic data and found no significant relative motions betweenthe Pacific group of hotspots and the African group of hotspots detected. We revised the model of True Polar Wander Path and suggest that the southward paleolatitude shift of Hawaiian hotspot (Tarduno et al., 2003) is not caused by the plume drift but by the True Polar Wander.

Plume-fed Asthenosphere Flow Model: Evidence from Isotopic Variation Along Mid-ocean Ridges

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Asthenosphere plume-to-ridge flow has often been proposed to explain both the existence of geochemical anomalies at the mid-ocean ridge segments nearest an off-axis hotspot, and the existence of apparent geochemical 'provinces' within the global mid-ocean spreading system. We have constructed a thin-spherical-shell finite element model to explore the possible structure of global asthenosphere flow and to determine whether plume-fed asthenosphere flow is compatible with present-day geochemical and seismic observations. In this model, lubrication theory approximations are used to solve for the flow profile in the vertical direction, and a ~100-km-scale mesh is used to solve for the mean horizontal asthenosphere flow. Asthenosphere is assumed to be brought up by mantle plumes, with 'sinks' of asthenosphere at spreading centers where compositional lithosphere is made, at trenches (where some, but not much asthenosphere is entrained and dragged down by subducting lithosphere), and also a

distributed sink of asthenosphere due to its cooling and attachment to the base of the aging and thickening oceanic lithosphere. We also assume that the strength of all the plume (hotspot) asthenosphere sources is equal to the sum of all the asthenosphere sinks, i.e. that the asthenosphere has a present-day steady-state thickness and hotspot fluxes have remained constant through time. In spite of these evident oversimplifications, the model appears to show considerable promise as a possible mechanism to explain observed patterns of MOR geochemical segmentation. This specific prediction lends support to the plume theory and plume-fed asthenosphere model proposed by Phipps Morgan et al., JGR, 1995.

Slab Dehydration, Subcontinental Lithosphere Thinning and Widespread Mesozoic/Cenozoic Volcanism in Eastern China: A Special Consequence of Plate Tectonics

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Subcontinental lithosphere "delamination" and the widespread Mesozoic/Cenozoic intra-plate basaltic volcanism in eastern China have been widely speculated as resulting from ascending hot mantle plumes or large scale lithospheric extension. We argue that the Mesozoic/Cenozoic Earth events in eastern China is a special consequence of plate tectonics [1]. The Mesozoic lithosphere thinning in eastern China results from "transformation" of the basal portion of the lithosphere into asthenosphere by hydration. The water that did so came from dehydration of subducted Pacific (or predecessor) oceanic lithosphere that is lying horizontally in the transition zone beneath eastern Chinese continent as detected by seismic tomographic models [2]. The Mesozoic volcanism may be genetically associated with the lithospheric thinning because the basaltic source is ancient isotopically enriched [3] lithosphere - being converted to the asthenosphere. The NNE-SSW Great Gradient Line (GGL) marked by the sharp altitude, gravity anomaly, crustal thickness, and mantle seismic velocity changes from the plateau in the west to the hilly plains of eastern China is an expression of variation in lithospheric thickness from probably > 150-200 km thick beneath the plateaus in the west to the thin, probably < 80 km thick, beneath eastern China. The "remote" western Pacific subduction systems ("wedge suction"[1]) induce asthenospheric flow from beneath eastern China towards the subduction zones, which, in turn, requires asthenospheric material replenishment from beneath the western plateaus to eastern China. As a result, such eastward asthenospheric flow experiences upwelling and decompression (from beneath thickened to thinned lithosphere), which causes the flowing asthenosphere (isotopically depleted) [3] to melt and produce Cenozoic eastern China basaltic volcanism. Such volcanism may have actually begun in the late Cretaceous [4]. Our proposed mechanism of lithosphere thinning (1) does not require hot mantle plumes that may have not existed beneath eastern China; the horizontally-lain transition-zone slabs act as a cold thermal boundary layer that sucks heat from above and below, thus preventing hot mantle plumes to rise from the lower mantle and to form in the upper mantle; (2) does not require lithospheric "delamination", which describes that deep portions of the buoyant cratonic lithosphere sink into the dense asthenosphere – a scenario that is physically difficult; (3) does not require lithospheric extension/stretching whose existence and scale in the Mesozoic remain elusive; (4) explains the lithosphere thinning in the entire eastern China, not just the North China Craton (NCC); and thus (5) questions the significance of South China continental subduction as a cause of lithosphere

thinning beneath the NCC. Our suggested mechanisms for the Mesozoic/Cenozoic volcanism in eastern China are consistent with the geochemistry of the basalts [3], physical scenarios of mantle melting [1] and geophysical observations [1,2]. These principles and observations (1) disfavor the suggestion of hot mantle plume origin of eastern China volcanism; (2) disfavor the suggestion of ocean ridge-like passive mantle upwelling and decompression melting; and (3) argue that the eastern China Mesozoic/Cenozoic basins cannot be used as evidence for continental extension; the basins may very well be an isostatic response [1] to the horizontally-lain dense slab materials in the transition zone. It is also important to note: (1) the GGL is likely a young feature as a result of Indo-Asian collision since the early Tertiary; (2) subduction-zone dehydration is necessarily incomplete [1,5] (lawsonite, which can contain ~ 11 wt % water, is stable up to 11 GPa [6]; serpentines within the oceanic lithospheric mantle [5] contains up to 13 wt % water, and is stable up to 7 GPa [7] before transformed to dense hydrous magnesium silicate phases at much greater pressures of ~ 5 to 50 GPa [6,8]), thus allowing slab water release at great depths at elevated temperatures (e.g., isobaric heating of the slabs in the transition zone) [1,5]; (3) mantle wedge suction [1], while less strong than ridge suction [9], is an important driving force for asthenospheric flow; and (4) the suggestion of more recent lithosphere accretion beneath eastern China is in fact a straightforward consequence of conductive cooling of the asthenospheric mantle.
References: [1] Niu, Y., Geol. J. China Univ., 11, 9-46, 2005; [2] Kárason, H. & R. van der Hilst, Geophys. Monogr., 121, 277-288, 2000; [3] Xu, Y.-G., Phys. Chem. Earth (A), 26, 747-757, 2001; [4] Yan, J., J.-F. Chen, Z. Xie & T.-X. Zhou, Chinese Sci. Bull., 8, 1570-1574, 2003; [5] Niu, Y., J. Petrol., 45, 2423-2458, 2004; [6] Williams, Q. & R.J. Hemley, An. Rev. Earth Planet. Sci., 29, 365–418, 2001; [7] Ulmer, P. & V. Trommsdorff, Science, 268, 858-861, 1995; [8] Frost, D.J., Geochem. Soc. Spec. Publ., 6, 283-297, 1999; [9] Niu, Y. & R. Hékinian, In Oceanic Hotspots, Springer-Verlag, New York, p. 257-279, 2004.

Late Mesozoic Through Cenozoic Magmatism in East Asia: Effect of Directly and Obliquely Subducted Slab Flexures

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Mesozoic through Cenozoic evolution of East Asia was related traditionally to plate motions in Pacific Ocean and marginal seas. After Molnar and Tapponnier's rejuvenation of the hypothesis by Argand on influence of the India-Asian collision on seismic activity and deformations in Inner Asia, numerous multi-disciplinary studies supported this point. The collisional hypothesis became dominating in explanations of tectonics not only in Inner Asia but also at the Eurasia-Pacific convergent zone. In the early 1990-th, the plume hypothesis was applied for explanation of volcanic activity in some areas of East and Central Asia. It was speculated also that diffused intraplate Cenozoic volcanism was produced by a broad asthenospheric upwelling from a deeper level ("hot region") (Tatsumi et al., 1990) or by convective flow ascending from the core-mantle boundary (Zonenshain et al., 1991). Studies of the last decade showed that Cenozoic rifting and magmatism in this area was due to combined effects of (1) generation of low-velocity sub-lithospheric mantle, (2) collisional events at plate boundaries, and (3) subduction of oceanic plates beneath a continent (Rasskazov et al., 1998). A high-velocity anomaly - "the stagnated slab" - at the mantle transitional zone (Fukao et al., 1992) and the low-velocity Transbaikal mantle domain at depth of 200-350 km (Rasskazov et al., 2003) were well recognized thomographically. The anomalous mantle region was suggested to be a time-integrated expression of subduction processes (Rasskazov et al., 2004). The aim of this presentation is to show spatial-temporal regularities of the Late Mesozoic through Cenozoic magmatism evolution which is indicative for formation of the high-velocity and low-velocity material. The latter could be stored firstly during closing of the Mongolia-Okhotsk Ocean finalized at ca. 140 Ma. After terrane accretion and structural reorganization at 113-107 Ma, subduction of the Kula-Izanagi plate defined the northern margin of the anomalous mantle region. Low-velocity anomalies extended from a continental margin landward over 1000 km beneath the Aldan shield of the Siberian craton. The structural reorganization between 65 and 50 Ma took place contemporaneously with accretion of the Okhotsk Sea plate to Eurasia. Block rotations and extension at the continental margin were accompanied by formation of the oblique Sikhote Alin slab flexure of the Pacific plate. Afterwards, the slab flexure was widening to the south due to landward growing of the directly subducted Honshu-Khingan slab fragment. The latter resulted in development of the southern margin of the anomalous mantle region. The structural reorganization between 21 and 15 Ma was coeval to accretion of the Philippine Sea plate to Eurasia with formation of the Japan-Korea oblique slab flexure, trench rolling-back effect, block rotations, and extension at the continental margin. The present-day subduction activity of the Pacific slab is focused at the oblique Japan-Korea and direct Hokkaido-Amur flexures.

Fracture Propagation on a Sphere: Implications for Non-Plume Origin of Large Igneous Provinces on Fragmenting Supercontinents

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Gondwanan and Rodinian fractures and associated large igneous provinces define geometrically regular, energy-minimizing arrays of interspersed hexagons and pentagons. The arrays fit the spherical projection of the truncated icosahedron, for which each edge-length subtends 23 degrees of great-circle arc. Lithospheric fractures and giant dike swarms follow the edges of the tessellations, while large igneous provinces and intracratonic basins occupy the vertices. The tessellated distribution of these large igneous provinces abjures impingement of randomly-dispersed mantle plumes for their origins.

Analogous fracture tessellations spontaneously propagate in a thin, spherical shell under uniform layer-parallel tension. A master fracture initiates at a weak point and zig-zags across the shell, spontaneously bending at approximately 120 degrees as it propagates. Secondary fractures branch outward from the bends to establish triple junctions. The secondary fractures then zig-zag and branch as they propagate, eventually forming a tessellated network of fractures and tiles.

The Gondwanan and Rodinian fracture tessellations propagated after formation and stagnation of supercontinents. Thermal expansion of insulated asthenosphere beneath the supercontinents may have generated homogenous, layer-parallel tension within the lithosphere. Separation of the tiles drove decompression melting and opened avenues for eruption of basalt from the asthenosphere. Large igneous provinces preferentially erupted at triple junctions because of greater local pressure relief. These diachronous eruptions were secondary and depended on the ability of the tiles to separate, controlled by plate boundary conditions.

Neoproterozoic Anorogenic Magmatism Associated with Rodinia Breakup: Not a Result of Mantle Superplume

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The splitting of Rodinia supercontinent at 750 Ma led to the development of new ocean floor, and cratonic fragmentation, which ultimately resulted intraplate anorogenic rift magmatism on the northwestern Indian shield, Madagascar, Seychelles, Australia, central and southern Appalachians and other landmasses.

The anorogenic bimodal Malani volcano-plutonic province (750 Ma) is spread over approximately 50,000 km2 in western Rajasthan, India. Besides this, equivalent to Malani is reported from Sind Province of Pakistan, Kutch, Madagascar, south China and Seychelles. The Neoproterozoic Malani anorogenic magmatic province of northwestern India is an example of Silicic Large Igneous Province (SLIP) development at a time of Rodinia break-up. The Malani magmatism is generally of terrestrial in origin. The volcanism resulted minor initial basalt flows, ignimbrite eruptions, rhyolite flows and ash fall eruptions through multiple fissure/rift systems that developed in the intraplate extensional tectonic setting. This was followed by A-type granite plutonism and terminal felsic/silicic dykes.

The ultimate causes and controls of continental rifting and associated anorogenic magmatism remain controversial questions amongst the earth scientists. It is postulated that wide spread magmatism and continental breakup is a result of impingement of hypothetical deep mantle super plumes beneath Rodinia. It is hypothesized that abnormally hot mantle region, having lateral dimensions of 6000-10000 km on the surface, originated from 2900 km deep near core-mantle boundary caused cracking and disintegration of Rodinia supercontinent at 750 Ma. However deep-mantle plume paradigm is seriously questioned and several alternate models are proposed to explain large scale magmatism and continental fragmentation. Geodynamicists assert that the endothermic phase boundary at 660-km depth isolates lower and upper mantle convection, and that propagation of lithospheric cracks triggers anorogenic magmatism through decompression melting of ordinary asthenosphere. Similarly, elucidates a top-down tectonic viewpoint, in which a stagnant supercontinent insulates the underlying mantle, leading to thermal expansion, partial melting resulting anorogenic magmatism along propagating rift zones. The amalgamation of Rodinia continent marks the end of orogenic accretion processes during Neoproterozoic time on the earth crust. The crust became thick and remained insulated for prolonged time. This caused increase of thermal gradient and lithospheric extension and Rodinia breakup, which ultimately led to silicic magma generation from the melting of crustal region. The Rodinia breakup resulted Neoproterozoic anorogenic magmatism on most of the landmasses.

Are the Precambrian Magma Chambers Responsible for the Cretaceous Deccan Trap Volcanism of India?

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We propose a genetic relationship between 65-68 Ma old Deccan volcanic province (DVP), extensional tectonism and several episodes of Precambrian magmatism. The model is compatible with regional tectonics and provides a plausible explanation of the spatial coincidence of the DVP with Precambrian West Coast and Son-Narmada rift zones. Plume theory and other alternative theories proposed for DVP so far ignore two factors (1) Reasons behind the selective spatial distribution of DVP along the West Coast and Son-Narmada rifts (2) Effect of geological past and the intra-continental stresses of the peninsular India on the DVP. Our theory takes into account these factors and shows that it is the geodynamical evolution of the host and the resultant stress vectors, which paved the way for the genesis of large igneous province of DVP.

The proposed concept involves two stages of geological evolution of the Indian peninsula which led to the genesis of DVP. The brief of postulated activities in each stage is given below.

Stage 1: 1. Due to intra-continental stresses, continental stretching along the West Coast deep crustal fault in peninsular India; 2. Decompression melting and magma generation in the upper lithospheric mantle below the West Coast fault; 3. Magma eruption where the plumbing system was available and Magma ponding where plumbing system was not available; 4. This phenomena continued for almost 350 Ma i.e. 460 Ma to 90 Ma.

Stage 2: 5. Progressive continental stretching for almost 350 Ma resulted in continental scale rifting around 90 Ma when Madagascar separated from India; 6. The magma, which was solidified in the chambers, heated up due to two factors (a) decompress ional melting; and (b) lowering of the solidus temperature by the addition of continental crust impurities to the system; 7. Temperature of around of 800-900oC was reached in those magma chambers which were affected by the breakup due to their location; 8. Rhyolitic magma was produced by fractional melting and felsic volcanism took place in India and Madagascar; 9. From 90 to 65 Ma, continental scale rifting between India and Seychelles progressed and corresponding advancement in magma melting resulted in chambers located beneath the affected region; 10. At 65 Ma, continental scale rifting between India-Seychelles resulted in enhancing the temperature for the magma stored in chambers due to factors mentioned in point 6; 11. Stored volume of magma melted and due to availability of plumbing ways through the West Coast fault erupted mostly along the west coast of India and partly flowed towards another adjacent weak zone of Son-Narmada rift 12. The huge volume of this Deccan volcanism is due to large amount of magma stored in the chambers which were located beneath India-Seychelles rift zone.

Large LIPs and the Mantle Squeeze: A Mass Balance Approach to Hotspots

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I propose a new simplified thermodynamic mantle model coupled with tectonic reconstructions that provides a possible non-plume alternative to the predicted large scale doming, flood volcanism preceded by uplift, and slightly hotter mantle temperatures of the plume hypothesis. The model indicates that mantle temperature rise and large volumes of melt can be produced as a result of overpressuring mantle material trapped between the 440 km transition zone, ringed subduction zones, capping continents, and/or advancing cratonic roots behind regressing slabs. The amount of melt, the degree of doming prior to magma emplacement, and the relationship to tectonic structures are determined by the following variables; the rate and volume of mantle overpressuring, external tectonic forcing mechanisms (slab-roll back, number and magnitude of plate driving forces), thickness of the lithosphere, and the degree of penetration of the 440/660 transition zones by subducting slabs.

While this is an early model and may not apply to all instances of large igneous province (LIP) emplacement, it explains much of the variation observed. For example, the Afar 'hotspot' may be explained by a large volume of mantle material compressed between the slab as it rolls back and the cold, deep cratonic root of Africa. As the mantle is squeezed it may warm and rise creating a large dome at the thinnest point in the lithosphere, the African-Arabian suture. The same collision that is overpressuring the mantle also exerts pressure on the continent, causing longitudinal splitting along the weak African-Arabian suture and the African plate. In this case, doming precedes rifting and continental rifting merely enhances the decompression melting of the overpressured mantle. However, in other cases (e.g. Central Atlantic Magmatic Province) rifting may precede uplift and doming depending on the forces acting on the plates, including the pressure of the mantle on the cratonic roots and/or subducting slabs. This model, along with the multitude of other non-plume models, suggests that plumes may be the exception rather than the rule when it comes to generating voluminous melts.

Mantle Convection - Plumes Rooted in Mid-Mantle

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I have discovered a new class of thermal upwellings in mantle convection simulations. They are not rooted in thermal boundary layers, but at varying depths in the mantle.

These are high resolution, Earth-like vigour thermal convection calculations in three-dimensional spherical geometry. The models are for compressible convection, with decreasing coefficient of thermal expansion with depth, as observed in experiments. The models have ~ chondritic rates of internal heating; and varying bottom heating that straddle estimated Earth values. Some of the models have included transition zone phase transitions. The models have depth dependent viscosity; with a viscous lithosphere and a lower mantle approximately 40 times more viscous than the upper mantle. The plate motion history of the past 120Myrs is applied as a surface velocity boundary condition.

I find passive localised and shallow upwellings are generated beneath the spreading ridges. The planform of downwellings is linear at the surface and become cylindrical as they descend into the mantle. Similarly upwellings at the base of the mantle start linearly but become more cylindrical rising from the junctions of the linear features. In the simulations described here these features are rare and weak.

There are also upwellings that are not rooted at the base of the mantle.They develop as follows. Regions which have not suffered recent subduction become hotter than average and tend to form sheets that rise passively and slowly. Downwellings from the surface fall onto the sheets and make them into bowls as the hot material is forced up around the sides. The rims of the bowls can become unstable producing cylindrical upwellings (plumes). Since they look a bit like water droplet splashes, I have abbreviated 'plumes not rooted in thermal boundary layers' as 'splash plumes'. The splash plumes originate at a range of depths. In fact the downwellings can push the sheets all the way to the core mantle boundary in certain cases where it is then difficult to tell splash plumes from 'traditional plumes'.

The best test for splash plumes will be seismic imaging. Their thin plumes and narrow bowls very near fast downwellings will require high resolution. These 'plumes' also have implications for fixity, temperature contrast, and lifespan which can all be tested.

The Many Potential Faces of Buoyant Mantle Upwellings: Diversity Within the Plume Family

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A focal point of the great plume debate seems to be the large headed, small tailed variety of buoyant mantle upwelling in which the plume head is both hot and compositionally homogeneous. Such flow morphologies occur naturally in 2-D and 3-D computer and laboratory models of convection within a temperature-dependent viscous fluid that is heated from below. They are also seen in experiments where a hot, low density-viscosity fluid is injected into a cooler, denser, more viscous ambient fluid. Another common feature of viscous convection experiments are predictions of significant interaction between surface (cool) and basal (hot) boundary layers. Slab-like downwellings tend to sink until they stall at a density interface, which also tend to be regions that support thermal boundary layers (TBLs). One of the more robust observations for the mantle is that lithospheric plates sink deeply into the mantle and that these plates are compositionally heterogeneous, with relatively well-defined upper and lower layers or laminates.

We report on results of 3-D laboratory experiments of convection within a viscous fluid that include, in a simplified manner, aspects of what we think we know about subduction, and how these influence upwellings in a way that may be relevant to the great plume debate. The experiments utilize corn syrup for a working fluid and are designed such that the key dimensionless numbers governing convection and transport fall within ranges (or approach values) that have been suggested for the mantle in the geophysical literature. Thermal convection occurs because the fluid is heated from below and cooled from above. An important feature of these experiments is they include the subduction of compositionally laminated slabs that sink though and ultimately stall and spread within a basal (hot) TBL. Experiments involve either three (2 slab laminates & ambient) or four (2 slab laminates, upper vs. lower ambient fluid layers) distinct chemical reservoirs. Important variables include the isothermal density and viscosity contrasts between the individual slab components and the ambient fluids. Results show a wide variety in upwelling morphologies evolving when such laminated plates are allowed to reside within a basal TBL. A range in morphologies from large-headed, small tailed upwellings to medium headed-medium tailed upwellings are recorded. Upwellings matching the description of the plume in the great plume debate (big, hot, homogeneous heads) are rare. Instead the buoyant upwellings exhibit striking levels of lateral and vertical structure in both composition and temperature. For example, one very common feature is a two-faced upwelling, that is morphologically symmetric about its centerline, but with very different compositions/temperatures on either side of this dividing line. Results from these relatively simple viscous, thermal-chemical convection experiments suggest that if such conditions exist in the mantle, then we can expect a rich diversity in upwelling styles. The commonly depicted, plume that is thermally driven, with a large hot head filled with uniform composition material may in fact be a rare occurrence. Instead upwellings from such polluted TBLs may be more like snowflakes, where no two are expected to be the same. (Warning: Application of these model results to the mantle requires a leap of faith that, among other things, there is a deep mantle TBL, that mantle Raleigh numbers are well above the critical value, that chemically heterogeneous slabs exist and make it into mantle TBLs and that scaling in geophysical fluid dynamics is valid.)

Thermal Structure Beneath Kamchatka and Plume to Arc Magmatism Transition

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The Kamchatka subduction zone is one of the most active seismic and volcanic regions in the world and located in the proximity of the Meiji Guyot mantle plume. We propose a convection model which shows the a hot blob rising from depths grater that 1000 km would change the initial spherical shape into a cylindrical shape deflected near surface by the Pacific plate movement.

Geochemical studies of volcanic rocks in Central Kamchatka show a complex pattern, from basalts of intermediate composition to alkaline basalts of plume type and adakites. Our models suggest that the buoyant plume cannot penetrate the cold subducting slab in order to enrich the mantle wedge and to produce the alkaline plume type basalts. Instead, a gap in the subduction process, likely created by accretion of new terrains, would create an easy way for the hot plume material to enrich the mantle wedge.

The contact between the hot plume and the oceanic plate offshore Kamchatka produces a rejuvenation of the ~ 100 Ma old Pacific plate, the thermal age being ~ 40 Ma. 2D steady state thermal models with such hot incoming slab show that the oceanic crust beneath the active volcanic arc has undergone melting and therefore adakitic volcanism.

Thermal Structure of the Cocos Slab Beneath Southern Mexico and its Relationship with the Arc Volcanism

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Southern Mexico is a very interesting area where the subducting Cocos slab drastically changes its geometry: from a flat slab in Central Mexico to a ~ 45º dip angle beneath Chiapas. Also, the currently active volcanic arc, the modern Chiapanecan volcanic arc, is oblique and situated far inland from the Middle America trench, where the slab depth is ~ 200 km. In contrast, the Central America volcanic arc is parallel to the Middle America trench and the slab depth is ~ 100 km. A 2D steady state thermo-mechanical model explains the calc-alkaline volcanism by high temperature (~ 1300º C) in the mantle wedge just beneath the Central America volcanic arc and strong dehydration (~ 5 wt.%) of the Cocos slab. In contrast, the thermal model for the modern Chiapanecan volcanic arc shows high P-T conditions beneath the coast where the Miocene Chiapanecan extinct arc is present, and is therefore unable to offer a reasonable explanation for the origin of the modern Chiapanecan volcanic arc. We propose a model in which the origin of the modern Chiapanecan volcanic arc is related to the space-time evolution of the Cocos slab in Central Mexico. The initiation of flat subduction in Central Mexico in the middle Miocene would have generated a hot mantle wedge inflow from NW to SE, generating the new modern Chiapanecan volcanic arc. Because of the contact between the hot mantle wedge beneath Chiapas and the proximity of a newly formed cold flat slab, the previous hot mantle wedge in Chiapas became colder in time, finally leading to the extinction of the Miocene Chiapanecan volcanic arc.

The position and the distinct K-alkaline volcanism at El Chichón volcano are proposed to be related to the arrival of the highly serpentinized Tehuantepec Ridge beneath modern Chiapanecan volcanic arc. The deserpentinization of Tehuantepec Ridge would have released significant amounts of water into the overlying mantle, therefore favoring vigorous melting of the mantle wedge and probably of the slab.

Small-scale Convective Instabilities in the Upper Mantle – A Generic Class of Hotspots Linked to Recent Continental Collision in Europe and the Circum-Mediterranean Region

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Many intra-plate hotspots (both continental and oceanic) appear to be associated with short-wavelength convective instabilities (diapirs) within the upper mantle, originating from Transition Zone (410-660 km) depths. We investigate the dynamics of such instabilities and, develop a model for a generic class of hotspots which form in regions of the upper mantle which have experienced recent subduction and continental collision.

Paleocene-Recent volcanism within western and central Europe, which is spatially and temporally linked to the development of a major intra-continental rift system and to domal uplift of Variscan basement massifs, has been attributed to the diapiric upwelling of small-scale, finger-like, convective instabilities from the base of the upper mantle [1]. Evidence for this model comes from the French Massif Central [1], the Eifel province of northern Germany [2] and the Bohemian Massif (Czech Republic) where both local and global seismic tomographic studies indicate the existence of localised zones of mantle upwelling extending to the base of the upper mantle, several hundred km across and up to 100-150 degrees Centigrade hotter than ambient mantle. Short-wavelength uplift of the lithosphere, without associated volcanism, also occurs further north in the UK, Scandinavia and Brittany; this may also be a sign of mantle upwelling.

A fundamental question concerns the relationship between this distinctive (short-wavelength) mode of mantle convection and the development of the Alpine orogenic belt. Beneath Europe and the Mediterranean region the Transition Zone is seismically fast [4] and may, therefore, be cooler than the overlying mantle and also compositionally distinct (containing, for example, a significant component of subducted oceanic crust). It has been argued that the Transition Zone is in fact a "slab graveyard" containing the remnants of subducted Tethyan (or older) oceanic lithosphere [4]. If this is the case, then the upwelling mantle diapirs are unlikely to be driven by either thermal or compositional buoyancy. So what process or processes does drive the mantle upwelling which triggers partial melting?

We evaluate a range of mantle convection models in the context of the regional plate tectonic setting of Europe and constraints provided by both local and seismic tomographic studies. We explore the role of discontinuities in the base of the lithosphere (e.g. Variscan terrane boundaries) and Tertiary lithospheric extension in nucleating diapiric instabilities which may subsequently propagate downwards, producing, "top downwards", small-scale structures which look like plume stems but which may have a totally different origin.

[1] Granet, M., Wilson, M. and Achauer, U. (1995) Imaging a mantle plume beneath the French Massif Central. Earth Planet. Sci. Lett., 136, p. 281-296.
[2] Ritter, J. R. R., Jordan, M., Christensen, U. R. & Achauer, U. R.

(2001) A mantle plume beneath the Eifel volcanic fields, Germany. Earth Planet. Sci. Lett. 186, 7-14.
[3] Wilson, M. & Patterson, R. (2001) Intra-plate magmatism related to hot fingers in the upper mantle: Evidence from the Tertiary-Quaternary volcanic province of western and central Europe. In: R. Ernst & K. Buchan (Editors) Mantle Plumes: Their identification through time. GSA Special Paper 352, pp37-58.
[4] Piromallo, C., Vincent, A. P., Yuen, D. A. & Morelli, A. (2001) Dynamics of the transition zone under Europe inferred from wavelet cross-spectra of seismic tomography. Physics of the Earth and Planetary Interiors, 125, 125-139.

<u>Monday Oral Sessions</u>

The Temperatures of Mantle Plumes

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By using the compositions of whole-rock samples and the Fo contents of olivine phenocrysts it is possible to estimate temperatures in the mantle sources of mafic and ultramafic lavas. The hottest present-day volcanism is on Hawaii where picrites with estimated liquidus temperatures between 1400-1450°C erupted. The lower temperature corresponds to a water content of 0.3-0.4%, the maximum likely in Hawaiian picrites. These eruption temperatures are some100-150 degrees higher than those of the source of MORB: Hawaii, the type example of an active plume, is the hottest of active hot spots.

In the recent past, temperatures were still higher. The 90 Ma old komatiites of Gorgona Island off the coast of Colombia, erupted at temperatures only slightly lower than those of the hottest Hawaiian lavas, but Gorgona picrites erupted at temperatures a little over 1500°C. The trace-element characteristics and the Nd and He isotope compositions of these lavas provide convincing evidence that their parental magmas formed through extreme fractional melting and that their immediate source was anhydrous. In the Archean magmas were still hotter. The most magnesian komatiites contain 30-32% MgO and erupted at temperatures close to 1600°C. We do not accept arguments that common Archean komatiites came from a wet subduction environment (some komatiites did indeed contain a small amount of water but these rocks have unusual compositions and are rare). We attribute the formation of normal komatiites to deep melting in abnormally hot mantle plumes.

Komatiites and the Temperature of the Mantle: “Some like it hot”.

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Archaean komatiites are the highest MgO lavas recorded on the Earth. Two end-member models have been suggested to explain their formation: i) anomalously high temperature, relatively ‘dry’, melting (in mantle plumes?) or ii) by volatile/water induced melting (in subduction zones?). As with modern-day mafic magmas, it is possible that komatiites were generated in both environments; the key problem is to recognise diagnostic characteristics that can be used to determine the environment in which any given komatiites formed.

Field constraints are most important. Many komatiites are demonstrably phenocryst poor lava flows that erupted non-explosively and crystallized spinifex textured flow-tops above olivine-rich cumulate lower zones at low pressures. Consequently, it is most unlikely that they were magmatically wet melts. Even if they were, they probably would have degassed water before crystallization and thus it is difficult to infer magmatic water contents by studying the products of in-situ or shallow crystallization.

The second diagnostic characteristic is whole-rock geochemistry, yet this is fraught with the problem that komatiites are high degree melts (up to 50% of the mantle) and thus major and many trace element compositions must converge regardless of whether they are formed by volatile or high temperature induced melting. Interpretation of the geochemistry is further complicated by the fact that komatiites require physical conditions of melt generation that do not occur today. Models of komatiite generation based on geochemistry must be physically plausible and all existing models require high mantle temperatures. Komatiite generation at subduction zones requires higher mantle wedge temperatures (+/- faster convection) than today, and thus implicitly requires the presence of high temperature mantle. We will present the arguments for komatiite generation by anhydrous melting and a viable physical model for their origin in high temperature mantle plumes. We will use as our example, one of the best-preserved sequences of Archean komatiites from the Belingwe greenstone belt in Zimbabwe.

High-Mg Magmatism Through Time: Implications for Mantle Plumes

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Of the many arguments that have been made for the existence of mantle plumes, the presence of high Mg magmas such as picrites and komatiites magmas with inferred potential temperatures greater than that which would be produced by normal decompressive or hydrous melting of upper mantle seems to be the most compelling. Compared to the ubiquitous low-Mg basalts erupted at mid-ocean ridges or in volcanic arcs throughout geological time, the most magnesian magmas identified thus far in the Phanerozoic are low-Mg komatiites with up to ~20% MgO (e.g., Baffin, Gorgona), the most magnesian magmas identified thus far in the Proterozoic are low-Mg komatiites with up to 22% MgO (e.g., Thompson), and the most magnesian magmas identified thus far in the Archean are high-Mg komatiites with up to 32% MgO (e.g., Abitibi, Barberton, Belingwe, Norseman-Wiluna). Although the production and preservation of mafic-ultramafic magmas has not been continuous, reflecting specific periods with unusually high rates of production and preservation (e.g., 1.9 Ga, 2.7 Ga) , there appears to have been an abrupt, not continuous, change in the maximum MgO content and therefore potential temperature of mantle-derived magmas at the end of the Archean. Such an abrupt change in mantle potential temperature, along with the plethora of other fundamental changes in geological processes that occurred at the end of the Archean, suggests that there was a fundamental change in the thermal structure of the mantle at that time. It has been suggested, however, that some or all high-Mg komatiites have been produced by hydrous melting. Although some komatiites do contain vesicles and/or igneous amphibole, they occur only locally, even within individual volcanic-stratigraphic units, which suggests that water was derived locally during emplacement. Critically, most komatiites (and many associated basalts) are moderately to strongly depleted of highly-incompatible lithophile elements relative to moderately incompatible lithophile elements, have positive epsilon Nd values, and have broadly chondritic gamma Os, consistent with derivation by partial melting of a long-term depleted mantle source. Because H2O is incompatible during melting, we may infer that melting was not facilitated by the addition of water or other metasomatic components. Indeed, the strong depletion in HILE suggests that the komatiite source, which may be otherwise interpreted to be representative of normal convecting asthenospheric mantle, may have contained as little as 20 ppm H2O. The majority of komatiites appear to have been generated by high-temperature, high-degree partial melting of normal convecting asthenospheric mantle, most likely in a thermal plume.

Observations of Heat Flow on Hotspot Swells

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Heat flow data collected on hotspot swells have been used to argue for and against sublithospheric thermal anomalies. The presence of sublithospheric thermal anomalies has been inferred from interpretations of anomalously high heat flow determinations, whereas the contention that swells result from normal melting processes within the lithosphere is based on 'normal' heat flow values. These arguments depend in part on the choice of a thermal reference model, but more importantly assume conductive heat transfer through the lithosphere. We review heat flow determinations collected on hotspot swells and argue that shallow fluid flow is likely obscuring the thermal conditions within or at the base of the lithosphere.

Discriminating between environments where heat is transferred conductively or convectively requires closely spaced heat flow determinations (1-2 km) collocated with seismic reflection profiles. Only Hawaii and Reunion have surveys satisfying these criteria. The Hawaiian survey consists of two profiles, one north of Oahu and one north of Maro Reef. The Reunion survey also consists of two profiles, both north of Mauritius. These heat flow profiles reveal greater scatter than anticipated with spectral peaks on the order of 10 km consistent with fluid flow. Root mean square variations along the Oahu and Maro Reef profiles are 15 and 5 mW m**-2, respectively, and along both Reunion profiles are about13 mW m**-2. Coupled heat and fluid flow models demonstrate that thermal buoyancy due to bathymetric relief is capable of driving significant fluid flow that may suppress the background thermal field. These models are consistent with heat flow patterns observed at individual seamounts and oceanic basement highs that are more easily sampled and characterized than large hotspot swells. We caution that the ability of fluid flow to mask variations in sublithospheric heat flux is under appreciated.

MORB Major-Element Systematics: Implications for Melting Models and Mantle Temperatures

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Klein and Langmuir (1987, 1989) and Langmuir et al. (1992) (hereafter, KL87) argued that MORB magmas, including those from Iceland, are fractionated aggregates of melts produced by combining small basaltic melt fractions from a wide range of pressures in melting columns. A crucial aspect of their modeling is their correlation of Na8 with crustal thickness. However, this hinges strongly on two extrema, one for Iceland, where the crustal thickness is controversial, and the other for the Cayman Trough, where the crustal thickness is based on geological inference rather than seismology. Also, experimental data show that low-pressure olivine-controlled fractionation is required for melts produced in the KL87 model to reach the composition range of observed MORB glasses. Here we reexamine the global correlations of KL87. To eliminate interlaboratory analytical differences, we use the Smithsonian database of basalt glasses. Also, we use a separate set of published and unpublished basalt glass compositions from Iceland, all analyzed on the electron microprobe at the University of Iceland. Neither the Iceland nor MORB data sets show even a hint of the olivine-controlled fractionation required by the KL87 model. For the East Pacific Rise, we confirm the result of KL87 that an inverse Na8-Fe8 correlation occurs at all length scales along the ridge. For the Mid-Atlantic Ridge, KL87 found "local" trends (< 100 km ridge length) with positive Na8-Fe8 correlations. For the North Atlantic south of the Charlie Gibbs Fracture Zone, we find that the data are dominated by two offset positive correlations, each of which extends more than 2000 km along the ridge. That is, the local trends of KL87 are actually regional. The Iceland data show a third trend for Na8-Fe8 that is offset from the other two. Thus, the Na8-Fe8 data for the Mid-Atlantic Ridge are best described as a series of offset positive trends rather than a single trend. For both the East Pacific Rise and Mid-Atlantic Ridge, the data are consistent with magma generation in the range 1-1.5 GPa from a heterogeneous mantle, which implies magma-generation temperatures of about 1260-1280 C. For ridges in other parts of the ocean basins, the amount of data in the Smithsonian database is inadequate for robust analysis of this type, but the data give no indication that higher magma-generation temperatures are required.

Magmatic Crystallization Temperatures of Tholeiite Magmas: Implications for the Existence of Thermally Driven Mantle Plumes

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To compare magmatic crystallization temperatures between ‘plume-related’ OIB and normal MORB tholeiite magmas we have examined in detail two well studied suites of rocks where we have both whole-rock and glass data as well as constraints on volatile contents. The two suites are the 1959 summit eruptions of Kilauea volcano, and MORB rocks and glasses from ODP Leg 148 (hole 896A). To model the magmatic crystallization of olivine we use the software PETROLOG (/Danyushevsky/, 2001) and the olivine melt model of /Ford et al./ [1983]. The effect of H_2 O on the olivine liquidus surface was modelled using the model of /Falloon and Danyushevsky/ [2000].

The 1959 summit eruption of Kilauean volcano provides a good example of a picritic suite of rocks where whole-rock compositions are controlled by the mechanical accumulation of olivine. Glass sampled from the eruptions by /Murata and Richter/ [1966] however define a liquid-line of descent controlled by equilibrium fractional crystallization of olivine (/Woronow et al.,/ 1996). Using Petrolog and volatile constraints from quenched picritic glasses from Kilauean volcano (/Clague et al.,/ 1991) we calculate magmatic olivine crystallization temperatures for the glass data of /Murata and Richter/ [1966] of between 1189.8-1065.6°C for the 1959 eruptions, which matches almost exactly the range of observed eruption temperatures (1190-1060°C, /Ault et al.,/ 1961). Using Petrolog we calculate a parental magma of 16.5 wt% MgO, containing 0.51 wt% H_2 O with an eruption temperature of 1328°C at 1bar and in equilibrium with the most magnesian olivine phenocryst from Kilauea volcano (Fo 90.7). The average result using 5 other olivine melt models is a parental magma of 16.5±0.3 wt% MgO at a temperature of 1327±15°C. /Eggins/ [1992] studied a Kilauean parent magma of 16 wt% MgO and demonstrated multiple saturation with peridotite (harzburgite) at 2 GPa 1450°C under nominally anhydrous conditions. Using Petrolog our parental composition is in equilibrium with olivine at 1429°C at 2 GPa (1485°C anhydrous).

/McNeill and Danyushevsky/ [1996] studied depleted MORB glasses from ODP Leg 148, hole 896A. The most magnesian glass had MgO of 9.43 wt% MgO and 0.05 wt% H_2 O. Using Petrolog a calculated parent in equilibrium with the maximum olivine observed (Fo 91.6) has 15.6 wt% MgO, 0.04 wt% H_2 O and a liquidus temperature of 1336°C at 1bar. The average result using 5 other olivine melt models is a parental magma of 15.8±0.2 wt% MgO at a temperature of 1334±5°C. We have performed reaction experiments on this calculated parental composition with peridotite MM-3 at 1.8 and 2.0GPa. The reaction experiments demonstrate that this calculated parent is in equilibrium with mantle peridotite (lherzolite) at 2 GPa 1460° C under nominally anhydrous conditions. Using Petrolog our parental composition is in equilibrium with olivine at 1436°C at 2 GPa (1462°C anhydrous).

The results of this study demonstrates that there is very little difference (<10°C) in the magmatic temperatures at 1bar, and temperatures and depths of origin, between two well studied OIB and MORB tholeiite suites, with the MORB suite having a slightly higher temperature. The results of this study support the conclusions of /Green et al./ [2001] and /Green and Falloon/ [2005] that their is no evidence for a temperature contrast of (delta)Tp ~ 200-250°C between 'Hot-spot' or 'Deep Mantle Plume' sources and ambient (MOR source) asthenospheric mantle.

Monday Poster Sessions

How Hot is Iceland?

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High potential temperature compared with surrounding mantle is a primary characteristic of mantle plumes. A temperature anomaly of the order of hundreds of Kelvin is thought to be required, even for a weak upper-mantle plume rising from the base of the mantle transition zone. (It should be mentioned in passing that this latter model ignores the fact that the base of the transition zone is a mineralogical phase change and there is no evidence that it is a strong temperature discontinuity.) Many independent methods have been used to estimate the temperature anomaly at various depths in the crust and mantle beneath Iceland. Seismic methods include measuring attenuation and the Vp/Vs ratio to place bounds on the temperature of the crust, and P- and S-wave mantle tomography to study the mantle. P- and S-wave receiver functions have been applied to study the depths of discontinuities, including those associated with the low-velocity zone (between ~ 80 and 135 km depth) and the 410- and 660-km discontinuities that form the upper and lower boundaries of the mantle transition zone. Seismic wave travel times have been used to estimate the velocities between the discontinuities. Temperature has also been estimated using petrological methods such as olivine glass geothermometry, the study of melt inclusions in basalts, CMASNF geothermometry of high-MgO glasses, major element systematics of Icelandic MORB and the search for an olivine control line in Icelandic picrite cumulates. Additional approaches include deducing thermal history by modeling the bathymetry of the north Atlantic, the subsidence of the ocean crust and uplift of the Hebrides shelf. Heat flow measurements from the oceans provide additional weak constraints on temperature.

All results either require or are compatible with a mantle potential temperature anomaly of no more than ~ 50-100 K beneath Iceland. The Icelandic crust is cooler than that beneath the East Pacific Rise. Seismic tomography is compatible with temperature anomalies of up to 200 K, decreasing to about 100 K at depths greater than 200 km where the seismic anomaly is weaker. This assumes that compositional effects are zero and partial melt is absent, however. Other seismic results require the presence of partial melt, necessitating substantial downward-adjustment of the temperature anomaly estimate from tomography. P-wave receiver functions show that the 410-km discontinuity is warped downward by ~ 15 km but that the 650-km discontinuity is flat. A hot upwelling penetrating the entire mantle transition zone would predict upward-warping of the 650-km discontinuity in addition to downward-warping of the 410-km discontinuity. The results are consistent with a temperature anomaly of about 100 K at 410 km but zero at 650 km. All petrological methods suggest relatively small temperature anomalies unless olivine control is assumed for Icelandic picrite cumulates, an assumption whose validity is questionable. Modeling of bathymetry and vertical motions suggests temperature anomalies of no more than 100 K.

A large majority of temperature estimates from the Iceland region are thus consistent with a modest temperature anomaly that is well within what is expected for upper-mantle variability from such processes as continental insulation and recent slab subduction. There is little evidence for the high temperatures required by a plume from the lower mantle rising through its own thermal buoyancy.

Why the High PGE Contents of Komatiites, Picrites and Allied Rocks Require Mantle Plumes

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The high concentrations of both Pd and Ir in komatiites, komatiitic basalts, picrites and some Continental Flood Basalts (CFB) require both high temperature and high degree partial melting of their mantle source reservoirs. The only mechanism by which the sufficiently high temperatures required can be achieved is through mantle plume processes which transfer heat from deep in the mantle to the regions of magma generation. Palladium is the most chalcophile metal known, and is retained in the mantle reservoir until all of the sulfides in the mantle reservoir are exhausted by high temperature, high degrees (>25%) of partial melting. Although Ir is also chalcophile, it is one of the most siderophile elements known. Iridium occurs in mantle and crustal phases as alloys with Os and possibly Ru. The Ir content of mantle-derived magmas is directly proportional to the degree of partial melting which produced them. Hence, whereas komatiites, which are high temperature magmas produced by high degrees of partial melting, have high Pd and Ir contents, boninites, which are moderately high temperature magmas that involve lower degrees of partial melting due to fluxing of slab-derived volatiles, have high Pd but low Ir contents.

The high PGE contents and geochemical signatures of some CFB are best explained by the interaction of high temperature, high MgO melts from mantle plumes with lithospheric mantle that has been depleted in S, but mildly enriched in the PGE, by previous melt extraction. High temperature magmas from a mantle plume are required to provide the energy required to melt the refractory lithospheric mantle. In addition, the high crustal contamination signature of the mafic and ultramafic rocks that host many Ni-Cu-PGE sulfide deposits suggests that the mantle-derived magmas that produced the ores had to be very energetic in order for them to digest the large mass of crustal rocks that were assimilated.

Thermal State of NW Kyushu Mantle Suggested by Petrochemistry of Primitive Basalts

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Based on Sr-Nd-Pb isotopes and incompatible element compositions, Cenozoic basalts in NW Kyushu, SW Japan is considered to be caused by mantle plumes with enormously high temperature from the 660 km discontinuity and/or core. Nevertheless, tomographic observations suggest that the 660 km discontinuity beneath NW Kyushu is cold. Moreover, petrochemistry of primitive NW Kyushu basalts indicates that their source is not so hot. Bulk rock MgO-FeO-NiO suggests that the basalts with MgO = 10-6 wt. % can equilibrate with the mantle. Results of previous melting experiments suggest that these basalts were last in equilibrium with the source at 1200-1300 degrees centigrade at 1GPa. These melting temperatures are relatively low and similar to those of MORB and subduction zone basalts, which suggest that NW Kyushu basalts were formed by relatively shallow mantle upwelling. Such mantle upwelling would be caused by lithospheric extention at the junction of the SW Japan arc and the Ryuku arc. Petrochemical similarity with NW Kyushu basalts suggests that origin of intraplate basalts from other than NW Kyushu can be explained by tectonic-controlled hypothesis.

Influence of Eclogite in Mantle Sources on 'Hot-spot' Temperatures

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Recent studies of compositions of olivine basalt and olivine-hosted melt inclusions from Iceland, Greenland, and Hawai`i point to the potential involvement of recycled ocean crust as eclogite in mantle sources. The most distinctive geochemical indicators (e.g., high Y/Zr, low Zr/REE; high Sr/REE) result from partial melting of rocks that originally were lower ocean crustal gabbroic adcumulates (1) with very low residual melt porosities (nearly no trapped intercumulus liquid). Abyssal gabbro adcumulates have significantly higher Ca/(Ca+Na) at given Mg# = 100*Mg/(Mg+Fe2+) than their original host MORB liquids and most have MgNo = 70-85. Experimental studies point to derivation of primitive basaltic liquids with low CaO/Al2O3 (0.5-0.9) and moderate to high MgNo (55-80) from eclogite with similar composition and also pyroxenite (e.g., 2). Basaltic experimental liquids have low total iron (FeOT) contents (6-10%) at given MgO (6-14%), do not lie along olivine-controlled liquid lines of descent and match many inclusion compositions hosted in olivine and other minerals in picrites from the North Atlantic Igneous Province (NAIP) and Hawai`i (e.g., 3, 4). The crystal-liquid exchange model for Cr-spinel of (5) predicts crystallization from such liquids of spinel that can be either more highly chromian (Cr# = Cr/[Cr+Al] = 60-75) than in MORB spinel, or which trends to lower Mg# at nearly fixed Cr#, or both. The trends result mainly from low Mg# and Al2O3 (13-15%) in eclogitic partial melts, the latter especially at pressures >3 GPa. Such trends in spinel are common among picritic basalts from these locations and also Gorgona. Highly chromian spinel with a trend toward iron enrichment thus is a mineral proxy for the influence of eclogite/pyroxenite in mantle sources at all these places.

The spinel compositions in turn allow estimation of liquid Fe2+/Fe3+, and indicate regional differences of oxidation states of recycled crustal components in mantle sources (West Greenland and Gorgona higher than Iceland). The inclusions demonstrate that most picrites are hybrid compositions produced by mixing of both primitive (including eclogite-derived) and differentiated magma strains, such that neither the olivine nor the spinel they contain crystallized along a single (olivine-controlled) liquid line of descent. Indeed picrites from Iceland also contain phenocrysts of calcic plagioclase and chromian endiopside. Inference of crystallization temperature from assumed relationships between forsteritic (Fo91) olivine and an estimated magnesian host liquid (MgO = 15-20%) thus is almost always contradicted by evidence from melt inclusions,olivine and spinel for magma mixing. Adjusting properly for oxidation states inferred from spinel compositions, liquids with compositions of the melt inclusions are capable of crystallizing quite forsteritic olivine (Fo90-92) at low-P and T = 1260-1325oC, the highest temperature being about the maximum indicated by olivine-liquid thermometry for any melt inclusion or natural glass found at any of Iceland, Greenland, or Hawai`i. The presence of strongly forsteritic olivine in picrites thus is no guarantee that they crystallized at temperatures in excess of 1400oC. Spinel compositions point to no higher temperatures of crystallization at either Skye or Gorgona than at Iceland and indeed suggest generally similar (but not komatiitic) primitive liquid compositions at all localities discussed here, with potential temperatures only about 50-100o higher than for primitive MORB.

1) Foulger, G.R., Natland, J.H. and Anderson, D.L., 2005. J. Volcan. Geotherm. Res., 141: 23-44; 2) Kogiso, T., Hirschmann, M., and Pertermann, M., 2004, J. Petrol. 45: 2407-2022. 3) Sigurdsson, I., Steinthorsson, S., and Gronvold, K.,2000. Earth Planet. Sci. Lett., 183: 15-16. 4) Sobolev, A., Hofmann, A., Sobolev, S., and Nikogosian, I., 2005. Nature, 434: 590-597. 5)Poustovetov, A., and Roeder, P., 2000. Canad. Mineral., 39: 309-317.

Evidence for High Temperature Mantle Plumes Based on Olivine-Liquid Thermometry

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Temperature is perhaps the most important variable in the debate over the existence of mantle plumes. If the temperature differences between hot spots and mid-ocean ridges are large (160-280 K) then the existence of thermal upwellings would appear more than plausible [Sleep, 1990; Schilling, 1991]. But if such temperature differences are nil [Anderson, 1998; Green et al., 1999], then the modern concept of plumes must be abandoned. Olivine phenocrysts from lavas erupted in ocean basins provide perhaps the most useful means for measuring temperature differences. Olivine compositions are highly sensitive to temperature, and in general, minerals provide a less homogenized account of the melting process compared to glass and whole rock samples.

An updated form of the Roeder and Emslie [1970] olivine saturation surface is applied to olivine phenocrysts from two hot spots, Hawaii and Iceland, and from a segment of the East Pacific Rise mid-ocean ridge (MOR) system, the Siqueiros transform. The Roeder and Emslie [1970] approach to thermometry is applied because mineral and host rock compositions can be directly input to estimate T, obviating the need to estimate primitive melt MgO (e.g., Green et al. [1999]). The updated olivine saturation surface shows that olivine-liquid equilibration temperatures at Hawaii and Iceland are hotter by 250 and 165 K respectively compared to MORs (error = 50 K). These temperature differences are greater than those obtained by Green et al. [1999] for Hawaii, but are more consistent with observed FeO contents for Hawaiian lavas. In addition, these estimates include the effects of water, alkalis, and silica on olivine-melt equilibria, and are robust against other variations in source or liquid composition, such as FeO and carbon dioxide. Translated to differences in mantle potential temperature, Hawaii and Iceland are hotter than ambient MORs by 213-235 and 162-184 K. Absolute estimates of mantle potential temperatures are less certain as they depend upon estimates of F and depth-of-equilibration; presuming F = 0.2 and that magmas are delivered from the base of the lithosphere, mantle potential temperatures are: Hawaii = 1961 K; Iceland = 1910 K; MORs = 1726-1748 K. Within error, estimates for MORs match T estimates obtained from ocean bathymetry [1723 K; Stein and Stein, 1992].These temperatures thus show that at least at Iceland and Hawaii, volcanism is driven by high temperature thermal anomalies whose magnitudes are consistent with the existence of thermally driven mantle plumes.

Does Hydrothermal Circulation Mask Anomalously High Heat Flow at Hot Spots?

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Sea floor depths and heat flow data are two of the primary observable constraints on mechanisms for hot spots. A challenge is that these two data reflect not only the effect of the source of the excess magma, but also combinations of "normal" lithospheric cooling and other local phenomena. While hot spots are associated with anomalously shallow depths, it is unclear if heat flow is anomalously high. Depending on the answer to this question, different mechanisms have been proposed for hotspot formation.

The shallow depth associated with hot spots was originally thought to reflect a hot mantle plume, rising from deep in the mantle, penetrating the approximately 100-km-thick oceanic lithosphere and causing heating to about 50 km of the surface. Although anomalously high heat flow was initially reported, consistent with significant lithospheric reheating, subsequent analysis showed that most if not all of the apparent anomalies resulted from comparing the data to reference thermal models that underestimated heat flow elsewhere. The small size or absence of a heat flow anomaly at midplate hotspots such as Hawaii implies that uplift may result from the dynamic effects of rising plumes and/or the associated compositional buoyancy, whose thermal effects are concentrated at the base of the lithosphere and hence would raise surface heat flow at most slightly, given that tens of millions of years are required for heat conduction to the surface.

Recently it has been proposed that high heat flow is not measured because extensive hydrothermal circulation transfers significant amounts of heat. If so, it is possible that significant lithospheric reheating may contribute to hotspot formation. Here, I compare heat flow data and other associated local factors from both hotspot regions and areas of similar ages far from hot spots to examine this issue.

Tuesday Oral Sessions

Timing and Duration of Volcanism at Large Igneous Provinces: Implications for Geodynamics and Links to Hotspots

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Estimates of timescales of volcanic activity at large igneous provinces (LIPs),

derived from radiometric methods and magneto-stratigraphic data, lead to the conclusion that vast portions of these enormous volumes of mantle-derived magma were erupted at rates far exceeding any contemporary site, and are therefore unrelated to any known plate tectonic melting regime. Furthermore, field evidence reveals that LIPs are built from very large, discrete eruptive events (ca. 103-104 km3 each) over periods of ~1 million years, rather than continuous volcanic activity. These features are most consistent with the startup plume model.
One continental LIP, the North Atlantic igneous province, and one oceanic LIP, the Caribbean plateau, have been studied in particular detail. 40Ar-39Ar incremental heating and U-Pb methods are capable of providing high precision age determinations for extrusive and intrusive constructional phases. In the NAIP case, initial volcanic activity (~62 Ma) coincident with the birth of the Iceland hotspot, penetrated thick continental lithosphere over a broad area (1000s of km diameter), then focused at ~55 Ma into a narrow spreading zone that led to plate separation (with eruption rates ~1000 km3/m.y. per km of rift). In the CLIP contemporaneous volcanism occurred over a similarly broad area on eastern Pacific oceanic lithosphere at the inception of the Galapagos hotspot (~93 Ma). A subsequent, geographically restricted phase of volcanic and intrusive activity occurred 80-76 Ma in response to plateau extension.

Clearly defined, age-progressive hotspot tracks connect these LIPs to their presently active hotspots. Geochemical "fingerprints" also link these LIPs to the associated hotspots.

Origin of Long-term Intraplate Volcanism in the Canaries, Madeira, Galapagos and New Zealand: Which are Consistent with the Plume Hypotheses?

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Intraplate volcanism in the Canary, Madeira, Galapagos and New Zealand regions can be traced back to at least 70 Ma and probably back more than 100 Ma. New age and geochemical data from seamounts to the NE of the Canary and Madeira Islands, specifically targeted to test the "hotspot (plume) hypotheses", confirms general age progressions with ages increasing in the direction of plate motion. These age progressive island-seamount chains, as is also the case for the Walvis and St. Helena chains in the southern Atlantic, can be explained by rotation around a common Euler pole, consistent with the hotspot hypothesis. Irregularities in the chains can be explained by a combination of factors, such as pulsing rather than continuous plumes, interaction of rising plume pulses (blobs) with edge driven convection against the African continental root and lithospheric control on the exact location and morphology of individual volcanic structures. Geochemical and age studies of the Madeira-Tore Rise suggest that its Cretaceous basement may have also formed from the Canary hotspot, as the mid Atlantic Rise passed over the hotspot.

In order to link the Galapagos hotspot to the Caribbean LIP, we also assummed the plume model and searched the Central American forearc for accreted parts of paleo-Galapagos Hotspot tracks. Accreted terranes with Galapagos-type geochemistry and ages ranging from ca 20-70 Ma were found, consistent with the hotspot hypothesis. Older samples from the Nicoya Peninsula in Costa Rica (111-139 Ma) and parts of the Guatemalan forearc basement (possibly as old as 170 Ma) also have Galapagos-type geochemistry but don't fit the classical plume head hypothesis. Either mantle plumes don't always begin with a single plume head or subduction has resulted in the accumulation of different volcanic structures derived from mantle reservoirs with similar geochemistry.

In the SW Pacific, new age and geochemical data show that the Hikurangi oceanic plateau formed contemporaneously and from a similar source as the Manihiki and Ontong Java plateaus, requiring at least two Ontong Java-sized plateaus to have formed at the same time (at ca 120 Ma) several thousand kilometers apart. This contemporaneous volcanism can best be explained by the plume head hypotheses. Beginning at ca 100 Ma, HIMU-type volcanism began on the Hikurangi Plateau and the neighboring Zealandia micro-continent. Extensive sampling from submarine parts of the Chatham Rise and Campbell Plateaus, as well as land-based work, show that the HIMU volcanism has continued until at least the Pleistocene. Almost the entire age range occurs on the Chatham Rise. Considering that the plate has moved many thousands of kilometers over this time period, the hotspot hypothesis cannot explain this volcanism.

In conclusion, although the hotspot (plume) hypotheses provides a good framework to explain many areas of intraplate volcanism, it cannot explain all intraplate volcanism.

The Geochronology of Hotspot Trails and the Timing of the Hawaii-Emperor Bend

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Recent studies of seamount trails in the Pacific have shown that at least two classes of hotspots are required to explain these topographic features in terms of their morphology and geochronology. On the one hand, the Hawaiian and Louisville hotspots may be explained by deep-seated mantle plumes that generate intra-plate volcanism over long periods of geological time, in a rather continuous and age progressive manner. Most characteristics of these two unique seamount trails are still consistent with the mantle plume theory and the standard hotspot hypothesis, even though new paleomagnetic and 40Ar/39Ar geochronology data have shown that these mantle plumes cannot be fixed in the mantle (moving up to 40 mm/yr with respect to the geomagnetic pole) and that these mantle plumes move slowly (but significantly) with respect to each other.

On the other hand, the Pacific plate is littered with short seamount trail segments that have persistent isotopic fingerprints. However, these short-lived seamount trails generally have irregular age progressions and show bends that are asynchronous with the infamous bend in the Hawaii-Emperor trail at 47 Ma. These observations are much harder to reconcile with "fixed hotspots" since (by definition) these age progressions and bends should give a consistent picture of the changes in plate motion, happening simultaneously across the entire Pacific plate.

It thus becomes clear that plate motion and fixed hotspots alone cannot explain these age systematics, but that both hotspot motion and changing lithospheric stress regimes may play an important role in the creation of seamount trails. The simple and elegant "hotspot" model that (almost without difficulty) may explain the primary hotspots such as Hawaii and Louisville, seems unsatisfactory in the explanation of age distributions for short-lived hotspots.

Critical Assessment of Radiometric Ages for Oceanic Hotspot Tracks, Based on Statistical Analysis of Individual Ages, and Evaluation of the Alteration State of the Material Dated

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The argon dating methods are most commonly used to determine the ages of material thought to be related to hotspot tracks. Rocks recovered from oceanic islands and/or the seafloor, tend to altered, resulting in loss of (some of the) radiogenic argon. The literature is peppered with unreliable ages. K-Ar dates and/or 40Ar/39Ar total fusion ages, in general, should not be treated as accurate estimates of the time of crystallization. 40Ar/39Ar stepheating ages must pass the requisite statistical tests (Baksi, 1999, 2005) to be termed proper plateaux and/or isochron ages. Further, the data must be examined closely in light of 36Ar contents, to eliminate "ages" obtained from altered material.

It has been shown (Baksi, 1999, 2005) that there is no evidence of a linear progression of hotspot track ages from the Indian and Atlantic Oceans. Specifically for the Ninetyeast Ridge (Kerguelen Hotspot), the Chagos-Laccadive and Mascarene Plateaus (Reunion Hotspot), New England Seamount (Great Meteor Hotspot) and the Rio Grande Rise and Walvis Ridge (Tristan da Cunha Hotspot). It will be shown that the ages purported to be linked to the St. Helena and Walvis hot spot-plume systems (O'Connor and LeRoex, 1992), are without merit.

For the Pacific Ocean, I will illustrate the dangers of using K-Ar dates and 40Ar/39Ar total fusion ages for the Samoan Shield, Cook-Austral Island Chain, New Hebrides-Samoa Lineament and the Galapagos seamounts (Natland and Turner, 1985; Turner and Jarrard, 982; Duncan, 1985; Sinton et al., 1996). Published 40Ar/39Ar stepheating ages for (altered) submarine rocks from the Western Pacific (Ozima and Saito, 1977; Ozima et al., 1977) clearly fail the relevant statistical tests. Stepheating ages for guyots in the Northwest Pacific (Winterer et al., 1993), also generally fail the relevant statistical tests. In tracing Easter Chain volcanism (O'Connor et al., 1995) and the Foundation Chain (O'Connor et al., 1998), a few ages need to be rejected; statistical evaluation shows that many of the other results are "too good", with probabilities of occurrence generally well over 0.90. The material dated was relatively fresh, as based on 36Ar contents. The plateau ages may be more precise than suggested by the authors.

All ages purporting to show linear age progression of hotspot tracks, must be carefully evaluated, using the techniques outlined herein. In light of the work of Sharp and Clague (2002), this includes the (classical) case of the Hawaii-Emperor Chain.

Volcanic Imprint of Oceanic Hot Spots and LIPs: Shallow/Local versus Deep/Global?

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A fundamental assumption of the mantle plume paradigm for the past 10-15 years has been that massive LIPs are formed by a short lived 'starting' plume head, followed by plume 'tail' rising from the deep mantle to create long-lived hotspots. Time-progressive lines of islands, seamounts and ridges are elegantly explained by the migration of tectonic plates over hotspots created by these narrow plume conduits. Thus, inferring narrow, underlying mantle plume 'tails' from comparably small regions of active hotspot volcanism has become an essential aspect of explaining the origin and characteristics of hotspot volcanism in terms of the mantle plume hypothesis. This has led to a situation where a major a priori question that must be addressed when interpreting age, geochemical and geophysical data for oceanic hotspot volcanism and nearby spreading centers is: "where is the mantle plume"?

However, the fundamental, simple assumption now inherent in the plume hypothesis of small hotspots marking the location of narrow plume 'tails' seems not to be holding up in light of age dating of new dredge samples from seamounts and aseismic ridges linked to the Galapagos (O'Connor et al., 2004, submitted 2005) and Foundation (O'Connor et al., 1998, 2001, 2002, 2004) hotspots. We review here these examples of how substantially improved age control for the volcanic imprint of key oceanic hotspots can point the way forward to testing both the plume paradigm and new alternatives. Such new information raises the issue of whether we are over-interpreting ocean island and spreading center data at the expense of fundamental information from older more widespread seamounts and aseismic ridges? Nonetheless, this limitation on data required to better test the plume hypothesis and alternatives is likely to continue due to the challenges associated with sampling and analyzing seawater altered seamount and aseismic ridge dredge samples.

The widely accepted explanation for the origin of Galapagos hotspot volcanism is motion of the Cocos and Nazca plates over a small narrow plume 'tail' located at the western end of the Archipelago (e.g. Geist et al., 1988, White et al., 1993, Kurz & Geist, 1999, Harpp & White, 2001, Harpp & Geist, 2002). Extensive volcanism extending across the Galapagos Archipelago/Platform is explained by interaction between this plume 'tail' and the Cocos-Nazca spreading center (e.g. Geist et al., 1988, White et al., 1993, Kurz & Geist, 1999, Harpp & White, 2001, Harpp & Geist, 2002, Werner et al., 2003, Schilling et al., 2003). Although the Galapagos Archipelago is one of the best studied active hotspot systems, very little age control is available for the far more extensive aseismic ridges and associated seamounts extending away from the Galapagos Archipelago on the Nazca and Cocos tectonic plates. We therefore reconnaissance-sampled these volcanic structures during a 1999 cruise of the R/V SONNE. Measured Ar/Ar ages suggest that the Galapagos hotspot influences a much larger region than inferred from small clusters of active ocean islands and seamounts (O'Connor et al., 2004, submitted 2005). Broad zones of overlapping hotspot volcanism are created on both the Cocos and Nazca plates. The complex tectonic history of the Cocos-Nazca spreading center has controlled how this volcanism is apportioned between the Nazca and Cocos plates. However, plume 'tail' - spreading center interaction does not seem to be the primary process controlling the volume and distribution of Galapagos hotspot volcanism. Thus our new data are not compatible with the widely held notion of a small Galapagos hotspot marking a comparably narrow plume conduit - with most hotspot volcanism reflecting interaction between the Galapagos plume and the Cocos-Nazca spreading center (O'Connor et al., 2004, submitted 2005). Although evidence for a very broad Galapagos hotspot melting anomaly can be interpreted as favouring the non-plume alternative models, another key prediction of the plume theory - age-progressive volcanism, the main observation leading to the birth of the plume model in the first place - has been reinforced for Galapagos hotspot volcanism on both the Cocos and Carnegie plates.

Measured ages for samples recovered during our 1998 sampling of the Foundation Seamount Chain, SE Pacific provides supporting evidence for the notion of broad hotspot melting anomalies associated with age progressive volcanism. The Foundation Chain, a narrow line of seamounts extending from the Pacific-Antarctic spreading center, is fundamentally age-progressive. However, broadening of the chain linked to changes in lithospheric structure suggest that the underlying hotspot melting anomaly is far broader than indicated by the width of the chain (O'Connor et al., 2001, 2002, 2004).

If the notion of plume 'tails' is not finding support from new Galapagos and Foundation age data then what is the situation regarding the equally important and elegant idea of 'starting' plume heads? Most studies tend to focus on direct sampling and geophysical profiling of LIPs. However, relying exclusively on this approach could be problematic given the great difficulty of sampling these massive structures. A complementary approach is to look at the temporal relationship between the volcanic traces of proposed 'starting' plume heads (LIPs) and 'tails' (seamount chains and aseismic ridges). Age-progression along the Walvis Ridge, South Atlantic, has suggested a very close temporal link between rapid Continental Flood Basalt emplacement and continental rifting followed by the onset of Walvis Ridge formation. But more recent age data for the St Helena Seamount Chain indicates that the established migration rate for volcanism along the Walvis Ridge is not yet sufficiently well constrained (O'Connor et al., 1999) to be cited as supporting the 'starting' plume head model. This opens up the possibility of testing both the 'starting' plume head model and important alternatives that propose a much longer/earlier history of continental hotspot activity than predicted by the 'starting' plume head model.

One of the main reasons for investigating hotspots and LIPs is the quest for a deep, global mantle process? Evidence for correlations between synchronous hotspot events or processes on a global scale and major changes in plate tectonic might well support some of the shallow/local alternative models for the origin of hotspots? However, identification of such synchronous events/processes that do not correlate with major changes in plate tectonics might better reflect a deep/global mantle process? Our recent studies are demonstrating that the distribution, composition and history of the volcanic imprint of oceanic hotspots must first be resolved in sufficient detail to identify shallow/local lithospheric processes before it can become possible to test for the signal of any possible deeper/global mantle process.

Cenozoic Vertical Movements on the NW European ‘Passive’ Margin: Responses to Upper Mantle Convection?

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The North Atlantic continental margins are archetypally passive, yet they contain evidence of post-rift vertical movements of up to km-scale. The Cenozoic history of such movements on the NW European margin, from Ireland to mid-Norway, has been examined by integrating published analyses of tectonic subsidence and/or uplift with higher resolution tectono-stratigraphic evidence of sedimentary responses (including results from the EC STRATAGEM project). Three episodes of differential vertical or epeirogenic movement are identified, in the early, mid- and late Cenozoic, distinct from at least one phase of compressive tectonism. Two types of epeirogenic movement are recognised, referred to as tilting (coeval uplift and subsidence over 100s of kilometres, rotations <1 degree) and sagging (strongly differential subsidence over <100 km, rotations of several degrees). Each epeirogenic episode involved relatively rapid (<5-10 Ma) km-scale tectonic movements that drove major changes in the patterns of offshore sedimentation to find expression in regional unconformity-bounded successions. Thus tilting in the early Cenozoic (c. 60-50 Ma) and late Cenozoic (from the early Pliocene, 4 ± 1 Ma) resulted in the basinward progradation of shelf-slope wedges from uplifts along the inner continental margin and offshore highs, as well as late Cenozoic changes in oceanographic current circulation; sagging in the mid-Cenozoic (c. 35-25 Ma) ended the progradation of early Cenozoic shelf-slope wedges and outstripped sedimentation to dreve the onset of contourite systems in underfilled basins.

The early, mid- and late Cenozoic epeirogenic episodes coincided with Atlantic plate reorganisations, but the observed km-scale tectonic deflections are too large to be explained as flexure in response to intra-plate stress variations. Mantle-lithosphere interactions are implied, but the succession of transient epeirogenic movements, of differing form, are difficult to reconcile with the various syn- to post-rift mechanisms of permanent uplift (e.g. underplating, delamination) or variations in regional dynamic support proposed in the hypothetical context of a plume beneath Iceland. The epeirogenic movements can be explained as dynamic topographic responses to different forms of upper mantle convective flow: tilting as coeval upwelling and downwelling above an edge-driven convection cell; sagging as a loss of dynamic support above a former convective upwelling. The observed succession of epeirogenic tilting, sagging and tilting is proposed to record changing forms of small-scale convection in the upper mantle of the NE Atlantic region during its opening. The evolution of upper mantle convection during ocean opening has been proposed to account for episodic post-rift tectonism on other Atlantic 'passive' margins and to be the underlying cause of plate reorganisations.

Constraining the Geometry and Flow of the Iceland Mantle Upwelling

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The Great Plume Debate is to some extent fueled by incomplete consideration of uncertainties in constraining datasets which allow inconsistencies between hypothetical models and constraining data to be excused. We will present our constraints on the range of low velocity geometries in the mantle beneath Iceland and on the geometry of flow beneath the region which, contrary to previous studies, does show evidence for flow related to the upwelling.

The low-velocity structure beneath Iceland is constrained by a suite of resolution tests designed to determine the range of velocity structures that satisfy the data. These include ray-theoretical squeezing experiments which attempt to force velocity anomalies into specific geometries while still satisfying the dataset, and finite-frequency experiments which use the Spectral-Element Method (SEM) to simulate full waveform propagation through various 3D velocity models. We find that the width of the upwelling conduit beneath Iceland must lie in the range of 100 to 200 km which is generally narrower than ray-theoretical tomography and broader then preferred geodynamic models. Separate tests on the minimum depth extent of the anomaly show that significant low velocities are required to 350 km depth using this regional dataset. Should the true conduit be at the narrower end of the possible range, both compressional and shear wave perturbations greater than 10% would be required to depths of at least 350 km.

Two end-member geometries, radial flow and ridge-channeled flow, have been proposed for the dispersion of material upwelling beneath Iceland. We use teleseismic shear-wave splitting observations to constrain the flow geometry beneath the region. The observed anisotropy pattern is inconsistent with radial flow away from the upwelling. Instead we propose a ridge-channeled flow model in which there is horizontal flow of material away from the upwelling axis beneath southeast Iceland toward the southern end of the Kolbeinsey Ridge and the northern end of the Reykjanes Ridge, both of which are west of the upwelling. This geometry is similar to the ridge perpendicular flow predicted for offridge hotspots towards the ridge. We hypothesize that upwelled material then feeds ridge parallel asthenospheric channels beneath the North Atlantic Ridge. Our interpretation is thus consistent with generation of V-shaped ridges by channeling of upwelling material down the Reykjanes and Kolbeinsey ridges.

Multiscale Seismic Tomography of Mantle Plumes and Subducting Slabs

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Local, regional and global tomographic studies are made to image mantle plumes and subducting slabs. Plume-like slow anomalies are clearly visible under the major hotspot regions in most parts of the mantle, in particular, under Hawaii, Iceland, South Pacific and Africa. The slow anomalies under South Pacific and Africa have lateral extensions of over 1000 km and exist in the entire mantle, representing two superplumes. The Pacific superplume has a larger spatial extent and stronger slow anomalies than that of the Africa superplume. The Hawaiian plume is not part of the Pacific superplume. The slow anomalies under hotspots usually do not show a straight pillar shape, but exhibit winding images, suggesting that plumes are not fixed in the mantle but can be deflected by the mantle flow. As a consequence, hotspots are not really fixed but can wander on the Earth's surface, as evidenced by the recent paleomagnetic and numeric modeling studies. Wider and more prominent slow anomalies are visible at the core-mantle boundary (CMB) than most of the lower mantle, and there is a good correlation between the distribution of slow anomalies at the CMB and that of hotspots on the surface, suggesting that most of the strong mantle plumes under the hotspots originate from the CMB. However, there are some small-scaled, weak plumes originating from the transition zone or mid mantle depths. Clear images of subducting slabs and mgma chambers in the upper mantle wedge beneath active arc volcanoes are obtained, indicating that geodynamic systems associated with arc magmatism and back-arc spreading are related to deep processes, such as convective circulation in the mantle wedge and dehydration reactions of the subducting slab. Evidence also shows that arc magma and slab dehydration may also contribute to the generation of various types of earthquakes in subduction zones. Most of the slab materials are stagnant in the mantle transition zone before finally collapsing down to the core-mantle boundary as a result of large gravitational instability from phase transitions.

The Role of Mantle Plumes in the Earth's Heat Budget

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The seismic tomography images obtained by Montelli et al. (Science, 2004) from a combination of high- and low frequency P delay times show very wide, diapir-like plumes instead of the classical large-head/thin-tail structure, suggesting that these observed plume 'tails' play an important role in transporting heat through the 670 km discontinuity. Because high-frequency delay times are proportional to the plume radius R, whereas low frequency times have a quadratic dependence R2, the finite-frequency analysis used by Montelli is a powerful method to constrain the width of the lower mantle plumes.

New, dedicated, resolution analysis of the plume images confirms this notion and shows a number of lower mantle plume segments where both the observed plume radii and velocity anomalies are sufficiently well resolved to directly estimate the heat and volume flux, if the viscosity and the chemical density difference were known. To deal with the large uncertainties in those (and several less influential) model parameters, we randomly generate 560,000 models and compute plume fluxes. For commonly accepted viscosities of the order of 1022 Pa s, the plume flux easily exceeds that deduced from the observed buoyancy flux by an order of magnitude. We conclude that the buoyancy flux may be a severe underestimate of the lower mantle flux, unless the viscosity is of the order 1023 Pa s and/or the plumes suffer loss of buoyancy through the effects of iron enrichment.

Histograms of accepted models show a 'maximum likelihood' convective regime where plume fluxes are of the order of 1 W/m2 at the center of the plume, with rise velocities of the order of 1 cm/yr. These estimates show large uncertainty, but, when extrapolated to all plumes, would be consistent with a situation in which the volume flux of downgoing slabs is exactly balanced by that in upgoing plumes, and in which the Earth has two well-separated convective regimes in which mass exchanges are limited by break-throughs of slabs and plumes at the 670 km discontinuity.

Constraints on the Observation of Mantle Plumes Using Global Seismology

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The existence of mantle plumes has been highly debated in the last few years. Constraints come from many disciplines, but seismology is the only method that allows us to 'see through' the Earth and provides us with a snapshot of the Earth's deep interior. Here, I will review the different tools that are used in global seismology to image mantle plumes and, most importantly, their limitations.

In seismology, two different data types are used which have very different sensitivity and resolution. Body waves are high frequency data which are studied using ray theory and can be used to image small scale structure. These data have been used in global tomography, but also to image sharp features such as mantle discontinuities and they are very suitable to study the possible existence of narrow plumes. However, data coverage is limited by the distribution of earthquakes and receivers and this is a problem in particular for oceanic areas, where most of the plumes are located. In addition, it is important to realise that body waves are only sensitive to velocity perturbations.

Thus, we do not know if the imaged features are caused by temperature anomalies only, or also compositional differences. Normal mode data, on the other hand, are sensitive to both velocity and density perturbations and can in principle provide us with temperature and composition varations in the mantle. However, normal modes only image the large scale features of the Earth and may not be able to show narrow plumes.

Seismologists have been very succesful in making global tomographic velocity models using body waves, which in some models are combined with normal mode data. Different models have very similar long-period structure and all show large areas of low velocities in the upper and lower mantle, which are often interpreted as super plumes (see for example Ritsema it et al., 1999). But, from velocity alone we do not know their temperature perturbation and we have to be careful in interpreting these features. Indeed, the first tomographic model showing temperature and composition variations was published recently (Trampert et al., 2004) which suggested that the super plumes are compositional in origin and dense rather than thermally bouyant.

In addition, seismologists have used transition zone discontinuities to determine if their topography agrees with plumes going trough the transition zone, or not. In particular SS-precursor studies show areas of thinner transition structure, which agrees with a thermal interpretation of a hot plume going through the transition zone. However, this relies on an interpretation of the transition zone discontinuities in terms of olivine phase transitions only and recent studies suggest that the phase transitions in garnet and ilmenite have an important influence on the transition zone discontinuities as well (Deuss & Woodhouse, 2001). This implies that we cannot use simple discontinuity topography observations to determine the origin of mantle plumes.

Thus, in priciple seismology will be able to provide us with strong contraints on the observation of mantle plumes. But, we should be very careful in only using the observations within their limitations and it might be too early at present to draw any strong conclusions for or against the existence of mantle plumes.

Guided Seismic Waves: Possible Mantle-Plume Diagnostics

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Seismic waves potentially provide by far the highest resolution view of the three-dimensional structure of the mantle, and the hope of detecting wave-speed anomalies caused by mantle plumes has been a major incentive to the development of tomographic seismic techniques. Seismic tomography is limited, however, by the uneven geographical distribution of earthquakes and seismometers, which can produce artificial tomographic wave-speed anomalies that are difficult to distinguish from real structures in the mantle.

An alternate approach may be possible, because low-wave-speed channels would act as waveguides that could transmit seismic waves efficiently over great depth ranges in the mantle. The same phenomenon causes fault zones to act as waveguides and provides a useful method for studying faults in the crust. Plume-guided waves would be little affected by bends or other geometric complexities in the waveguides (think of a French horn or a fiber-optic cable), and their dispersion would make them distinctive on seismograms and would provide information on the size and structure of the waveguide.

The main unanswered question is whether guided waves in plumes could be excited sufficiently to be observable. Earthquakes do not occur in the deep mantle, but two other possible sources of excitation can be imagined: (1) shallow earthquakes at or near plume-fed hotspots; and (2) coupling to seismic body waves in heterogeneous regions of the deep mantle. In the first case, downward-traveling guided waves transformed to seismic body waves at the bottom of the waveguide would have to be detected at teleseismic distances. In the second case, upward-traveling guided waves generated by teleseismic body waves would be detected on seismometers at hotspots. Qualitative reasoning based on considerations of reciprocity suggests that the signals in these two situations should be similar in size and appearance.

A failure to find these guided waves experimentally could mean either that the waveguides (plumes) do not exist or that the excitation mechanisms and/or seismometer networks are inadequate. Distinguishing these two possibilities would require careful analysis. Anticipated major improvements in seismic instrumentation, such as the EarthScope initiative, make this a propitious time to undertake such a project.

Is the "D" Region the Source of Mantle Plumes?

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The mantle plume hypothesis requires existence of at least one boundary layer in the deep interior that can experience thermal instabilities that rise to the surface as concentrated upwellings. While the possibility of mid-mantle thermal boundary layers has not been conclusively ruled out, there is little direct observational support for their existence. As a result, the D" region in the lowermost mantle, a several hundred kilometer thick layer above the core-mantle boundary (CMB), is widely invoked as the putative mantle plume source. A thermal boundary layer is expected above the CMB based on theories of the geodynamo, which predict output of heat from the core of from 0.5 to 15 TW. The large uncertainty in geodynamo heat output gives large uncertainty in estimates of the degree of heating from below experienced by the mantle. Nonetheless, there is general agreement that a thermal boundary layer is present in D", and efforts have been made to study the detailed seismological structure of the lowermost mantle to assess the processes occuring in this region. D" structure has several characteristics that indicate that the boundary layer is more complex than a simple thermal boundary layer. Large-scale patterns of seismic heterogeneity exist in D", with two massive low shear velocity provinces beneath Africa and the south Pacific, both of which appear to extend upward 500-1000 km from the CMB. While commonly described as 'superplumes', this appears to be a misnomer. Both regions have very sharp lateral gradients on their margins; both have unusual Vs/Vp velocity ratio perturbations, with much stronger decreases in Vs than in Vp; and there is preliminary evidence that these regions are anomalously dense. It appears that these are not large thermal plumes, but are instead large chemical heterogeneities. Other regions of D" have relatively high seismic velocities and abrupt increases in Vs and Vp about 250 km above the CMB. If relatively low temperatures are responsible for the high seismic velocities, it is plausible that these regions involve the post-perovskite phase transition that was discovered in 2004. The strong positive Clapeyron slope of this phase transition predicts destabilization of the boundary layer, but ironically, this involves regions where mantle down-wellings are believed to exist, not where plumes are hypothesized. A summary of these and other seismological observations and the challenges they present to the notion of D" as a source of mantle plumes will be given.

The Surface of Venus Records Ancient Impacts, Not Young Plumes

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The assumptions and speculations that comprise terrestrial plumology have become ever more convoluted as their predictions have been falsified. Although Venus has no features like those attributed to terrestrial plumes, plumology was exported to Venus, even before high-resolution Magellan radar imagery became available in 1991-94, to explain an assumed need for loss of heat by a planet that obviously lacks plate tectonics. Venusian, like terrestrial, plumology also became dogma by repetition and self-citation, but its specific rationalizations are quite different.

The Venusian features conventionally attributed to plumes have the characteristics expected of variably eroded and buried impact structures and impact-melt constructs, and likely record late-stage planetary accretion older than 3.9 Ga. Accepted by all as of impact orign are 1000 small (maximum rim diameter 275 km, but mostly <50 km) little-modified impact craters. The maximum age of these is widely assumed to be <1 Ga although size-frequency distribution, and consideration of dense-atmosphere effects and bolide strengths, permit much greater age. These are gradationally distinguished, via increasing surface smoothing and degradation in highlands and burial by sediments in lowlands, from several thousand older circular structures commonly assumed to be endogenic. (800 or so of the large old structures are assigned to pigeonholes such as "coronae", whereas many other large ones, and nearly all small ones, are ignored in conventional analysis.) Many of these old structures are much larger than any of the young impact structures, and most have the rimmed-basin morphology, and often the cookie-cutter superpositions, expected of impact structures. None of the scores of conflicting published conjectures as to how plumes, antiplumes, and related endogenic processes might form these old structures have addressed their consistent circularity, morphology, and superpositions. Four of the youngest of the old structures have circular rims 800 to 2000 km in diameter and, if indeed of impact origin, are, by analogy with dated late-stage lunar Imbrium Basin, about 3.9 Ga. Unearthlike broad, yet very low, volcanoes in, and overflowing ("volcano-corona hybrids"), ancient impact basins do not resemble terrestrial volcanoes or large igneous provinces and likely are of impact melts, as are pancake-spreading magma-lake(?) plateaus 1000-2000 km in diameter. Venus apparently preserves an eroded and partly buried landscape of late-stage planetary accretion because (as is consistent with all available geophysical and compositional data) its mantle is too cold and dry for earthlike circulation.

Plumology may be inapplicable also to Mars. Half of the surface is of eroded impact-saturated rubble, and most of the other half has a similar landscape buried beneath thin sediments. Rationales that local volcanic highlands were formed by plumes are strained, and their magmatism may be of impact origin.

Venus' Many Circles: Extraterrestrial Clues for the Great Plume Debate

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Venus has long been considered Earth's sister based on solar distance, size, density, and presumed composition. Yet, like many siblings, Venus and Earth took quite different evolutionary paths. Venus lacks evidence of plate tectonics, marked on Earth by linear global features. Rather, Venus displays a wide range of circular features: impact craters (1-270 km), coronae (60-2600 km, 200-km mean), volcanic rises (1500-2400 km), and crustal plateaus (1500-2600 km); the latter three are variably interpreted as the surface expressions of diapiric structures, be they thermal (i.e., plume), compositional, or undefined. Some workers suggest that all coronae represent impact features, and others propose that all of Venus' circular features resulted from bolide impact.

Venus provides an excellent opportunity to test plume and alternate plume hypotheses. 1) Venus is expected to have a heat budget similar to Earth, and as such requires a mechanism by which heat is transferred from core (or mantle) to crust. 2) Venus lacks plate-tectonic processes, thus plate tectonic-related alternate hypotheses are not viable. 3) Venus preserves an excellent surface record (albeit remote) unmodified by erosion and plate-tectonic processes. 4) Widely available NASA Magellan data provide 3D surface views at high resolution, allowing first-order geologic analysis, coupled with subsurface constraints based on gravity-topography data. 5) Venusian 'fieldwork' only requires computer access, making data collection, data analysis, and hypothesis testing accessible to all.

Morphologically, structurally, and geologically distinct features on Venus likely formed by a variety of mechanisms. Volcanic rises appear most consistent with plume-lithosphere signatures based on size, morphology, ADC (apparent depth of compensation) and geologic history. Although we previously argued that crustal plateaus (marked by shallow ADC) represent the surface signature of thermal plumes on thin lithosphere, recent detailed structural analysis of plateau surfaces appears more consistent with progressive crystallization of huge lava ponds, perhaps the result of bolide impact on thin lithosphere and massive partial melting of the mantle. Coronae seem to represent at least three types of genetically unrelated features: 1) domical features (~60-500 km) marked by radial fractures and extensive flows likely representing (compositional) diapiric structures; 2) circular topographic lows (~100-400 km) that lack radial fractures and extensive associate flows, possibly recording bolide impact on locally weak crust; and 3) huge features (~800-2600 km; e.g., Artemis, Hengo, Quetzalpetlatl), best explained by a thermal plume hypothesis.

Meteorite Impacts as Triggers to LIPs and Hotspots

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The combined effects of impact melting, enhanced by sub-crater decompression melting in computer simulations of ~200 km craters produce characteristic high melt volumes of approximately 106 km3 derived from the uppermost ~150 km of the Earth's mantle. The coincidence between expected frequency of such impact events combined with the similarity in magma volumes of large igneous provinces (LIPs) suggests that large meteorite impacts may be capable of triggering LIPs and mantle hotspots from a point source which is subsequently buried, as eg: oceanic plateaus. There are two main aspects to test this idea; firstly what are the distinctive macroscopic criteria predicted from an impact model, and secondly, how may these be recognised in the geological record of the Earth. We illustrate the impact melting potential with a detailed model for the Ontong Java Plateau, and use this as a discussion point to assess predicted geochemical, geophysical and geological characteristics of such a process. These might include; geotherms and melting; mixed volcanic versus impact signals; paucity of shock relative to thermal features; distal deposits, spherule beds, ejecta and ash layers; where to look?; proximal-distal-global markers; ocean drill cores and sequence startigraphy etc.

Impact Induced Martian Mantle Plumes: Implications for Tharsis

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Tharsis province is a major center of Martian volcanism and tectonismcharacterized by large gravity and topography anomalies. Initial development of Tharsis occurred rapidly during the earliest epoch of Mars history. The distribution of volcanic and tectonic activity associated with Tharsis led to the suggestion that the planform of Martian mantle convection is dominated by a single, large, long-lived upwelling. The origin of the upwelling is debated. One hypothesis is that the upwelling is a thermal plume originating at the core-mantle boundary similar to a terrestrial plume but much larger. An alternative hypothesis is that the upwelling is associated with late stage evolution of a local Martian magma ocean produced by a large impact during planetary formation. The physical processes controlling evolution of an impact induced melt region suggest that, within the uncertainties of various parameters, in situ crystallization to a partially molten solid state and a relatively long adjustment timescale are a possibility. Fully three dimensional spherical shell simulations of thermochemical mantle convection indicate that such an initial state generates a localized mantle upwelling - an impact induced plume. A scenario consistent with observational constraints on the volume of magmatic material and emplacement rate is suggested.

Tuesday Poster Sessions

Patterns of Rhyolitic Volcanism in the Path of the Yellowstone Hot Spot

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The Snake River Plain-Yellowstone Plateau (SRP-YP) developed over the last 16 Ma as a bimodal volcanic province in response to the southwest movement of the North American plate over a fixed melting anomaly. Volcanism along the SRP-YP province is dominated by eruptions of explosive high-silica rhyolites and represents some of the largest eruptions known (Mason and others, 2004). Basaltic eruptions represent the final stages of volcanism, forming a thin cap above voluminous rhyolitic deposits. Volcanism progressed episodically from southwest to northeast along the plain in successive volcanic fields comprised of nested caldera complexes. Most major caldera-forming eruptions within a particular field are separated by about 0.2 to 1 m.y., similar to the present-day Yellowstone Plateau volcanic field. Major ignimbrite eruptions from volcanic fields are separated in time by as much as 2 m.y. from the eruption of the youngest caldera-forming event in one field to the next caldera-forming event in the younger, adjacent field. Spatially, adjacent volcanic fields are separated by 50-150 km from center to center. Passage of the North American plate over the melting anomaly at a particular point in time and space results in uplift, regional tectonism, massive explosive eruptions and caldera subsidence, resurgence in selected areas, and finally basaltic volcanism and subsidence (Pierce and Morgan, 1992; Pierce and others, 2002). Smaller rhyolitic lava flows occur during both pre- and post-caldera phases.

The Heise volcanic field in the eastern SRP, Idaho immediately to the southwest of the Yellowstone Plateau volcanic field, provides a definitive example of the SRP-YP volcanic field cycle. Five large-volume rhyolitic ignimbrites constitute a time-stratigraphic framework of late Miocene to early Pliocene volcanism in the eastern SRP. Field relations and high-precision 40Ar/39Ar age determinations establish that four of these regional ignimbrites were erupted from the Heise volcanic field forming the framework of the Heise Group; the source of the fifth unit is outside the Heise field. The Heise units include the Blacktail Creek Tuff (6.62± 0.03 Ma), Walcott Tuff (6.27± 0.04 Ma), Conant Creek Tuff (5.51± 0.13 Ma), and Kilgore Tuff (4.45± 0.05 Ma; all errors reported at ± 2 sigma). Facies and magnetic fabric data indicate that these units erupted from separate calderas, each with a set of discrete vents. Major eruptions in this province are separated in time and space while less voluminous minor rhyolitic eruptions fill in the spectrum. Large caldera forming eruptions and development of individual volcanic fields are related to rate of movement of NA plate, amount of material available in crust for melt, the degree of depletion which has occurred in the crust, and flow dynamics in the upper crust.

Timescales of Flood Volcanism Recorded by Pressure Variations in Coeval Mafic Intrusions: A Fluid Inclusion Study of the Skaergaard Intrusion, East Greenland

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Secular variations in the pressure of mafic intrusions emplaced into the basal portion of flood basalt successions provide constraints on the timescale of volcanic built-up and subsidence. Because mafic intrusions solidify in a few hundred thousand years or less, changes in the pressure of such intrusions provide succint constraints on the duration of volcanism and is, typically, on a finer timescale than radiometric age determinations. As an example, we have determined the pressure of the formation of fluid inclusions in quartz from granophyre bodies, that is cm- to metre-sized pockets dominated by intergrown quartz and alkali feldspar, in the Skaergaard Intrusion emplaced into the basal portion of the East Greenland flood basalt succession. The results demonstrate that the pressure for different zones of the intrusion, corrected to the pressure at the position of the roof in contact with the overlying volcanic rocks, increased from 0.8 ± 0.5 to 3.0 ± 0.5 kbar during solidification. This pressure increase can be explained by the emplacement of 7.3 ± 1.5 km of flood basalts over the intrusion. The cooling model of Norton and Taylor (Journal of Petrology 20, p. 421-486, 1979) shows that the time elapsed between the formation of the low and high pressure rocks in the intrusion was c. 260,000 years. This is, however, most likely a minimum value because they assumed a constant pressure of 1 kbar. We therefore surmise that 7.3 ± 1.5 km of flood basalts were emplaced over the Skaergaard Intrusion in less than 3-400,000 years. These flood basalts erupted immediately landward of anomalously thick oceanic crust of the Greenland-Iceland Ridge. The volcanic productivity over the Skaergaard Intrusion is similar to that calculated for the oldest and most landward seafloor of the Greenland-Iceland Ridge (Holbrook et al., Earth and Planetary Science Letters 190, p. 251-266, 2001).

Global Gravity, Bathymetry, and the Distribution of Submarine Volcanism through Space and Time

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The seafloor is characterised by numerous seamounts and oceanic islands which are mainly volcanic in origin. Relatively few of these features (<~ 0.1%) have been dated and so there is little known about either their tectonic setting or age. One parameter that is sensitive to whether a submarine volcano formed on, near, or far from a mid-ocean ridge is the elastic thickness, Te, which is a proxy for the flexural strength of the lithosphere. Most previous estimates of Te are based on using the bathymetry to calculate the gravity anomaly for different values of Te and then, selecting the Te that best fits the observed anomaly. The problem with this approach is that, for most seamounts, bathymetric data are usually limited to single-beam echo-sounder data acquired along individual ship tracks. These data do not define the shape of the seamount. Therefore, gravity modelling usually assumes either that the seamount has infinite extent perpendicular to a ship track or is circular in planform. Either of these assumptions may bias Te. The gravity anomaly derived from satellite altimeter data, in contrast, has furnished information on the shape of seamounts, as has been shown most recently by Wessel (2001). We have therefore used a technique, developed originally by Smith and Sandwell (1994) and Lyons et al. (2000), to predict bathymetry directly from the satellite-derived gravity anomaly. By comparing predicted and observed bathymetry in the vicinity of each feature in the Wessel (2001) data base, we have been able to estimate Te at > 10,000 submarine volcanoes. We present here the results of our analysis and examine its implications for the tectonic setting, age, and distribution of submarine volcanism through space and time.

Duration and Timing of the Deccan CFBP

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Previous dating studies of the Deccan CFBP have concentrated upon the ‘classic’ sections exposed along the Western Ghats escarpment. These data have provided crucial preliminary insight regarding the timing and duration of the CFBP, and have indicated a geologically rapid eruption at, or near to, the Cretaceous-Tertiary boundary (KTB; 65.0 0.1 Ma). This argument has remained pivotal to arguments citing Deccan volcanism as a primary or contributory cause to global biotic extinction, and to the wider models of CFBP generation. However, whilst ‘classic’ sections provide easy access to parts of the Deccan succession, they do not offer an entire chronological record of eruptions.

High-precision 40Ar/39Ar ages,taken within a well-defined and detailed stratigraphical context are presented for the Deccan. Data from the stratigraphically highest and lowest basalts bracket the entire Deccan lava succession, and thus provide a comprehensive estimate for the timing and duration of this volcanic episode. Analyses were performed on more than 20 selected samples, using incremental laser heating on plagioclase separates. Results are reported relative to the GA1550 biotite standard.

The new data suggest a duration of 2 – 3 Myr for the eruption of the main Deccan province (MDP). The earliest flows (66.8 0.4 Ma) occur in the north-western corner of the MDP where they were erupted onto the Late Cretaceous, dinosaur-bearing, Lameta beds. Importantly, these basal lavas indicate that the onset of flood volcanism began some 1.5 – 2 Myr before the (Cretaceous-Tertiary boundary (KTB). The final Deccan flood basalt eruptions are of Paleocene age (63.6 0.4 Ma) and are preserved in the south-western Deccan. The onset of Deccan CFB volcanism began in the north of the province during the late Maastrictian, and rapidly reached an acme of eruption during Chron 29R. This eruptive acme continued across the KTB and into the Danian, with successively younger lava fields building on the southern flank of the evolving Deccan volcanic edifice.

The SWELL Pilot Experiment off Hawaii - What Can We Learn About the Hawaiian Hotspot from Surface Waves?

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The SWELL Pilot Experiment was one of the first long-term deployments of ocean bottom seismic equipment to record long-period surface waves to a period of 90s. The superior quality of the dataset allowed us to image the southwestern edge of the Hawaiian swell. A surprisingly deep situated low-velocity anomaly suggests that the cause for the swell relief is sub-lithospheric. We have also embedded the dataset in our global database. Initial research suggests that the low-velocity anomaly is not centered beneath the Hawaiian island chain but slightly off-center to the southwest where the swell bathymetry is shallower than in the northeast.

The pilot experiment used differential pressure gauges (DPG) as sensors. For the deep-ocean environment off Hawaii, it remains to be seen whether ocean bottom seismometers can reach similar signal-to-noise levels.

Comprehensive Imaging of the Eifel Plume, Central Europe

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Volcanic eruptions occurred in the Eifel mountains in the western part of Germany since Mesozoic time. Two new volcanic fields evolved in the last 600 ka and the latest eruptions occurred only 11-12 ka B.P. At the same time strong uplift (up to 250 m in 600 ka) occurred in the region. To study the deep structure of the Eifel region 10 European institutions shared their facilities to operate a network with 84 permanent and 158 mobile stations including 32 broadband instruments during an 8 months field experiment. The network had a 500 km by 500 km aperture and the mobile stations were deployed between Nov-3-1997 to June-23-1998.

The 3D P-wave model contains a column-like low-velocity anomaly (LVA, -1% to -3%) in the upper mantle underneath the Eifel volcanic fields reaching down to at least 400 km depth. The S-wave model has a prominent LVA of up to -5% in the upper 100 km of the mantle. At 200 ± 50 km depth there is no clear S-wave velocity anomaly. Below the S-wave velocity reduction is about -1%, and it extends at least to the transition zone. Receiver functions also find the positive S-wave anomaly at 200 ± 50 km depth. The 410 km discontinuity is depressed by 20±5 km indicating an increased temperature, while the 660 km discontinuity appears to be unperturbed. The top of the low-velocity anomaly is found at about 50-60 km depth by receiver functions as well as Rayleigh and Love wave dispersion models.

Teleseismic P-wave attenuation shows a strong absorption anomaly in the lithosphere and a weaker anomaly in the mantle. The lithospheric damping anomaly is interpreted as a magmatic intrusion zone that scatters the wave amplitudes. In the asthenosphere temperature-induced solid-state anelastic attenuation is assumed. A study of the teleseismic shear-wave splitting (SKS) indicates a local anomaly in the Eifel which may be due to plume-related asthenospheric flow. The P- and S-velocity anomalies in the lithosphere and upper asthenosphere can be explained by an increase of temperature by about 100-150 K plus 1% melt. In the lower asthenosphere, above the transition zone, the excess temperature of the plume is at least 70 K, because the velocity anomalies in the tomography model are underestimated.

Seismic Evidence for a Lower Mantle Origin of the Tanzania Hotspot

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Global seismic tomographic imaging has shown a large and coherent low-velocity anomaly in the lower part of the mantle beneath Africa. It has been suggested that this anomalous structure may be responsible for the unique geological history of Africa. But the link between the structure in the deep mantle and surface tectonics remains unclear. In this study we carry out tomographic inversions for the seismic velocity structure beneath southern Africa, utilizing “banana-doughnut” traveltime sensitivity kernels of body waves recorded by broadband temporary and permanent seismic stations in the region. Preliminary results show a ridge-like low-velocity feature in the upper part of the lower mantle (900 – 1200 km depth) beneath eastern Africa. The low-velocity feature is 300-400 km wide beneath the Kaapvaal craton and becomes broader beneath Tanzania. At shallower depth and in the mantle transition zone, the low-velocity anomaly becomes localized, forming a cylindrical feature beneath Tanzania, which is consistent with an anomalously thin mantle transition in the area.

Our observations have important implications for the deep earth engine. Models of mantle convection driven by a combination of basal and internal heating predict a transition in the shape of a buoyant upwelling from tabular to cylindrical near the basal boundary layer. The ridge-like low-velocity anomaly in the upper part of the lower mantle beneath southern Africa may thus represent upwelling from the instability of a boundary layer in the mid-mantle, possibly above the top of the African superplume. Furthermore, the ridge-like low-velocity anomaly beneath southern African cratons suggests that volcanism in eastern Africa is not the result of passive upwelling driven by plate separation but mainly the consequence of deep, buoyant mantle convection.

Identifying the Origin of the Newberry Hotspot Track

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Located in the northwestern United States, the Newberry hotspot track consists of a sequence of age-progressive volcanic domes and lava flows, showing a monotonic age progression from east to west ending at the Newberry Caldera. The northwest trending Newberry track crudely mirrors the better-known

Yellowstone hotspot track. While located on the North American Plate, the Newberry track cannot be the product of plate motion over a stationary mantle source as its orientation is oblique to plate motion. Instead three end-member tectonic models have been proposed: (1) subduction counterflow, (2) gravitational flow along lithospheric topography, and (3) lithospheric faulting. Our preliminary SKS splits imply anisotropy primarily comes from the asthenosphere and that the anisotropy orientation does not vary with depth beneath the Newberry track. The first order observation is that the SKS splits are not aligned with the Newberry hotspot track as the subduction counterflow model or the gravitational flow model would require, indicating either the splits are not sensitive to mantle flow oriented along the track or the track is not the product of asthenospheric flow. Our splitting observations strongly argue for one layer of anisotropy, making the second explanation preferable. This leaves the lithospheric faulting model as the most likely causal process.

Upper Mantle Structure Beneath the Azores Hotspot From Finite Frequency Seismic Tomography

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The Azores archipelago represents one of the classic hotspots that interact with the mid-ocean ridges. While geochemical studies and a variety of geophysical observables have provided clear evidence for the influence of the deep mantle materials on the formation of the plateau, the seismic structure beneath Azores has never been imaged directly at regional and local scales. Here we construct the first high-resolution P-wave velocity models of the mantle structure beneath the hotspot from teleseismic body waves recorded by 5 portable seismic stations on the Azores islands and the Global Seismic Network station CMLA. Unlike in conventional tomography based on ray theory, the three-dimensional sensitivity kernels of body wave travel times are used to account for waves front healing, scattering, and other diffraction effects of realistic seismic waves. Our inversion from 186 P-wave relative travel times revealed a pronounced low velocity anomaly in the shallow mantle (less than 200 km depth) along the Azores islands and beneath the center of the Azores plateau (38.5N, 29W). From ~250 km to at least the middle of transition zone, the low velocity anomaly forms a plume-like column beneath northeast of Terceira (~200 km away from the center of plateau), bending toward southwest in the shallow mantle. These results are consistent with other geophysical and geochemical observations and provide seismic evidence for the proposed hotspot-ridge interaction model, in which the magma plumbing system bends towards the Azores triple junction, supplying melt preferentially southwestward along a lateral sublithospheric channel.

Uplift and Rifting on Venus: Role of Plumes

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Venus, although Earth's "twin" in size and composition, lacks plate tectonics. However, Venus does show evidence of recent uplift as well as both tectonic and volcanic activity. The planet's most pronounced geoid and topographic highs, Atla and Beta Regiones, lie at nodal points in a network of chasmata. The chasmata, linear to arcuate troughs, extend 1000's of km and may be sites, of current rifting. Great circle arcs fit the chasmata system at the 89.6% level. These arcs total 54,464 km in length, when corrected for Venus' smaller size this comes within 2.7% of the 59,200 km estimate for Earth's spreading ridges. Hundreds of coronae, enigmatic circular features, adorn Venus' surface, ranging in diameter from 60-2600 km with a median of 250 km. Coronae have been modeled and attributed to diapiric-upwellings; however, ancient impacts have been proposed as an alternative explanation. The distribution of coronae over Venus' surface is highly non-uniform, with an excess near chasmata. Indeed, some coronae have rims that intertwine with chasmata walls, suggesting contemporaneous formation. The raised areas of both of Atla and Beta Regiones are ringed by numerous coronae, but neither has coronae at or near their crests at the highest geoid levels. Using an evolutionary classification of coronae, we use inferred coronae stage to assess the relative activity at Atla and Beta, and we conclude that Atla has been active more recently.

Venus' craters, unlike coronae, have nearly a random distribution over the planet's surface, with a slight, but statistically significant deficit close to chasmata. A minority of craters are modified, but an excess of the tectonically or volcanically disturbed craters occurs near chasmata and the uplifted regiones. Impact craters on Venus can independently determine relative age, degree of modification, and reorientation of an area. Low crater densities exist with coronae and surprisingly, even out to 4 radii, whereas we would expect locally higher densities of craters if coronae were themselves very old impact features. Furthermore, modification of craters adjacent to and within coronae argues for the existence of long-term tectonic and volcanic activity, as opposed to formation of coronae by instantaneous, ancient impacts.

We attempt to relate coronae formation to the existence of plumes on Venus. Our goal is to clarify the mechanism of uplift on Venus, and in turn to link the process to the global system of rifting.

Wendesday Oral Sessions

Plumes and Uplift

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Hotspots are so-called for good reason. Not only is there excess magmatism, but there is also increased heat flow, and surface uplift due to thermal and dynamic buoyancy. Surface uplift persists where a hotspot is active e.g. Hawai'i and Iceland and decays away from the hotspot, consistent with predictions from plume models. During the early stages of hotspot (and plume) development, where a large igneous province may be formed, uplift may be both rapid and large. Here, model predictions are more contentious, but uplifts of the order of one or more kilometres, radiating over a distance of several thousand kilometres, are expected. Are they found?

In this session specific case studies will be used to illustrate the consistency of the plume model with predicted and observed uplift patterns. I shall focus specifically on the Siberian LIP which, others have argued, has no associated uplift and, by implication, no associated plume. This suggestion has been made despite the rapid eruption of between 3 and 4 million cubic kilometres of basalt, making it the largest continental flood basalt province on Earth. I shall summarise data which indicate that the main uplift occurred not in the region of Norilsk, but in the West Siberian Basin-Khatanga Trough region, to the northwest of Norilsk. Uplift could have exceeded 1 km, but unfortunately we have no way of determining the total extent of subaerial uplift in this region.

Alternative models, such as the EDGE model, have been used to explain the apparent lack of uplift associated with LIPs generally, and the Siberian Traps in particular. However, this is arguably false logic. Any realistic EDGE model, where hot mantle flows from beneath thick cratonic lithosphere into an adjacent region with thin lithosphere, and where the mantle is sufficiently hot to generate the large volumes of magma, would cause uplift in the overlying lithosphere. Thus, ironically, the magnitude of uplift predicted for the EDGE model could be similar to that predicted for a plume.

Uplift Associated with the North Atlantic Igneous Province

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The magnitude, planform extent and rates of uplift related to North Atlantic Igneous Province (NAIP) activity are estimated using a combination of stratigraphical, sedimentological and paleontological information from outcrop and well logs across Britain, Ireland and the surrounding continental shelf. Two principal phases of uplift are recognized. The first uplift phase is associated with emplacement of the British part of the NAIP (61--58 Ma) and is relatively limited in both spatial extent (few 100 km) and magnitude (few 100 m). A significant proportion of this uplift was permanent, associated with igneous addition to the crust in the vicinity of the surface outcrop. These observations can be explained by upwelling of relatively small volumes of unusually hot and/or fertile mantle directly beneath the region. A second phase of more widespread transient uplift was initiated in the latest Paleocene (around 56 Ma), peaked coeval with the Late Paleocene Thermal Maximum event (around 55 Ma) and decayed through the Eocene. Sedimentary basins adjacent to the west of Britain and Ireland were uplifted by up to 1 km, while regions 500 km to the SE were uplifted by less than 100 m. These large amounts of uplift require unusually hot mantle beneath the plate and the lack of local magmatic activity means that this hot mantle was moving laterally. Phase 2 uplift begins just before and peaks coeval with Europe-Greenland break-up and associated development of volcanic passive margins, so that uplift and magmatism are probably related. Significant uplift of Britain and Ireland over 1000 km away from the break-up zone means that plate boundary processes such as edge-driven convection cannot alone have been responsible for uplift. Phase 2 uplift of Britain and Ireland is therefore best interpreted as the south-eastern quadrant of an uplifted swell, which may have had a diameter of around 2000-3000 km and a maximum amplitude of over 2 km. In both the first and second uplift phases, onset of major uplift preceded maximum uplift by at most 1 Myr and possibly by significantly less. These rapid timescales can be explained by injection of hot mantle into a low viscosity asthenosphere channel.

Surface Responses to Mantle Plume: Sedimentation and Lithofacies Paleogeography in SW China Before and After the Emeishan Flood Volcanism

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The Middle Permian Maokou limestone that immediately underlies the Emeishan flood basalts in southwest China are variably thinned/eroded. Its isopachs delineate a subcircular uplifted area, suggesting a rapid, kilometer-scale crustal doming prior to the Emeishan volcanism. Unusual depositions of Permian age are also present in this region. Specifically, carbonate gravity flows, submarine incised canyon fillings were developed along the western margin of the postulated uplifted area, and rifting trenches, alluvial fan deposits were formed on the eastern margin at the boundary between the inner and intermediate zones. These deposits all rest on the Maokou Formation and are in turn covered by the Emeishan basalts, implying the synchronism between crustal uplift and depositional events. They likely resulted from differential uplift of the inner zone relative to other zones. Comparison of paleogeography lithofacies before and after the Emeishan flood volcanism highlights the determinant role of mantle plume activity in the geologic evolution in SW China and furthermore reveals a two-phase crustal uplift in this region. The rapid (< 3 M.y.), differential erosion of the Maokou Formation was likely related to plume-induced dynamic uplift. This uplift was apparently followed by subsidence resulting in deposition of the marine clastic rocks sandwiched between the basalts and Maokou Formation in the east, and submarine basalts along the western margins of the province. A second phase uplift, attributed to underplating of plume-derived melts at the crust-mantle boundary, is characterized by a plateau-type, prolonged (~ 45 Ma) uplift and was responsible for the formation of the Chuandian "old land". Prevolcanic lithospheric doming also provides a new framework to evaluate the geology, geochemistry, and geophysics of the Emeishan LIP. Systematic spatial variations are observed across the domal structure in the distribution and thickness of clastic and carbonate sediments, the extent of erosion, thickness, and chemistry of volcanic rocks, and the crust-mantle structure. All these features, which are best explained by a mantle plume, may be used to track older plume sites in the geologic record.

The Deccan Beyond the Plume Hypothesis

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The widely accepted mantle plume model postulates that (i) the currently volcanically active Réunion Island, in the Indian Ocean, is fed by the narrow "tail" of a mantle plume that rises from the core-mantle boundary, (ii) the Deccan continental flood basalt province, of India, originated from the "head" of the same plume during its early eruptive phase near the end of the Cretaceous, and (iii) the Lakshadweep-Chagos Ridge, an important linear volcanic ridge in the Indian Ocean, is a product of the plume. It is not generally appreciated, however, that this so-called "classic" case of a plume contradicts the plume model in many ways. For example, there is little petrological evidence as yet that the Deccan source was "abnormally hot", and the short (~1.0-0.5 m.y.) duration claimed by some for the eruption of the Deccan is in conflict with recent Ar-Ar age data that suggest the total duration to have been at least ~8 m.y. The Deccan CFB was associated with the breakup of the Seychelles microcontinent from India. Geological and geophysical data from the Deccan provide no support to the plume model and arguably undermine it altogether. The interplay of several intersecting continental rift zones in India is apparently responsible for the roughly circular outcrop of the Deccan. The Lakshadweep-Chagos Ridge, and the islands of Mauritius and Réunion, are located along fracture zones, and the apparent systematic age progression along the Ridge may be a result of southward crack propagation through the oceanic lithosphere. This idea avoids the problem of a 10-degree palaeolatitude discrepancy which the plume model can only solve with the ad hoc inclusion of mantle roll. Published Ar-Ar age data for the Lakshadweep-Chagos Ridge basalts have been seriously questioned, and geochemical data suggest that they likely represent post-shield volcanism and so are unsuitable for hotspot-based plate reconstructions. "Enriched" isotopic ratios such as higher-than-N-MORB values of 87Sr/86Sr, observed in basalts of the Ridge and the Mascarene Islands may mark the involvement of delaminated enriched continental mantle instead of a plume. High values of the 3He/4He ratio also do not represent a deep mantle component or plume. The three Mascarene Islands (Mauritius, Réunion, and Rodrigues) are not related to the Deccan but reflect the recent (post-10 Ma) tectonic-magmatic development of the African Plate. I relate CFB volcanism to continental rifting, which often (but not always) evolves into full-fledged sea-floor spreading. I ascribe the rifting itself not to mantle plume heads but to large-scale plate dynamics themselves, possibly aided by long-term thermal insulation beneath a supercontinent which may have surface effects similar to those predicted for “plume incubation” models. Non-plume, plate tectonic models are capable of explaining the Deccan in all its greatness, and there is no trace of a mantle plume in this vast region.

Crustal Seismology Helps Constraining the Nature of Mantle Melting Anomalies. Galápagos Volcanic Province, A Case Study

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Wide-angle seismics provides accurate information on the crustal velocity structure and the geometry of the crust-mantle boundary, and velocity-derived density models can be subsequently used to estimate mantle density required to explain observed gravity and topography anomalies. A connection between the seismic parameters and mantle melting parameters can be established based on existing empirical relationships between crustal thickness and seismic velocity of igneous rocks and the mean pressure and fraction of melting within the mantle melting region.

In this work, we compare seismic velocity and density models of the crust and uppermost mantle along five transects crossing the Cocos, Carnegie, and Malpelo ridges in the Galapagos Volcanic Province (GVP). The similar results obtained in all profiles suggest that all the volcanic edifices of the GVP are the product of a single, long-lasting, stable mantle melting anomaly (i. e., the Galápagos hotspot, GHS), in conjunction with a regular process of ridge edification, which has been active for at least the last 20 m.y. The velocity-derived crustal density models account for the gravity and depth anomalies considering uniform and normal mantle densities, indicating that the ridges are isostatically compensated at the base of the crust. A remarkable feature that is systematically observed is an overall anticorrelation between lower crust velocities (and densities) and total crustal thickness. A 2-D steady-state mantle melting model is developed and used to illustrate that it is very difficult to account for the seismic structure of the ridges if it is assumed that the source of the GHS is a thermal anomaly, even if vigorous mantle upwelling coupled with deep damp melting is included in the model. It seems easier to account for the estimated crustal structure if a more drastic, major element heterogeneity, is also considered. Based on these results, we suggest that the primary source of the GHS is a compositional heterogeneity, which may represent a mixture of depleted mantle and recycled oceanic crust. Such a mantle source explains well the isotope and trace element patterns showed by GVP basalts.

Midplate Volcanic Overprinting: New Wine in Old Bottles

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In addition to fresh fracture systems, younger midplate volcanism commonly occupies older lines of weakness, such as older fracture zones, ridge-parallel faults, abandoned spreading centers and pseudofaults created during original spreading-ridge propagation. Ages of emplacement of such overprinted volcanoes are commonly not a linear function of distance, and may be entirely out of order or nearly simultaneous over long distances. Directions and rates of plate motion cannot safely be inferred from the orientations of lines of overprinted volcanoes: crack propagation is not everywhere the main control. Ponded broad lenses of fertile magmas beneath the base of the lithosphere can be tapped by the opening of new fissures, as in the Hawaiian and Samoan chains, or through older fissures, especially where the lithosphere is in tension.

Wednesday Poster Sessions

Delamination Origin for Columbia River Flood Basalts and Wallowa Mountains Uplift in NE Oregon, USA

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The Columbia River Basalts, erupting 17-6 Ma and covering ~175,000 km2 in the U.S. Pacific Northwest, represent the most recent flood basalt event on Earth. The well-mapped, large, continuous areal extent of most early flows allows for detailed flow interface analysis. As demonstrated in a companion abstract [T C Hales et al.], significant crustal uplift preceding flood basalt eruption, a feature typically associated with impingement of a rising mantle plume head, was not present here. Rather, mild pre-eruptive subsidence followed by syn-eruptive and post-eruptive uplift of 300 m, on average, occurred over a broad, 200 km diameter region to the south and west of the dike swarms that produced 90% of these basalts over 1.5 million years, with extreme uplift present in several granite-cored mountains. In addition, from a conventional, fixed deep mantle plume source reference frame for Yellowstone, North American plate motion predicts a hotspot location at 17 Ma that is 400 km south of this area. Though some volcanism (e.g. Steens and Malheur Gorge basalt) was present here at that time, the majority of flood basalt volcanism (e.g. Columbia River Basalts) occurred nearly 400 km away in northeast Oregon, southeast Washington, and western Idaho.

With these simple, well constrained contradictions to the standard plume head hypothesis for hot spot initiation in mind, we deployed the first seismic array focused on imaging the upper mantle in northeast Oregon. Using ~150 teleseismic P-wave arrivals collected over 5 months at the six-station array of broadband, three component seismometers, we find high velocity mantle, +4% Vp relative to IASPI91, beneath northeast Oregon at 70-150 km depth and interpret this anomaly as the melt-depleted mantle source region for the Columbia River Basalts. Assuming an experimentally based density change for depletion of garnet peridotite, this volume of residuum could provide sufficient isostatic support for the total volume of crustal uplift in the broad region. Yet, when considering the local areas possessing excessive uplift (i.e., the Wallowa, Cuddy, and Elkhorn Mountains) within this broadly uplifted region, it is apparent that a different mechanism for uplift is necessary. Mechanical foundering of the lithosphere would allow for large-scale mantle upwelling and decompression melting to occur prior to uplift. Furthermore, the removal of compositionally dense, eclogitic roots to the granitic plutons would decrease density locally, allowing for anomalous areas of uplift. Therefore, we propose that lithospheric delamination provides a better explanation for uplift history and Columbia River flood basalt volcanism than a standard mantle plume.

Continental Breakup Magmatism and Transition to Hot-Spot Influenced Seafloor Spreading From the Moere Margin to the Norway Basin

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Being part of the North Atlantic Igneous Province (NAIP), the Moere margin off mid-Norway is a volcanic passive margin, offset from the volcanic Voering margin to the north by the East Jan Mayen Fracture Zone (EJMFZ). Both margin segments were created during the earliest Eocene (~54Ma), associated with emplacement of large volumes of igneous rocks. In year 2000, an ocean bottom seismometer (OBS) profile was acquired across the Moere margin to the Aegir Ridge, a spreading axis dying in the Late Oligocene. The P- and S-wave data were modeled by a combined ray-tracing and inversion into a 2D velocity model. Due to low magnetic data coverage, a satellite derived gravity map was used to reinterpret the EJMFZ system, but no other proposed fracture zones could be identified. The revised EJMFZ trace was used to re-evaluate spreading direction in the Norway Basin, which is quite asymmetric as it is condensed on the southwestern side. The magnetic track recorded along the OBS profile was used to identify magnetic seafloor spreading anomalies by forward magnetic modeling, and projected onto synthetic flow lines half spreading rates were derived along-profile. Maximum rate was above 3 cm/a between A24A and A24b. The OBS transect shows a rapid transition from continental to oceanic crust with little tectonic thinning of the continent. Breakup magmatism created igneous crust up to 10-11 km thick, tapering down to thin oceanic crust at A23 time, the increased melt potential was thus spent ~2.5 Ma after continental breakup. There is a conspicuous correlation between half spreading rate and igneous crustal thickness. As this is not observed in a normal seafloor spreading environment, both plate spreading velocity and magma production should be governed by a common cause, presumably hot asthenosphere restricted to the rift zone causing both increased melting and extra buoyancy driving force on the plate edges. Later seafloor spreading in the Norway Basin resulted in both thin oceanic crust (4-5 km) typical for slow spreading ridges, and a complete lack of fracture zones along its 500 km length, similar to the ultra-slow spreading Gakkel Ridge. A V-shaped pattern seen in the gravity field around the northern part of the Aegir Ridge corresponds to increased crustal thickness in the OBS model, demonstrating the northeast migration of asthenosphere zones with increased melt production at a speed of 0.3-0.6 cm/a. These observations indicate that once the breakup magmatism abated, the influence on the seafloor spreading from the Iceland hot-spot was present but very weak in the Paleogene. Also, the maximum magma productivity was estimated to be just above 250 cubic-km/Ma/km, considerably lower than seen in other parts of the NAIP. Comparing igneous thickness and P-wave velocity with mantle melting models does not support active mantle upwelling as an important melt-producing process during early seafloor spreading.

Kaapvaal Craton, South Africa: Repeated Basic Magmatism, Diamonds and Plumes

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The Kaapvaal craton in southern Africa contains remarkably well-preserved suites of igneous rocks that provide major constraints on plumes through time. Some of the oldest komatiites (Barberton-type locality) occur here, suggesting that keel/lithosphere formation began 3.5 Ga ago in this region. The best-preserved Proterozoic flood basalt sequence in the world is found in the Ventersdorp Sequence (2.7 Ga). Lavas range from high magnesian to normal basalt. Feeder dykes are known, demonstrating that magmas were emplaced vertically and did not flow large distances laterally from outside the craton margin. The Bushveld Complex (2.06 Ga) is the largest known layered intrusion. It formed from magmas that were both high magnesian and normal basalt. Importantly, 1 million cubic km of magma was emplaced within a period of 65,000 years. It was immediately preceded by the largest known felsic volcanic event, the Rooiberg Group, presumed to be a crustal melt. Once again, this feature demonstrates that the basic magmas were emplaced vertically, not laterally. Finally, the Drakensberg lavas of the Karoo Supergroup (0.18 Ga) represent another major flood basalt outpouring with early high magnesian basalt followed by normal basalt.

Despite these major basic magmatic episodes (and many smaller events between) a stable keel survived. Through this keel has erupted major diamondiferous kimberlite swarms at 1.2, 0.5 and 0.1 Ga. Mantle nodules and inclusions in diamonds reveal ages from over 3.0 Ga and assorted younger ages that may reflect the above-mentioned major basic magmatic events. Thus, a significant proportion of the 200 km-thick Archaean lithosphere survived these magmatic events. Pathways for magma through this lithosphere probably caused the resetting ages, suggesting that the magma source (plume) did not continue to ascend above a depth of 200 km. The similarity in magmatism for the last 2.7 Ga suggests that similar processes have operated for this time period.

The Setting of LIPS in the Lithosphere Through Time: One Test of the Plume Hypothesis

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A fundamental prediction of the plume hypothesis is that hot plumes rising from the mantle can impinge anywhere on the lower surface of the rigid lithospheric shell of the Earth. There can be no first-order 'top down' control. Therefore, if large igneous provinces, LIPS, result from impingement on the base of the lithosphere of upwelling mantle plumes, however modified by interaction with that upper thermal boundary layer during emplacement, they should occur in geological provinces of all ages, and in all tectonic settings. I believe that a strong case can be made that LIPS are indeed geologically and tectonically ubiquitous in this sense, they formed in cratonic interiors, cratonic margins, oceanic lithosphere, and active orogenic belts. LIPS may therefore be the result of a deep-seated process such as plume entrainment that is 'blind' to a mantle-enveloping shell.

The heterogeneity of the lithosphere with regard to both strength and state of stress appears to control its response to the LIP-generating process. Thus two such magmatic episodes within the same craton at different times, may in one case be associated with continental break-up, and in another only with rifting. Compare within Laurentia, for example, the association in space and time of the ~200 Ma central Atlantic magmatic province with the initial opening of a major ocean basin, and the ~1100 Ma Keeweenawan province and its association with the aborted mid-continent rift system. Again, LIP formation is totally independent of the lithospheric setting, taking place both within an assembled supercontinent in the former case and during supercontinental assembly in the latter. This is also consistent with a plume origin.

It is in active convergent margin orogenic zones that LIPS are perhaps least common. Subducting slabs may inhibit their emplacement in the overriding lithosphere, although along the Transantarctic and Andean margins emplacement of Mesozoic LIPS appears to be controlled by supra-subduction zone extensional regimes. It has been suggested that a buoyant plume beneath a subducting slab may lower its angle of descent, resulting in deformation in the interior of an overriding continent, for example in the cases of the Laramide and Gondwanide orogenies. 'Flat-slab' zones may therefore provide as yet untapped opportunities for seismic tests of the existence of plumes.

Testing a Propagating Shear-Zone Hypothesis for Age-Progressive Magmatism in a Continental Setting: The Oregon High Lava Plains

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A frequently proposed alternative to the mantle plume hypothesis for age-progressive volcanic systems is propagating rifts or shear zones. In the oceanic setting this may be difficult to test by study of the structures themselves because the voluminous volcanic systems overwhelm pre-existing structures. In the continental setting it will more commonly be possible to test the propagating shear zones model by careful evaluation of the time-space patterns of faulting. The Oregon High Lava Plains province is used to illustrate an approach.

Rhyolitic volcanism of the Oregon High Lava Plains is age-progressive, younging to the west from 10 Ma to recent along a 250 km long trend from the Owyhee Plateau to Newberry volcano. The system can not be explained as the direct result of the motion of a plate over a mantle plume because the azimuth of the trend (N75W) is 120 degrees off of the back-azimuth of plate motion. One model proposed to explain the volcanic trend is a propagating shear zone, the Brothers fault zone. Whether or not this fault zone has propagated is testable by evaluation of the time-space patterns of faulting. Recent Ar/Ar dating provides the necessary age constraints. Seven domains with rocks of known age were chosen to cover the province spatially and temporally. Faults in these domains were digitized in a GIS; 3,973 points were entered on 321 faults. Old rocks (~7.5 Ma) in the part of the province where the rhyolitic volcanic system recently arrived (~1 Ma) are significantly more deformed than younger rocks. This is part of a pattern that is inconsistent with propagation of Brothers fault zone over the time-frame of age-progressive volcanism. Alternative models for the High Lava Plains relate it to the Yellowstone melting anomaly, whether that be the result of a mantle plume or shallow mantle upwelling.

Compressional Structures Do Not Show Regional Horizontal Compression Near the Iceland Hotspot

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Oceanic crust is generally formed at diverging plate boundaries under condition of rifting and extension where normal faulting predominates within rift zones. However, reverse fault plane solutions are occasionally found for earthquakes along the Mid-Atlantic Ridge. Furthermore, field observations of striae and in situ measurements in places show compression and reverse faulting.

Does horizontal compression play an important role at oceanic diverging plate boundaries? This question is particularly intriguing in areas above hot spots where the high tectono-magmatic activitiy may, locally and temporarily, cause compression. Horizontal compression induces shortening in the rocks and closes fractures, and thus has implications for the kinematics of the plate boundaries, the magmatism, and the fluid circulation along the fractures. We have systematically looked for evidence of such compression. One of the best ways is to study older and accessible structures in eroded crust that was once formed at the plate boundaries but shifted away.

We have found several cases of reverse-slip motion in our study of thousands of fractures in two areas in Iceland. We selected eight examples from the eroded Tertiary and Quaternary crust of the Borgarfjörður and Hreppar rift-jump blocks, respectively, in West and South Iceland. These examples are among the few structures were both striae and marker horizons could be used to deduce the sense of reverse-slip motion. These structures are commonly found in the field and used as indicators of compression. We find that in our cases the structures have variable kinematic origins and are not the result of regional compression. Vertical displacement along these structures is always small, i.e. less than 10 m, and their strike is inconsistent with stress fields derived from other fractures in the surrounding area. We believe reverse-slip motions occur: (a) In association with dykes, sills, or cone-sheets without evidence of shortening across intrusions; (b) Due to local bends and irregularities of steeply-dipping regional and secondary normal faults. (c) At the tips of steeply-dipping normal faults uplifted by underlying propagating dykes.

If horizontal compression acts in Iceland, its magnitude is not sufficient to shorten the rocks on a regional scale, to close the fractures, or to cause folding. Most reverse-slip motions are local adjustments to companion structures, without regional compressional stress or shortening, and can lead to misinterpretation if not put into the correct context.

Overview of Tectonic Deformation in Past and Present Rift-Jump Blocks, West and South Iceland

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Plate boundaries become unstable above hotspots when they drift over these areas of high volcanic production. The configuration of the plate boundary may suddenly change as rift segments and transform zones connecting propagating and receding rifts are relocated. Blocks of crust may be transferred from one plate to the other by these rift jumps. These rift-jump blocks are characterised by intense fracturing and a complex fracture pattern reflecting a time-varying stress field. Extinct rifts, rift-jumps and rift propagation are identified by their structural relationships, regional tilt, unconformities, paleomagnetic and petrological signatures. In this presentation we focus on the fracture pattern of rift-jump blocks.

Several rift-jumps have occurred in the Iceland area since the initiation of spreading between Greenland and Europe. Two such rift-jumps have been identified in Western and Southern Iceland, south of 65° N. The Borgarfjörður Block of West Iceland is located between the Snæfellsnes Rift Zone (active during 15-5 Ma) and the Reykjanes-Langjökull Rift Zone-RLRZ (active since about 6 Ma). Traces of an old transform zone or an oblique rift exist in this block. The intra-plate Snæfellsnes Volcanic Zone has been active since 2 Ma, and the 1974 Borgarfjörður earthquakes and prominent geothermal manifestations lie near the eastern tip of this chain. The

Hreppar Block is located between the RLRZ and the Eastern Rift Zone (active since about 3 Ma), and lies north of the presently active transform zone, the South Iceland Seismic Zone (SISZ). A long-term plan to study the tectonics of these rift-jump blocks has been set up in order to better understand the mechanisms of unstable plate boundaries in time and space. Below is an overview of a few interesting results to date.

In both blocks the fracture density changes as a function of stratigraphical level within the crustal section. The fracture pattern, tectono-magmatic activity and stress field are complex and change with time. The fracture population consists of six fracture families striking parallel, but also oblique and perpendicular to the rift zones. In the Borgarfjörður Block, the rift-parallel fractures constitute only 1/3 of the total. Dominant fracture directions vary with rock age, but the six fracture families appear from the time when the two rifts and a transform zone connecting them acted together. Among the six families in the younger Hreppar Block, four are most prominent in the late Tertiary and Quaternary rocks. A simpler pattern of conjugate strike-slip faults appears in the Holocene lavas of the presently active SISZ. Some of the active faults of this zone can be traced into the older crust where they are injected by dykes.

Fault types are similar in both blocks, with both normal faulting and strike-slip faulting of opposite senses occurring along all six directions. At the southern boundary of the Hreppar Block, the locations of geothermal manifestations are strongly influenced by the tectonics of the transform zone. In the Borgarfjörður Block, on the other hand, the distribution of geothermal activity is influenced by intraplate deformation, characterised by normal faulting earthquakes. Despite the role of earthquakes, the local openings leading to geothermal manifestations at the surface occur along the six fracture families that are inherited and reactivated from the underlying crusts of the Hreppar and Borgarfjörður rift-jump blocks.

Paleogene North Atlantic Igneous Province and the Iapetus Connection

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The prevailing paradigm for the early Paleogene North Atlantic igneous province holds that the large volumes of basalt erupted during continental breakup were generated by decompression of the ancestral Iceland plume arriving at the base of Pangaea ~60 mys ago. Based on a comparative study of the geochemistry of early Paleogene basalts from the conjugate margins of the North Atlantic Ocean basin, we explore an alternative model. In this model, mantle sources tapped by partial melting reflect ambient upper mantle conditions at that time, specifically lateral differences in sublithospheric mantle composition coupled with modest temperature anomalies (<100 K). Basalts from central east Greenland are dominated by tholeiites enriched in iron and titanium, strongly fractionated rare earth element ratios, low Zr/Nb ratios, and radiogenic isotope compositions corresponding to immature HIMU values. These characteristics are not shared by early Paleogene basalts erupted in southeast and west Greenland that are low in titanium, depleted in incompatible trace elements, and possess radiogenic isotope compositions similar to depleted OIB and MORB. The isotopic compositions of basalts from central east Greenland reflect a mantle source with a mean age of ~600 Ma, while those from southeast and west Greenland are derived from significantly older mantle (>2 Ga). Such regional differences are not readily explained by current plume models, but can be related to features of the regional basement geology. It is probably no coincidence that the southwestern boundary of the Caledonian front and zone of closure of the Iapetus ocean correspond closely to the southwestern limit of the geochemical anomaly associated with the central east Greenland volcanic province. We attribute the distinctive basalt geochemistry and high melt productivity accompanying rifting within the Caledonian suture zone to the presence of subducted Iapetus crust in the upper mantle along this portion of the rifted margin. Given the depleted nature of basalts from southeast and west Greenland, similar "recycled" material was not available south and west of the Caledonian suture zone. Likewise, comparisons between central east Greenland and modern ridge system suggest that source heterogeneities north of the Caledonian front have changed through time. The connection between subduction processes involved in supercontinent assembly and mantle heterogeneities sampled during breakup reduces the necessity to derive recycled material from a lower mantle plume early in the development of the North Atlantic Ocean basin, although it may be important at Iceland today.

Geologic Evidence for a Mantle Plume Origin for Yellowstone: The Pattern and Scale of Volcanism, Faulting, and Uplift Along the Yellowstone Hotspot Track

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A NE-migrating pattern of volcanism, faulting, and uplift define the 750-km-long Yellowstone hotspot track (YHT). Based on the geology associated with the YHT, we favor formation of the YHT by mantle plume (active mantle, deep-sourced) over that by lithospheric-tectonics (a passive mantle responding to lithospheric tectonics, particularly extension). A plume mechanism is supported by (1) youthful uplift and dissection of as much as 1 km NE of Yellowstone that precedes volcanism, (2) crustal tilting away from Yellowstone on leading margin of Yellowstone hotspot, and (3) the highest geoid anomaly in the US that is centered on and extends NE (ahead) of Yellowstone. The following large-scale processes associated with Yellowstone are more directly explained by an active, deep-sourced, rather than passive, mantle upwelling: 1) Yellowstone has the largest concentration of geysers and other geothermal features in the world and heat flow 50 times normal, 2) large-volume volcanism and intrusions occur with Yellowstone and the YHT, and 3) 1) the scale of uplift and faulting extending south and west from Yellowstone span a width of ~400 km,. The eastern Snake River Plain (ESRP), in the younger part of the YHT, has active faults on its margin and volcanic rift zones across the ESRP that are at high angles to its trend, inconsistent with formation of the ESRP by lithospheric rifting driving mantle upwelling. After 10 Ma, both caldera-forming volcanism and high rates of faulting have migrated NE along the YHT at the same rate and direction as predicted by North American plate motion over a mantle plume. The YHT is parallel to but failed to follow a major crustal flaw (the Great Falls tectonic zone in the larger Madison mylonite zone) even though the zone is only 40 km N of the YHT, favoring a fixed mantle plume rather the lithospheric pull apart (rift) origin. The YHT started ~16 Ma with widespread flood basalt volcanism (Columbia River Basalts and correlative flood basalts in Oregon and N California) and formation of the N-S, 1,100-km-long Nevada-Washington rift zone, similar to other plume-head events. Modeled asthenosphere parallel to this N-S rift is buoyant and consistent with a relict plume head. The simultaneous NW progression of rhyolite volcanism across southern Oregon may involve plume-head spreading, slab subduction, and strike-slip faulting and not necessarily negate a plume origin of the YHT. Finally, recent tomographic studies have imaged a 100-km-wide low velocity zone to at least 500 km beneath Yellowstone (Yuan and Dueker, in press 2005).

Passive Margin Evolution: Are Plumes an Integral Part of Continental Breakup?

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When continental crust undergoes rifting and extension that results in formation of new oceanic crust, a transition zone between undeformed continental crust and oceanic crust is formed. This zone becomes a locus of later sedimentary deposits and, as long as it remains tectonically quiescent, is termed a ‘passive margin’. Traditionally, passive margins have been classified as ‘volcanic’ or ‘non-volcanic’. This nomenclature is misleading, however, as all passive margins are ultimately volcanic, i.e. ocean crust formation is a volcanic process. We propose a classification based on timing of onset of volcanism, with ‘volcanic’ margins simply a result of early onset of volcanism and ‘non-volcanic’ margins resulting from continental stretching without volcanism before intiation of sea floor spreading. With this scheme, the role of plumes as sources of early volcanism is less clear. This poster will discuss these points, with a focus on the South Atlantic.

Does a Fault in the Plate Circuit Ruin Intra-ocean Comparison of Hotspot Tracks?

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Whether hotspots are plumes that are relatively fixed in the mantle is an important question of modern geodynamics because of its implications for modes of mantle convection and the widespread use of the hotspots as a reference frame for plate reconstructions. Although once widely accepted, the "fixed" hotspot approximation has come under recent scrutiny as some results that apparently contradict this assumption have been reported. One source of doubt about fixed hotspots is the finding of a discrepancy between hotspot tracks predicted in different oceans. Typically, investigators have tried to predict the path of the Hawaiian-Emperor seamount chain from the motion of Indo-Atlantic plates over the hotspots transferred to the Pacific using a plate circuit through Antarctica. Several such studies have found that the predicted Hawaiian-Emperor track has little or no bend and diverges significantly from the trend of the older, Emperor Seamounts. One interpretation is that the Indo-Atlantic and Pacific hotspots experienced significant and potentially rapid relative motion prior to 40 to 50 Ma. An alternative interpretation is that plates in the plate motion circuit may not have been rigid throughout the time interval encompassed by the reconstructions. Both Antarctica and the south Pacific plate are poorly explored areas that have been postulated as the locus of this missing motion. In the Pacific, paleomagnetic data from Ontong Java Plateau display a discrepancy that suggests ~15 degrees less northward motion than the rest of the Pacific, approximately the same offset indicated by intra-ocean hotspot comparisons. Furthermore, Jurassic basalts from the plateau edge are out of place compared with other coeval Pacific crust by the same amount. Other south Pacific paleomagnetic data may support this finding and suggest that there is an unrecognized break in the southern Pacific plate. Within Antarctica, Late Cretaceous and early Cenozoic relative motion between east and west Antarctica has been shown in several studies; although, the amount, timing, and rotation poles are uncertain. It seems clear that a break in the plate circuit is not only plausible, but likely. What is more, recent reconstructions of Pacific and Indo-Atlantic paleomagnetic data into the hotspot reference frame show good agreement whereas reconstructions using plate motions fail to bring the paleomagnetic data into coincidence [Andrews, D. L., R. G. Gordon, and B. C. Horner-Johnson, EOS, Trans. AGU, 85, Fall Mtg. Suppl., Abstr. V51B-0540, 2004; Gordon, R. G., D. L. Andrews, B. C. Horner-Johnson, and R. R. Kumar, EOS, Trans. AGU, Jt. Assem. Suppl., Abtr. GP22A-06, 2005]. This result suggests that the discrepancy between observed and predicted hotspot tracks results from one or more flaws in the trans-Antarctic plate circuit, rather than significant intra-hotspot motion. Whether hotspots are have little motion relative to one another is still an open question; however, the failure of efforts to reconstruct hotspot tracks using plate circuits is not a compelling argument against the fixed hotspot hypothesis.

Co-location of Eruption Sites of the Siberian Traps and North Atlantic Igneous Province: Implications for the Nature of Hotspots and Mantle Plumes

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One of the striking exceptions to the mantle plume head-tail hypothesis that seeks to explain the exceptional magmatism of large igneous provinces (LIPs) and hotspot tracks is the ~250 million-year-old Siberian Traps. The lack of a clear hotspot track linked to this LIP has been one motivation to explore non-plume alternative mechanisms. Here, we use paleomagnetic Euler pole analysis to constrain the location of the Siberian Traps at the time of their eruption. The reconstructed position coincides with the region that also saw eruption of the ~61-58 million-year-old North Atlantic Volcanic Province (NAVP). Together with LIP volume estimates, this reconstruction poses a dilemma for some non-plume models: the partial-melts needed to account for the Siberian Traps should have depleted the enriched upper mantle source that is in turn crucial for the later formation of the NAVP. These analyses suggest the existence of a long-lived (>250 m.y.) lower mantle chemical and/or thermal anomaly, in the region of the present-day Iceland hotspot. These observational constraints also suggest that a nascent plume is not needed to produce flood basalt volcanism - plume material filling a rifting lithospheric thinspot may be sufficient.

NE Atlantic Breakup and Evolution of the Norwegian-Greenland Conjugate Volcanic Margins: Field Evidence to the Great Plume Debate

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A set of regional transects across the conjugate Norwegian-Greenland margins in NE Atlantic integrated with potential field data and modelling reveal important vertical and lateral variations in crustal configuration and composition associated with continental breakup near the Paleocene-Eocene transition and its preceding phase of extension in Late Cretaceous-Early Tertiary times. The Norwegian-Greenland volcanic margins belong to the North Atlantic Large Igneous Province, and several observations substantiate their formation by impingement of the Iceland plume on a lithosphere under extension. In particular, preceding extension culminated with regional uplift and subsequent erosion towards the end of Paleocene, and lithospheric breakup was accompanied by a massive, regional magmatic event, resulting in thick seaward dipping reflector sequences that manifest massive eruptions of lavas covering large areas along the continent-ocean transition. Refinement of the continent-ocean boundary and seafloor spreading anomalies along the conjugate margins provide improved geometrical and azimuthal constraints on early opening plate reconstructions that, in turn, confirm high early opening spreading rates and contribute to a better understanding of the coupling between volcanism and early sea floor spreading. Furthermore, a denser OBS data coverage contributes to a more detailed (3D) mapping of magmatic continental underplating (7+ km/s lower crustal body) volumes and distribution, constrained further by potential field modelling. From high-quality OBS data the Vp/Vs ratio can provide constraints on physical properties of the underplated material to enlighten its nature as either a compact melt body or most probably highly intruded lower crust. Therefore, improved constraints can be reached through modelling of various syn-breakup processes, such as: regional extension and magmatism (including estimates of volumes and rates); extent and timing of the subsequent continental heating; and the interplay of sedimentation, magmatism and vertical motion. Seismic mapping shows a distinct lateral distribution of breakup-related rocks revealing the influence of the along-strike segmentation and its role in the tectono-magmatic margin evolution. In particular, the Norwegian margin is divided into a series of rifted, sheared, and oblique-segments that appear to have experienced different structural, magmatic and temperature histories. Details on margin physiography during early opening are crucial for understanding the driving force for vertical movements at a local and regional scale.

Bermuda: Lava-lamp Plume, Edge-driven Convection, or/and Response to Distant Plate Reorganization?

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The ca. 600x900km Bermuda Rise (BR) represents old (ca. 150-90Ma) oceanic lithosphere currently elevated up to ca. 800-1000m (residual depth anomaly). The rise, compensated at ca. 50km depth, is accompanied by a 5-10m geoid high and a small (5 to 10 mW/m2), poorly resolved heat flow high. The uplift began in Middle Eocene times but continued at reduced rates into the Miocene. Igneous activity was confined to the rise summit, where pillow basalts began to build a 100km long chain of four volcanoes (Bermuda is the largest) during or immediately after rise uplift began.

Geophysical modeling, largely in the 1970s-1980s, has been reasonably successful in matching observations with some combination of distributed heating in the lower lithosphere, and/or shallow mantle convection involving the lower part of the thermal lithosphere.

However, the lack of the expected hotspot trace, among other factors, led Sclater and Wixon (1986), Vogt (1991) and King and Anderson (1998) to consider shallow mantle convection that is attached to and moving with the lithosphere.

Hawaii-Bermuda differences (Both BR and the short volcanic chain on its crest are perpendicular, not (sub-)parallel to putative plate motion; absence of a continuous hotpot "trace" plus evidence against migration of Bermuda uplift with time; lack of subsidence of rise and volcanic pedestal) have been attributed by plume advocates to the slower motion (15-30 mm/a at Bermuda vs 90mm/a at Hawaii) over the subjacent mantle, and/or a "weak", lava-lamp-like plume under Bermuda. The latter behavior is required to account for the lack of a hotspot trace east of Bermuda, and the 20-30my gap in igneous activity between Bermuda and the youngest (65Ma) postulated Bermuda-hotspot-generated igneous bodies in Mississippi. However, as noted by Cox and van Arsdale (2002) particularly the Duncan (1984) fixed-hotpot model does crudely predict the directions and ages of igneous activity from Mississippi to Kansas (115Ma), observations which other models must write off as coincidental.

A new compilation of unusual coeval tectonic and magmatic events around the world suggests Bermuda was not a temporally isolated event, but one of many local/regional responses (e.g. Rona and Richarson, 1978) to global plate reorganization occasioned by the Eocene replacement of rapid (ca 100 mm/a) northward subduction of Tethyan oceanic lithosphere by slower(50mm/a) collision of Indian with Eurasian continental crust. Because plate reorganizations in general require reorganizations of passive asthenosphere return flow ,global synchronism might be explained (following Anderson, 2002) without appealing to global reorganization of plume-type mantle convection(Vogt,1975). However, some kind of local or regional "pre-conditioning anomaly" in the subjacent mantle lithosphere/asthenosphere below Bermuda is then required (e.g.,location relative to continental edges and MOR axis (Vogt,1991); fertile patch or zone of weakness) to explain how and why Bermuda happened WHERE it did.

A plume type model for Bermuda could be supported (or not) if 1) future seismic experiments resolved velocity anomalies in the lithosphere, asthenosphere, or deeper below the predicted present location of the Bermuda hotspot, ca. 500 km east of Bermuda; 2) seismic experiments resolved anomalies in the lithosphere between the BR and Mississippi; and/or 3) geochemical or isotope characteristics of the Mississippi-Kansas igneous bodies in some significant way resembled those of Bermuda lavas and lamprophyre sheets. Non-plume formation models would be supported by 1) pre-existing (i.e., pre-Eocene) "pre-conditioning" anomalies in the lithosphere within which the BR and volcanoes developed and 2) turbidites offlap the BR in a way to suggest simultaneous uplift over the entire BR, vs outflow from a narrow plume.

The Deccan Basalt – Basement Contact: Evidence for a Plume-Head Generated CFBP?

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The widely accepted 'plume head' model of continental flood basalt (CFB) genesis predicts a pre-volcanic, domal uplift. This should be accompanied by associated regional erosion immediately prior to, and during the onset of the main eruptive phase. However, once initiated, rapid lava effusion generates a swiftly-growing volcanic edifice that may effectively bury evidence of these early uplift and erosion stages. By contrast, non-plume, 'edge-driven convection' (EDC) models do not predict significant pre-volcanic uplift; an absence of regional uplift or erosional indicators in the pre-volcanic geological record has thus been used to help substantiate such models. The current work synthesizes evidence gathered from extensive Deccan fieldwork, conducted over a period of 20 years, in an effort to resolve whether or not models predicting 'plume head' uplift and erosion actually satisfy the field observations.

The nature of the basement-basalt contact is examined at key localities around the periphery of the Deccan Volcanic Province (DVP), India. Each locality offers a different geological setting and, when considered together, reveals the nature of the pre-, syn-, and late-stage volcanic environments, and the growth of the DVP edifice. High precision 40Ar/39Ar data confirms that the lavas comprising the DVP become younger both southward and south-eastward, thus supporting models invoking a southward migrating locus of volcanism. In the northern DVP, early lavas include K-rich picrites which lie with angular unconformity upon Late Cretaceous marine limestone and fluvial sandstone successions. In some instances thick conglomerate sheets containing both basement and basalt clasts intervene between the tilted sedimentary succession and overlying lavas. These provide evidence of significant erosion having occurred in the earliest phases of DVP eruption. Only at a much later stage did the lava fields arrive at the eastern and southern periphery of the DVP. Here, they quiescently over-ran pre-existing topography and contemporaneous lacustrine environments.

Thursday Oral Sessions

Geochemistry and Mantle Plumes

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The notion of mantle plumes has been variously invoked in the geochemical literature, and there is some danger that the existence of mantle plumes is debated on the basis of the weaker, rather than the stronger arguments for their support. It remains difficult to identify mantle plumes on the basis of geochemistry, both because mantle plumes are physical phenomena, and because it is only occasionally possible to infer the depth of origin of intraplate material on the basis of geochemistry. Geochemistry is used to distinguish intraplate basalts from those generated in other tectonic settings, but only some of those basalts may be associated with mantle plumes. Thus, the isotope and trace element geochemistry of basalts from Auckland, the Cape Verdes, certain seamounts, and Hawaii, have many similarities implying that they are derived from non-MORB relatively enriched mantle. However, it is most unlikely that they are all associated with mantle plumes, irrespective of how mantle plumes are defined. The key aspect of magmas that have been associated with mantle plumes is that they have relatively high volumes, and melt generation rates – they are volume anomalies that necessarily reflect some form of physical anomaly in the melt generation zone, whether that is temperature or volatiles. At present there is little evidence that they are characterised by relatively high volatile contents. These high volume magmas share some geochemical similarities that are in turn therefore associated with melting within upwelling material, widely termed mantle plumes. Finally, the links between mantle components, recognised primarily on the basis of their radiogenic isotope ratios, and mantle plumes will be explored.

Magmatic Evolution of Mauna Loa Volcano: Implications for a Chemically and Thermally Zoned Mantle Plume

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Hawaii is regarded as the archetypal expression of a mantle plume. The Hawaiian plume is thought to be zoned in both temperature and composition, and the magmatic evolution of Hawaiian volcanoes, and their inter-volcano compositional differences, are widely interpreted in terms of melting within the plume. Our studies of samples from Mauna Loa volcano include historical lavas (0.2 ka), 14C-dated prehistoric lavas (0.2 - 36 ka), lavas recovered by the Hawaii Scientific Drilling Project (10 - 100 ka) and lavas from Mauna Loa's submarine southwest rift zone (<100 - >300 ka). This magmatic record is comparable with that of the ~ 400 ka record for Mauna Kea volcano obtained by the Hawaii Scientific Drilling Project, and provides another excellent opportunity for testing and/or modifying the plume model. During this period, Mauna Loa will have transited >30 km to the NE and should record differences in both source components and melting processes in the composition of its lavas if the plume model is tenable. High precision Pb and Sr isotopic ratios, in combination with X/Nb ratios, clearly indicate that lavas older than 100 ka are distinct from younger lavas (<36 ka). The younger lavas are more variable, and tend to have higher Sr and lower Pb isotopic ratios than the older lavas. The older lavas have Pb and Sr isotopic ratios that approach those of Loihi, the youngest volcano along the so-called Loa trend. These data are in accord with a zoned plume model, but require bi-lateral asymmetric zoning and heterogeneities, rather than concentric zoning.

The major elements, and most of the trace data, are another matter. Melting experiments on peridotites indicate that changes in the extent of melting, or in the depth of melt segregation, will result in differences in SiO2, MgO and FeO in the magmas. Given a thermally-zoned plume, one should expect to see differences in these variables over time as the volcano transits the plume. This is the case for Mauna Kea. The normalized SiO2 content of the lavas decreases over time, along with eruption rates, as the volcano approaches the post-shield stage. Paradoxically, there are no such temporal changes of composition in Mauna Loa lavas. With the exception of some alkalic radial vents, all Mauna Loa lavas follow well-defined olivine-control trends that are indistinguishable from modern historical lavas. The implications are that although the plume may be compositionally zoned on a scale of ~ 30 km, either melting and melt segregation processes have remained remarkably constant over a broad region of the plume, or alternative processes are at work.

Magma Genesis in a Mantle Plume: Based on High-pressure Melting Experiments and Growth History of Some Hawaiian Volcanoes

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The significance of recycled oceanic crust (eclogite) component in generation of hot spot magmas has received much attention [e.g., Hauri, 1996; Campbell, 1998; Takahashi et al., 1998; 2002]. The mechanism of magma production in the hybrid partial melt zone (consisting of eclogite and peridotite), however, is not well understood. The role of the interface that separates these lithologically different domains in the source region is an essential but unknown factor in plume magma genesis. The goal of this study is to model magma generation in the Hawaii plume based on new experiments by and the growth history of Hawaiian volcanoes discovered by studies based on JAMSTEC Hawaii cruises (e.g. Koolau, Tanaka et al., 2002; Haleakala, Ren et al. 2004).

The basalt/peridotite sandwich melting experiments were conducted at 2.5 to 3.5 GPa and 1400-1550 C for 10-100 hrs in order to study the reaction kinetics of the basalt/peridotite interface and the chemistry of melts produced by reactions between layered basalt and peridotite. Both melts and solid were analyzed with EPMA and LA-ICPMS. It is found that melts formed above the peridotite solidus (>1475 C at 3 GPa) are silica under-saturated alkalic basalts (alkalic picrite) similar to OIBs (Loihi). As temperature decreases, the melt composition becomes olivine tholeiites (picrite) similar to those in Kilauea in the temperature range where basalt interacts with peridotite wall rocks by melt infiltration (1475-1450 C at 3 GPa). At temperatures below the solidus of most fertile peridotite the melts formed in the basalt layer are isolated from the peridotite matrix by opx reaction band and have composition of silica-saturated basaltic andesite (<1425 C at 3 GPa). The basaltic andesite melt could be the source component for the silica-rich Makapuu stage of Koolau volcano.

Based on these experiments, temperature profile of the Hawaiian mantle plume is constructed. Magma feeding zone under Loihi may be highest in temperature (1475 C) and decrease as the volcano migrated away from the plume axis. At the most voluminous olivine tholeiite stage in Kilauea volcano (1450 C) as much as 50 vol.% of melts are supplied from eclogite source. As the volcanoes migrate further away from the plume axis, melting in the peridotite matrix diminishes and the silica-rich melts formed in the eclogite domain becomes prevailing (Mauna Loa to Koolau stage, 1425 C). Based on this model absence of tholeiite magma in most hot spots may be explained by the absence of entrained eclogite blocks or very small in size if any. Independent analyses based on Fe-Mg of magma source indicate that entrained eclogite blocks are most abundant in Hawaii and Iceland plumes. Magma production rate in mantle plume may be controlled by 1) plume flux, 2) potential temperature, 3) thickness of the plate and 4) amount of the entrained eclogite blocks. Potential temperature of a plume based on melting model of simple peridotite source may be up to 100 C overestimated in the case where melting of entrained eclogite component is prevailing in magma genesis.

Do Hotspot Basalts Share a Common Mantle Source?

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Iceland is the ideal place in which to study the mantle source(s) for hotspot basalt because its location on the Mid-Atlantic Ridge causes the source to melt to large degrees on-axis and small degrees off-axis. Icelandic basalt ranges in composition from highly depleted picrite to moderately enriched mildly alkaline basalt; a much larger range than at any other hotspot. It forms a single array on a logarithmic plot of Nb/Y vs. Zr/Y that is distinct and parallel to the array defined by N-MORB, thus supporting the conclusion of Pb-isotope studies that the N-MORB source is not a significant component in the source of Icelandic basalt. The most depleted Icelandic basalts are more depleted in incompatible elements than are most N-MORB and yet they are still relatively rich in Nb. This relative enrichment in Nb can be expressed numerically as delta-Nb, which is the deviation from a reference line separating the Iceland and N-MORB arrays. Thus virtually all N-MORB has delta-Nb < 0 and all Icelandic basalt has delta-Nb > 0.

Nearly all OIB, and basalt from most LIPs (e.g. Ontong Java Plateau; Columbia River Plateau) plot in the Iceland array and therefore have positive delta-Nb, suggesting that this parameter reflects a fundamental characteristic of the source of hotspot basalt. Most basalt erupted in continental rift systems also has positive delta-Nb, irrespective of whether rifting is accompanied by uplift (e.g. East Africa; Basin and Range) or not (e.g. Scottish Midland Valley; North Sea). This suggests that the mantle component with positive delta-Nb (probably subducted oceanic crust) is present on all scales, from large mantle upwellings as inferred to be present, for example, beneath Iceland and Hawaii, to streaks of enriched material present in the upper mantle and preferentially sampled through small-degree melting beneath passive continental rift systems. Rare, near-axis MOR seamounts with positive delta-Nb demonstrate the existence of small-volume streaks or blobs of this enriched material in the upper mantle. Although positive delta-Nb is a characteristic feature of basalt at most hotspots, magmatism on the Siberian Platform and in the early phase of activity of the North Atlantic Tertiary province is dominated by basalt with negative delta-Nb (i.e. it resembles N-MORB).

Thus, there is no simple correspondence between OIB-like basalt (with positive delta-Nb) and postulated deep-mantle upwelling (plumes). Small seamounts and OIB-like basalt formed as a passive response to lithospheric extension clearly do not involve mantle plumes. On the other hand, some LIPs are composed of basalt that is not OIB-like and more closely resembles N-MORB. The geochemical diversity of hotspot basalts requires that if mantle plumes do exist then they cannot all share a common mantle source.

Eastern Anatolia: A Hot Spot in a Collision Zone Without a Mantle Plume

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The Eastern Anatolian region is considered to be one of the best examples of a continental collision zone in the world. It contains one of the highest plateaus of the Alpine-Himalayan mountain belt with an average elevation of 2 km above sea level. Geological records indicate that the region was beneath sea level until Serravalian (~13 Ma), and then experienced an abrupt block uplift, consequently being elevated above sea level. This was followed by a widespread subaerial volcanism in Eastern Anatolia and the surrounding regions (e.g. Georgia, Armenia, Azerbaijan and Iran). Volcanic activity produced a wide range of volcanic products (i.e. lavas and pyroclastic units), spanning the whole compositional range from basalts to rhyolites. Great volumes of volcanic material reaching over 1 km in thickness in places erupted onto the surface, covering almost two-thirds of the region. The region gradually gained a regional domal shape comparable to that of the Ethiopian High Plateau, although the Anatolian dome has a north-south shortened asymmetrical shape possibly due to collision (Sengor et al., 2003).

The existence of a regional dome structure and widespread magmatism are both regarded as evidence for the existence of a mantle plume and these do indeed exist in Eastern Anatolia. By these properties, the Eastern Anatolia region can be regarded as the site of a "melting anomaly" or "hotspot" resembling closely the setting proposed for mantle plumes. However, geologic and geochemical data provide evidence against a plume origin. The results of the Eastern Turkey Seismic Experiment Project (Sandvol et al., 2003), coupled with geological and geochemical findings, support the view that both domal uplift and extensive magma generation can be linked to the mechanical removal of a portion or the whole thickness of the mantle lithosphere, accompanied by passive upwelling of normal-temperature asthenospheric mantle to a depth as shallow as 38 to 50 km. This process might have taken place either by delamination (Pearce et al., 1990; Keskin et al., 1998), slab-steepening & breakoff (Keskin, 2003), or a combination of both. The Eastern Anatolian example is important in showing that not only plumes but also shallow plate tectonic processes have the potential to generate regional domal structures in the Earth's lithosphere as well as large volumes of magma.

The Hf-W Perspective on Whether a Trace of the Earth's Core Exists in Hot Spot Volcanic Rocks

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Radiogenic 187 Os/188 Os in ocean island basalt is traditionally interpreted to represent recycled crust, whereas coupled 186 Os/188 Os and 187 Os/188 Os enrichments were interpreted as a small core contribution in e.g. Hawaiian lavas [1]. A core origin for radiogenic Os would establish that the Hawaiian mantle source originated at the core-mantle boundary. Importantly, coupled Os isotope enrichments hitherto only been found in hot-spot related lavas, possibly arguing against general core-mantle mixing and for mantle plumes. The extinct Hf-W isotope system enables an independent test of the core contribution interpretation because W partitions into the core while Hf remains in the mantle. Both elements are refractory, and the bulk Earth Hf/W ratio is well established. A two parts in ten thousand 182 W/184 W ratio difference (i.e. 2 e182 W) between chondrite meteorites and silicate Earth [2 & refs. therein] translates into a similar difference between the Earth's core and mantle. Because W is strongly enriched in the core and incompatible during mantle melting and 182 Hf-decay to 182 W only occurred during the first ~50 Myr of solar system history, W isotope may be a very sensitive tracer of small core contributions to the Earth's mantle. Hawaiian lavas do not have any resolvable W isotope anomalies, which puts the core contribution hypothesis into question [2]. However, it was pointed out by Brandon & Walker [3] that a recycled component may mask the W isotope signature because of the significant W enrichment that e.g. sediments may show. Th and W follow each other very closely in magmatic (and arc related non magmatic) processes and display a mean silicate Earth ratio of 0.19 ±0.06 [4]. Using Hawaiian Th concentrations as a proxy for W and the petrogenetic model of Norman & Garcia[5], a source around 10 ppb W is estimated; on the same order as previously modelled [2]. Importantly, such a moderately depleted mantle source indicates that recycling contamination of high [W] crust to the Hawaiian source was insignificant, and the sensitivity of the W isotope tracer is maintained. While Hf-W was only extant during a brief initial period in Earth history, Re-Os and Pt-Os are long-lived decay systems, and e.g. sulphides or metalliferous sediments may fractionate Pt-Re-Os in a way that the observed Os-correlations can be generated. It thus appears as if the contact with the core is lost, and that constraints on the origin of the at least the Hawaiian source cannot be made from Os-isotopes.

1. Brandon, et al., Science, 1998, 280, 1570-1573.
2. Schersten, et al., Nature, 2004. 427, 234-237.
3. Brandon & Walker, EPSL, 2005. 232, 211-225.
4. Newsom, et al., GCA, 1996. 60, 1155-1169.
5. Norman, & Garcia, EPSL, 1999. 168, 27-44.

Thursday Poster Sessions

The Evolution of Floreana Island, Galápagos Archipelago II: The Result of a Contaminated Mantle Plume

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The Galápagos Archipelago has been attributed to a mantle plume since the hypothesis was proposed in the early 1970s. The plume is rooted ~250 km south of the Galápagos Spreading Center (GSC) in the western archipelago, beneath Fernandina and southwestern Isabela Islands. Evidence for the archipelago's plume origin includes: 1) islands and seamounts exhibit an age progression broadly consistent with eastward motion of the Nazca plate (e.g., White et al., 1993); 2) regional tectonic reconstructions indicate that the GSC has migrated northward over a stationary hotspot over the past 8 m.y. (Wilson and Hey, 1995); 3) recent s-wave tomographic studies suggest the presence of a steeply-dipping, well-defined low velocity zone extending 400 km beneath the western archipelago (Toomey et al., 2001); 4) thinning of the transition zone beneath the western archipelago suggests a thermal plume traverses through it (Hooft et al., 2004); 5) the Galápagos platform is underlain by crust more than twice as thick as normal oceanic crust; 6) variation in geochemical and isotopic signatures of Galápagos lavas can be explained as the result of mixing between a heterogeneous, three-component plume and the depleted upper mantle (Harpp and White, 2001); 7) 3He/4He ratios vary up to nearly 30 times atmospheric values and are highest where the plume is rooted (and there is no correlation between 3He/4He and [He]; Kurz and Geist, 1999; Graham et al., 1993); and 8) geochemical, gravity, and bathymetric anomalies along the GSC peak when the ridge is closest to the islands (e.g., Schilling et al., 2003).

Floreana Island is located 150 km east (i.e., downstream in terms of plate motion) of the root of the Galápagos plume. Floreana lavas have distinct geochemical and isotopic signatures from those of the western shield volcanoes, and Floreana magmas originate from shallower depths as well. Floreana basalts are enriched in radiogenic Sr and Pb, and depleted in 3He/4He ratios relative to the western shield volcanoes, which are interpreted to represent the pristine plume signature; significantly less variation exists in Nd isotopic ratios. Floreana's mantle source has to have been enriched in Rb/Sr, U/Pb, and Th/Pb for much longer than12 m.y., the age of the underlying lithosphere. The anomalous characteristics of Floreana's melts can be explained simply with a heterogeneous mantle plume, enriched in elements commonly associated with metasomatic activity. Recent models of plume ascent indicate that heterogeneities can be spatially preserved spatially during ascent from the core-mantle boundary in filament-like structures. We propose that the source of Floreana magmas is metasomatized ancient lithosphere that has been recycled to the lower mantle.

Evolution of Helium Isotopes in the Earth's Mantle

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The presence of primordial 3He in ocean island basalts (OIB) has been considered the primary evidence for the existence of a primitive, unmelted reservoir in the deep Earth. A new global data compilation relating helium isotopes of OIB and mid-ocean ridge basalts (MORB) to Sr-Nd-Pb isotopes and trace element abundances yields new insights into mantle dynamics. The compilation is based on data from the online GEOROC and PetDB databases. Oceanic islands are divided into groups based on the highest 3He/4He ratios measured in mineral separates: (1) "low 3He/4He" (3He/4He <7 RA); (2) "MORB-like 3He/4He" (8±1 RA); (3) "moderately high 3He/4He" (9-15 RA); (4) "high 3He/4He" (>15 RA). These designations enable us to follow the geochemical characteristics of OIB sources based on their 3He/4He ratios despite the global paucity of combined He-Sr-Nd-Pb isotope data on individual samples. The geochemical compositions of the four groups of OIB are not distributed randomly within the global range but show the following systematics: (i) lower 143Nd/144Nd ratios are associated with lower 3He/4He, (ii) for a constant 143Nd/144Nd ratio, higher 206Pb/204Pb ratios are associated with lower 3He/4He groups, and (iii) low 3He/4He ratios are accompanied by low 206Pb/204Pb, 207Pb/204Pb, 208Pb/204Pb ratios and high Th, U abundances independent of partial melting effects.

The new compilation shows there is a direct relationship between the 3He/4He groups and Th+U contents of OIB (, with only Samoa as an exception). Thus, 3He/4He in OIB appear to reflect the production rates of 4He from recycled oceanic crust plus sediment variably enriched in (Th+U) in plume sources. OIB displaying the strongest primordial 3He/4He signal are chemically and isotopically (i.e. Sr, Nd, Pb) most like mid-ocean ridge basalts. Thus the global compilation confirms that OIB and MORB sample mantle regions with different helium isotope signatures. However, the compilation indicates a common melting history for the sources of MORB and OIB over geological time. We show through modeling that helium isotopes in the mantle can be explained through continuous, incomplete degassing by continent and ocean crust formation. It appears that the high 3He/4He component in plume sources does not represent unmelted primitive mantle but rather “old” depleted mantle, isolated from convection and upper mantle degassing for 1-2 billion years.

Inverse Trace Element Modeling of Mantle Components from Late Cenozoic Basalts in Central Asia

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Analyses of Sr-Nd isotopes in the Late Cenozoic basaltic lavas of a vide territory of the Central Asia (e.g. Hangai, East Sayan, Khamar-Daban) revealed three distinct components (end-members) referred to as A, B and C (Rasskazov et al., 1999). The component A is moderately depleted (87Sr/86Sr ~0.704, 143Nd/144Nd ~0.5128), whereas components B (87Sr/86Sr ~0.7045, 143Nd/144Nd ~0.5122) and C (87Sr/86Sr ~0.7053; 143Nd/144Nd ~0.5127) are enriched (Rasskazov et al., 2002; Barry et al., 2003; Yarmolyuk et al., 2003). Despite the good concordance of the published data, the interpretations between the different studies are remarkably different. Rasskazov et al. (2002) and Barry et al. (2003) suggest that component A belongs to convective sublithospheric mantle and components B and C reflect composition of lithospheric mantle. Acknowledging lithospheric features of the B and C components, Yarmolyuk et al. (2003) propose that these are recycled lithosphere that has resided long term in the deep mantle (lower-upper mantle transition and D’’ layer) and that these components are sampled by a plume. For the component A they suggest a deep source of the lower mantle. In this presentation we apply inverse trace element modelling to distinguish mineralogy of the mantle sources for these isotopic components. We use Rb as the most suitable highly incompatible trace element and plot individual datasets for each component on Rb/Ci…n – Rb diagrams, where Ci…n are concentrations of different trace elements. Slope and intercept for individual datasets on such diagrams provide information on concentrations of elements in their sources and bulk distribution coefficients for these elements (Ormerod et al., 1991). For component A we find significant correlations for Ci…n elements; Ba, K, Sr, Pb, Hf, Ti, Y and REE (except La and Ce) and for component C – for U, Ta, Sr, P, Zr, Ti, Y and REE. For component B we find only limited number of correlations for Ci…n elements; Sr, Pb, P, Ti and Y, showing that basalts with such Sr-Nd isotopic features do not belong to the same uniform dataset (therefore, do not belong to the same mantle source). Component C is characterized by gradual increase of slopes and decrease of intercepts in order of REE compatibility. Heavy REE and Ti exhibit negative intercepts, implying distribution coefficients above unity for these elements. Component A shows gradual increase of slopes with almost the same positive intercepts for most of REE. Exception is a negative intercept for Yb. Intercept for Ti is positive. On basis of the inverse trace element modeling we suggest that component A is within garnet-spinel transition stability field (about 55-65 km depths) without Ti-bearing phases. The component B is shallower component of heterogeneous lithosphere. Component C is deeper sublithospheric mantle component within garnet stability field with Ti-bearing phases. The work is supported by RFBR grant 05-05-64477.

References: Barry, T.L., Saunders, A.D., Kempton, P.D., Windley, B.F.,Pringle, M.S., Dorjnamjaa, D. and Saandar, S., 2003, Petrogenesis of Cenozoic basalts from Mongolia: evidence for the role of asthenospheric versus metasomatised lithospheric mantle sources. Journal of Petrology, v. 44, p. 55-91.; Ormerod, D.S., Rogers, N.W., Hawkesworth, C.J., 1991, Melting in the lithospheric mantle: Inverse modelling of alkali-olivine basalts from the Big Pine Volcanic Field, California. Contributions to Mineralogy and Petrology, v. 108, p. 305-317; Rasskazov, S.V., Bowring, S.A., Harris, N., Brandt, I.S., Brandt, S.B., Ivanov, A.V., Lhur, J.F., Coleman, D. and Housh, T., 1999. Lithospheric domains in East Sayan: Pb, Sr, and Nd isotope constraints on sources of the Late Cenozoic magmatism in the northern segment of the Riphean Tuva-Mongolian massif. In: Rifting in intracontinental setting: Baikal Rift System and other Continental Rifts, Irkutsk-Tervuren, p. 163-166.; Rasskazov, S.V., Saranina, E.I., Demonterova, E.I., Maslovskaya, M.N., Ivanov, A.V., 2002, Mantle components in Late Cenozoic volcanics, East Sayan (from Pb, Sr, and Nd isotopes). Russian Geology and Geophysics, v. 43, p. 1065-1079.; Yarmolyuk, V.V., Ivanov, V.G., Kovalenko, V.I. And Pokrovskii B.G., 2003, Magmatism and geodynamics of the Southern Baikal volcanic region (Mantle Hot Spot): results of geochronological, geochemical, and isotopic (Sr, Nd, and O) investigations. Petrology, v. 11, p. 1-30.

Fluid Inclusion Evidence for Water in the Mantle Beneath Hawaii

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Post-erosional alkalic lavas from Salt Lake Crater, on the apron of the Koolau volcano on Oahu (Hawaii) contain a rather unique group of mantle xenoliths, representing the oceanic lithosphere. In order to have information on the composition of free fluids present in the Hawaiian solid mantle at depths > 50-60 km, we have analyzed fluid inclusions in garnet pyroxenites, which are part of a collection on loan from the Smithsonian Institutions.

Studied pyroxenites are dry and consist of clinopyroxene, orthopyroxene, olivine and garnet. Abundant fluid inclusions are present in all mineral phases, mostly contained within intergranular and intragranular trails, indicating late trapping. In ortho- and clinopyroxene, however, a few early fluid inclusions are preserved; these are present isolated, or form small clusters within single grains. In clinopyroxene, early inclusions predate orthopyroxene and spinel exsolutions. Most early inclusions are decrepitated; previous studies (Frezzotti et. al., 1992) indicated that a few small (< 8 μm) early inclusions still preserve high-density to superdense CO_2 fluids, with densities up to 1.21 g/cm3 - the highest density ever recorded in CO2 mantle fluids - corresponding to pressures of 1.8-2 GPa, at the inferred mantle temperatures of 1100°C.

A new detailed Raman study in selected high-density and superdense early CO2 inclusions reveals vibrational bands at 3638 cm-1 and 2609 cm-1, which are characteristic of OH- stretching vibrations for isolated water molecules, and of H2S, respectively. A few inclusions additionally show the typical vibration for diamond.

Fluids contained within inclusions are CO2-rich, and contain H2O and H2S, ± diamond, defining a complex fluid mixture in the C-O-H-S system in the mantle beneath Hawaii, at P = 2 GPa. The non systematic presence of diamonds within fluid inclusions, strongly suggest that these phases did not form within fluid inclusions. Diamonds were already present in CO2-H2O-H2S mantle fluids, indicating that inclusions trapped a deep fluid, which originated in the asthenosphere.

We argue that such fluids, migrating within the asthenospheric mantle represent a strong metasomatic agent able to induce partial melting at the base of the lithosphere at normal mantle temperatures, obviating the need for concentrated hot jets localized under "hotspot" volcanoes, and deep mantle reservoirs.

Testing Magmatic Emplacement Mechanisms in the Balcones Igneous Province of Texas

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Various intraplate volcanic fields, large igneous provinces, and continental flood basalt provinces have long been considered to be the result of mantle plumes interacting with the lithosphere. This idea has been strengthened by the recognition that the geochemical and isotopic compositions of intraplate magmatism differ significantly from those of mid-ocean ridge and arc settings. Regional and global tomographic evidence of the presence of mantle plumes in a number of locations is mounting, however, not all intraplate magmatism fits the mantle plume model. Ad-hoc refinements to the original models of Wilson and Morgan to explain anomalous characteristics has recently prompted a global debate within the geoscience community ranging from the number of mantle plumes that exist, to the very existence of mantle plumes at all. An outgrowth of this ongoing debate has been the proposal of a number of alternative models that attempt to explain the existence of intraplate magmatism in the absence of a mantle plume source. The Balcones Igneous Province (BIP) of south central Texas provides an excellent opportunity to investigate magmatic processes that occur in a continental intraplate setting. An integrated field, geochemical, and geochronologic study is in progress in the BIP to understand the petrogenetic processes and magmatic emplacement mechanisms responsible for its formation. The BIP is an arcuate zone of Late Cretaceous (86-77 Ma) intraplate volcanic and intrusive igneous bodies approximately 400 km in length by 100 km in width. Initial geochemical analyses (n=12; major element, trace element, rare-earth element, radiogenic isotope (Sr, Nd, Pb) and mineral composition) from the BIP suggest magmatism resulted from small degrees of partial melting in the garnet stability zone of a depleted mantle source that had experienced re-enrichment in incompatible trace elements. Although previous workers have suggested BIP magmatism may be related to OIB type sources, it is likely that several upper mantle magmatic processes were involved. Initial geochronological analyses (n=7; U/Pb SHRIMP, 40Ar/39Ar) from the BIP demonstrate magmatism occurred over a much shorter time-period than previously thought. Regional geophysical data indicate the BIP coincides with the inner margin separating Neoproterozoic (1.3 Ga) cratonic lithosphere, from much younger (Paleozoic to Mesozoic) transitional lithosphere of the southern margin of the North American continent. Uncertainties exist regarding the lithospheric transition zones to the west into Mexico and Trans-Pecos (TP) Texas, because Mesozoic and Cenozoic tectonic events have effectively masked much of the earlier evidence in the region. Our work has produced new geochronological evidence from TP Texas that demonstrates mafic magmatism was present in the region at 73 Ma (U/Pb SHRIMP), similar in age to that of the BIP, suggesting the BIP may extend 400 km further west that previously recognized. Alkaline silica undersaturated igneous complexes in northern Coahuila, Mexico appear to provide a spatial link between the south Texas and TP Texas segments. In a broader regional context, the BIP may represent a small portion of a Middle to Late Cretaceous Gulf Coast diffuse igneous province, as large as 1400 x 200 km, comprising igneous centers in central Arkansas, northeast Louisiana and central Mississippi. Similar geochemical compositions and emplacement ages across the region support this idea.

The Evolution of Floreana Island, Galápagos Archipelago I: The Result of Upper Mantle Heterogeneities

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The Galápagos Archipelago poses a number of challenges to the mantle plume hypothesis: 1) volcanism is not consistently time transgressive, with many exposed lavas exhibiting ages younger than those predicted by plate motion vectors (e.g., White et al., 1993). This pattern of volcanism that is “too young” extends up to 500 km away from the hotspot, along the Cocos and Carnegie Ridges; 2) a complex array of volcanic alignments throughout the region indicates control by lithospheric stresses, likely related to the transform fault at 91°W on the Galapagos Spreading Center (GSC; Harpp and Geist, 2002); 3) the Cocos and Carnegie aseismic ridges that emanate from the archipelago do not conform to subsidence trends predicted by normal cooling of a reheated lithosphere; 4) several Galápagos volcanoes erupt lava that is isotopically indistinguishable from MORB produced at the GSC, some with isotopic signatures similar to those observed at the GSC over 800 km away from the archipelago; 5) much of the geochemical variation in the archipelago can be attributed to low degree, deeper melts of enriched upper mantle heterogeneities; and 7) 3He/4He ratios resemble those of MORB (or lower) in many parts of the archipelago.

Floreana Island is located 150 km east (i.e., downstream in terms of plate motion) of the most active volcanoes, and exposed lavas are up to 1.1 Ma. Eruptive vents on Floreana are aligned parallel to lineaments observed throughout the eastern archipelago. Floreana lavas have geochemical and isotopic signatures distinct from those erupted elsewhere in the archipelago, and unlike the other Galapagos volcanoes, lack a garnet signature. IFloreana basalts are enriched in radiogenic Sr and Pb ratios relative to the western shield volcanoes. Floreana’s mantle source has been enriched in Rb/Sr, U/Pb, and Th/Pb for much longer than 12 Ma, the age of the underlying lithosphere. Contributions from this enriched source decrease systematically to the north, west, and east of Floreana. The anomalous characteristics of Floreana’s melts can be explained as the result of melting of an upper mantle heterogeneity, enriched in elements commonly associated with metasomatic activity; metasomatism was ancient, however, and cannot be contained within the young lithosphere. Regional lithospheric stresses initiated by the 91°W transform fault initiate melting of the enriched asthenospheric material beneath Floreana, which erupt along lines of tensional stresses. The enriched anomaly has a low solidus, which causes melting at shallow levels, where it would not ordinarily occur otherwise.

Mantle Redox Conditions in LIPs: Constraints from the North Atlantic Igneous Province

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The North Atlantic igneous province (NAIP) has long been viewed as a region of anomalous mantle upwelling related to plume activity, continental rifting, and a heterogeneous mantle source. Prior to continental rifting in the Tertiary, the northern portion of the region was the site of closure of the Iapetus ocean basin. This tectonic event may have contributed to heterogeneities within the upper mantle and altered its oxidation state relative to the ambient mantle. Vanadium has been shown to be a useful indicator of redox conditions due to its multiple valence states (e.g. [1-2]), and the vanadium to scandium ratio (V/Sc) for basalts from mid-ocean ridge and arc environments has been proposed as a useful proxy for fO2 conditions during partial melting (e.g. [3-4]). We compare V/Sc ratios from basalts from early Tertiary successions in the NAIP with those from Iceland, and relate the variations to differences in both redox conditions and melting systematics. We examine these relationships in detail for the central east Greenland (CEG) flood basalt province, which is commonly attributed to arrival of the ancestral Iceland plume at ~55-57 Ma. To test the relative importance of melting systematics, source composition, and oxygen fugacity on the Sc/V systematics for NAIP basalts in both space and time, we incorporated both Sc and oxygen-fugacity-dependent V mineral-melt partitioning data of [5] into the polybaric decompression melting model REEBOX [6]. Our model captures the salient compositional features of CEG and Iceland basalts, which are related to the role of residual garnet in the mantle source and differences in fO2. To model the entire range of east Greenland lavas requires that the Paleogene mantle source was ~0.5 log units more oxidized than the Iceland source. These differences may be attributed to a change in the composition of the Iceland plume or reflect the involvement of metasomatized upper mantle associated with Iapetus subduction in the formation of the east Greenland basalts. We further examine the compositional variability in mantle redox conditions throughout the NAIP during continental break-up. Regions distal to the axis of the proposed Iceland plume and Caledonian front appear to be fundamentally different from central east Greenland, suggesting that the upper mantle in these areas was either more oxidized or markedly different in composition. This study of the NAIP provides the basis for comparisons of redox conditions in other LIPs.

[1] Canil, D., 1997, [2] Canil, D. 1999, [3] Li and Lee, 2004 [4] Lee et al., 2005 [5] Canil and Fedortchouk, 2000, [6] Fram and Lesher, 1993

Plumes or Rifting? : The Mesozoic Dykes of the Falkland Islands and Their Relationship to the Break-up of Gondwana.

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Many researchers consider mantle plumes as being the driving force behind continental fragmentation. Here we report new major and trace element, Sr-, Nd- and Pb-isotope data a Ar-Ar geochronogical data for mafic Mesozoic dykes of the Falkand Islands. All analysed samples are of the low TiO2 magma type recognized throughout Gondwana. New 40Ar-39Ar data on plagioclase phenocrysts separates from three intrusions yield a single statistically viable age of 182.3±1.5 Ma, concordant with ages reported from the low-Ti Karoo lavas of Lesotho and Lebombo. Within the Falkland Islands, four distinct magma types are recognized. One group of intrusions exhibit Sr-, Nd-, and Pb- isotope ratios (87Sr/86Sr = 0.707 to-0.714; eNdt -5 to -12; 206Pb/204Pb 17.75-18.25), high La/Ta (44-56), and low Nb/Zr ratios (0.03-0.07) which are consistent with significant interaction with Gondwana lithosphere by the process of AFC, and are typical of many of the Jurassic magmatic recognized throughout Gondwana (e.g Ferrar Province). The remaining three groups, however, exhibit considerably more depleted Sr- and Nd-isotope ratios (87Sr/86Sr 0.703-0.706; eNdt +4 to-2) indicating more limited, or indeed, negligible, interaction with Gondwana lithosphere. This lack of lithospheric input to magmatism gives us a clear window into the mantle source region from which the magmas were derived. The MORB-like geochemistry of these isotopically depleted magmas does not necessarily require a plume origin. It is therefore conceivable that plate boundary forces were the most important driving force for magmatism during Gonwana break-up rather than a mantle plume of apparently diverse composition.

Pliocene-Quaternary Alkaline Basalts of the Sredinny Ridge of Kamchatka: Evidence for Melting of Recycled Oceanic Crust in Tectonic Setting of a Modern Island Arc System

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Volcanic rocks of island-arc tectonic settings are characterized by definitive trace element features such as depletion in high field strengths (HFS) elements relative to large ion lithophile (LIL) elements. This is interpreted as evidence for transport of LIL elements from subducting slab by aqueous fluids and enrichment of overlying mantle wedge by these elements. HFS elements are not soluble in the aqueous fluids and therefore mantle wedge is relatively depleted by these elements. Alkaline nepheline-normative volcanic rocks without HFS-depletion pattern, though often found in the island arc tectonic setting, are considered as unusual or atypical. Here we investigate the atypical Pliocene-Quaternary alkaline basalts of the Sredinny Ridge of Kamchatka to reveal their structural position. We also apply inverse element modeling to show difference in source of melting between typical island-arc HFS-element depleted and atypical alkaline magmas. In the Kamchatka there are two (frontal and rear) Pliocene-Quaternary volcanic belts with typical HFS-element depleted rocks. These volcanic belts are subparallel to the seismofocal zone and are conventionally considered as being related with two

regions of the mantle wedge above water-bearing mineral decomposition fields within the modern subducting slab. Coeval alkaline volcanic rocks were found mainly within the rear volcanic belt. These alkaline rocks are characterized by trace element pattern similar to continental rift basalts and oceanic island basalts. They are referred to as within-plate, riftogenic or oceanic type basalts by different authors (e.g. Volynets, 1994; Churikova et al., 2001; Ivanov et al., 2004; Portnyagin et al., 2005). Using TiO2 content in basalts as a proxy for the within-plate-geochemical type, we distinguish about fifty within-plate-type volcanic centers in the Sredinny ridge (used authors data among geological survey and literature data). These volcanoes form five linear chains, which are oblique to the general trend of the rear volcanic belt. These volcanic chains are subperpendicular to the axis of Pacific plate movement (hence they are subparallel to magnetic anomalies of the Pacific plate crust). еДХМХВМШЕ within-plate type volcanoes in south (Bakening, Taburetka) and north (Nachikinsky), which do not belong to these linear chains of the Sredinny Ridge, situate above surface projection of transform faults. Using new and published trace element data obtained for basalts along the rear volcanic belt we distinguish two pure end-member types; the island-arc type and within-plate type with spectrum of transitional compositions. Applying inverse trace element modeling for the end-member types, we found that typical island-arc HFS-element depleted magmas were generated from a spinel-bearing mantle source (40-60 km depths), whereas atypical within-plate magmas originated from a deeper garnet-rich source. Eclogite (recycled oceanic crust) is the best candidate for this garnet-rich source. The work is supported by RFBR grants 04-05-64800 and 05-05-64477. References: Churikova, T, Dorendorf, F. and Worner G., 2001, Sources and fluids in the mantle wedge below Kamchatka, Evidence from across-arc geochemical variation. Journal of Petrology, v. 42, p. 1567-1593.; Ivanov, A.V., Perepelov, A.B., Puzankov, M.Yu., Yasnygina, T.A., Malykh, Yu.M. and Rasskazov, S.V., 2004, Rift- and arc-type basaltic volcanism of the Sredinny Ridge, Kamchatka: case study of the Payalpanvolcano-tectonic structure. In: Metallogeny of the Pacific Northwest: tectonics, magmatism and metallogeny of active continental margins, edited by A.I. Khanchuk et al. Dalnauka, Vladivostok, p. 345-349. Portnyagin, M., Hoernle, K., Avdeiko, G., Hauff, F., Werner, R., Bindeman, I., Uspensky, V. and Garbe-Schonberg, D., 2005, Transition from arc to oceanic magmatism at the Kamchatka-Aleutian junction. Geology, v. 33, p. 25-28. Volynets, O.N., 1994, Geochemical types, petrology, and genesis of Late Cenozoic volcanic rocks from the Kurile-Kamchatka island-arc system. International Geology Review, v. 36, p. 373-405.

Communicating the Plume Debate to Undergraduate Geoscience Students

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The mantle plume model is presented as the explanation for age-progressive intraplate volcanism (e.g. Hawaii) and anomalous plate margin volcanism (e.g. Iceland) in most introductory geology textbooks. This model is also presented in igneous petrology and tectonics textbooks. Should alternatives be presented to undergraduate geoscience students?

Dutch (1980; J. Geo. Ed., v. 30, p. 6-13) described a three-tiered hierarchical classification of theories: central, frontier, and fringe. All theories begin as fringe theories; most will be discarded. Some are supported but have some unresolved inconsistencies and/or serious alternatives; these are frontier theories which constitute the mainstream thinking of a scientific discipline. Central theories are no longer seriously disputed, and form the foundation of a discipline. Plate tectonics is a central theory in geology and mantle plume theoryis a frontier theory.

A quick review of introductory and physical geology textbooks reveals that most treat mantle plume theory as a central theory. Only Press et al. (2004; Understanding Earth 4th edition; WH Freeman Co.) suggest a

controversy. Other authors should follow their lead. Some might argue that describing the uncertainty of such a well known theory could weaken public perception of the state of the science. Others might argue that the foundations of the debate are too sophisticated for this level. Students are introduced to the idea that anomalous temperature is just one of three ways to cause melting, so that hot spots might not be hot and may be the result of something other than a plume should be comprehensible and reinforce other learning. These ideas can be explored in greater depth in upper division courses. That there is debate about the basic workings of the earth should be exciting to students; there are big questions that remain to be addressed in their careers.

Re-Os-Pt Partitioning in Sulfur-bearing Solid/Molten Iron Metal at 3-22 GPa and 1300-1775 C: Is the Earth's Outer Core So Giving?

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Recently, some high-MgO basaltic lavas have been shown to exhibit coupled enrichments in 186 Os/188 Os and 187 Os/188 Os. One way to have this enrichment is by strong fractionation of Re and Pt (preferring liquid metal) from Os (retained more in the solid metal) during crystallization of the inner core. By fractionating Pt and Re from Os, the Earth's outer core would develop highly radiogenic 186 Os/188 Os and 187 Os/188 Os ratios, and it has been suggested that perhaps the only way to have the lavas with this enriched component on the Earth's surface is by transfer of material from the core-mantle boundary, a process that provides evidence for the existence of deep mantle plumes. In this contribution, we test the above geochemical hypothesis by performing Re-Os-Pt partitioning experiments between sulfur-bearing solid/molten iron metal. Pressure and temperature, besides bulk composition, are potentially important factors in controlling the partitioning systematics, and experiments were designed to cover a wide, and so far the largest (3-22 GPa) pressure and temperature (1300-1775 C) range. It must also be noted that the highest-pressure datum in this work is still more than an order of magnitude less than the pressure at the outer-inner core boundary (330-360 GPa). The starting mix was prepared from high-purity Fe-metal and FeS (7 wt% S in the bulk), and metallic Re-Os-Pt (each 1 wt%), and finely ground in an agate mortar. Experiments were designed to have 8-21 wt% sulfur in the liquid metal (Sliq), within the range proposed for the outer core. Experiments were performed using MA6/8 multianvil modules with 18/11 (Cast-MgO cell; graphite furnace; zirconia insulator) and 8/3 (Cr-MgO cell; Re furnace; LaCrO3 insulator) pressure cells, Type C thermocouples, and MgO capsules. To ensure bulk homogeneity, each charge was taken above the liquidus temperature, kept there for at least 30 mins, and then brought to the target temperature at 5-10 C/min. At the target temperature, run duration was 3-4 hours. After each experiment, the sample was mounted in epoxy and longitudinally ground for optical and electron microprobe analyses. Concentrations of all the elements were determined using JEOL-8800 JXA microprobe with WD spectrometry. Owing to slow diffusive equilibrium in metal-bearing systems, analyses were done within 10-15 micron of the interface, and 8-35 analyses were obtained. Spot and raster modes were utilized to analyze solid and liquid metal, respectively, with analyses covering almost the entire portion of the liquid part of the charge. All the charges were free of metallic nuggets. The liquid metal phase was identified by its dendritic texture, and the solid and liquid metal phases have a sharply defined boundary. The retrieved partition coefficients (Dsolid-metal/liquid-metal) show a strong positive dependence on the sulfur content (9-20 wt%) of the liquid metal. Between 3-22 GPa, and at similar Sliq (12 wt%), values of DOs, DRe, and DPt range from 6-8.5, 4.6-5.9, and 3.2-3.3, respectively, and thus it appears that pressure does not have a remarkable effect on the D values. It is important to note that even though it is necessary to know the absolute D values, it is the relative fractionation, that is Pt/Re, Pt/Os, and Os/Re that we are most concerned with, as it is the fractionation of Os from Pt and Re that is necessary to generate enriched 186 Os/188 Os and 187 Os/188 Os ratios. In the pressure range studied, with increasing Sliq, DOs/DRe remains virtually unchanged. Also, at a given Sliq, DOs/DRe seems to be pressure independent, implying that with increasing pressure, Os and Re do not readily fractionate from each other. At 3 GPa, DPt/DOs and DPt/DRe actually decrease with increasing Sliq, indicating, that Pt significantly fractionates from both Re and Os. Importantly, however, at a given Sliq, DPt/DOs and DPt/DRe increase with pressure, indicating, that Pt is actually strongly becoming more compatible in the solid metal. The results above are exactly the opposite to what is envisaged in the plume scenario, we are testing here. Thus, if the trend of increasing DPt/DOs and DPt/DRe and the relative constancy of DOs/DRe described above continues to the depths of outer-inner core levels in the planet, then it becomes even more difficult to suitably, and rather strongly, fractionate Pt and Re from Os, as needed in geochemical models. Hence, on the basis of the experimental data presented here, it seems impossible to generate the required fractionation of Re, Os, and Pt from each other (in a core that contains sulfur as the principal light element), and an outer core, Os isotopic component in some basaltic lavas can be dismissed. Possible future endeavors to more severely address the Os signals should focus more on cautiously pushing the limits of the multianvil modules to higher pressures by using sintered diamond cubes, perhaps more ways to do post-mortem on tiny, diamond-anvil cell samples to properly understand the partitioning systematics at ultra-high pressures, narrowing the huge uncertainty in the nature of light element(s) in the outer core by combining experiments with cosmochemistry, and the effect of a multitude of light dilutant on D systematics. It would also be beneficial to define the possible reservoirs of Re, Os, and Pt in the most accessible upper mantle rocks and the factors controlling the distribution and fractionation of these elements in a variety of tectonic as well as rock settings, to ultimately help us understand the Os signals.

Recycling of Archean Peridotitic Komatiite in the NW Kyushu Source

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Based on Sr-Nd-Pb isotope and trace element features of the NW Kyushu basalts, their sources were considered to be mixtures of depleted upper mantle and recycled components such as ancient oceanic crust.

Nevertheless, recent high-pressure melting experiments of basalt/peridotite hybrids have revealed that partial melting of basalt/peridotite hybrids cannot form NW Kyushu basalts since these basalts are enriched in Fe and depleted in Al compared with experimental partial melts of basalt/peridotite hybrids. Results of previous high pressure melting experiments indicate that cpx in the NW Kyushu source is the first disappearing phase at low pressure, and that the NW Kyushu source has high FeO* compared with typical peridotites. Among terrestrial materials used as starting materials in experiments, a peridotitic komatiite is only one with these characteristics. Model calculations suggest that partial melting of Archean peridotitic komatiite can essentially explain major element, trace element and Sr-Nd-Pb isotope features of NW Kyushu basalts. Thus, the simplest explanation for the NW Kyushu source is recycling of Archean oceanic crust with peridotitic komatiite composition.

The Vøring Plateau Volcanic Margin : A Key Rock Succession to Understand Continental Breakup During the Initial Stages of the Opening of the NE-Atlantic

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The Vøring rifted passive margin is located at the central segment of the Norwegian Margin and forms part of the North Atlantic Igneous Province. Drilling at the Vøring Plateau and the SE Greenland margin during the Ocean Drilling Program, recovered volcanic rock successions that erupted during the initial stages of breakup of Greenland from Fennoscandia. Hence, the mid-Norwegian margin now represents the transition region between an old Proterozoic cratonic lithosphere and a geologically young Cenozoic oceanic lithosphere.

The ODP Leg 104, Site 642E cores of the Vøring Plateau consist of a Lower Series (LS) of basic dykes, glassy andesite/dacite lava flows, and interbedded volcaniclastics which underlies a 770 m thick Upper Series (US) of transitional-type mid-ocean ridge basalts. The resampling strategy of core 642E in the framework of a EUROMARGINS sub-project aimed to attain an improved sampling density of the heterogeneous LS and the transition to the homogeneous US. The degree and processes of mantle-crust interaction are investigated by ICP-MS, TIMS and multi-collector ICP-MS trace element and radiogenic isotope geochemical analyses. The US tholeiitic MORB flows are characterized by slightly LREE enriched and consistently parallel convex C1-normalized REE patterns. The REE compositional differences are due to different degrees of partial melting of a uniform source, coupled to variable extent of fractional crystallisation of the mantle melts. On the contrary, the tholeiitic basalt dykes of the LS have somewhat concave MORB-like REE patterns. The LS basaltic andesitic and dacitic flows are more enriched in LREE, forming steep concave C1-normalized REE patterns. The samples have a negative Eu anomaly and can be interpreted as resulting from interaction of mantle melts with crustal material and/or of significant crustal melting by crustal underplating. Isotope data of Leg 104 samples from the LS and US show a dichotomy in terms of Sr and Nd isotopic composition. The US is isotopically relatively homogeneous with typical mantle-source derived isotope ratios (87Sr/86Sr ± 0.703) while the LS shows more radiogenic ratios and a higher variability (e.g. 87Sr/86Sr > 0.710).

The marked diversity of the US and LS samples from Site 642E offers opportunities to distinguish geochemical signatures related to crustal contamination from those related to intrinsic mantle source variations of the plume component.

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Layered Mantle Alternative to Mantle Plumes: Evidence from the Pacific Plate

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The features of central volcanic vents do not readily allow perception of the arrangement of enriched mantle sources beneath the active volcanoes of linear island chains. From experimental petrology, all basaltic magmas derive from fairly shallow depths in the mantle at or near the bases of lithospheric plates, and they carry with them the geochemical attributes of magma sources at those depths and no deeper. Whether even several central conduits in a 100-km radius, such as at Hawaii, penetrate the top of a plume or the top of a widespread layer of enriched mantle is topologically impossible to determine. Inferred patterns of "plume zoning" can also be interpreted in terms of a layered mantle, and in any case are not consistent among volcanic chains. The volcanoes themselves do not reveal whether their sources have cycled down to the base of the mantle and then upward again in a plume conduit through the entire mantle. Nor do the diverse geochemical attributes of the basalts, however they are distributed in time and space, divulge deep mantle sources. Instead, most geochemists argue that their enriched characteristics ultimately derive from contact with the atmosphere, the oceans, the hydrothermal processes that drive differentiation in the ocean crust, weathered continental crust, and the waters of rivers and streams. Thus the source of basalts from seamounts and islands may be a shallow layer beneath the lithosphere within which low-degree melts or fluids derived from buoyant subducted materials or delaminated subcontinental lower crust and upper mantle have concentrated, rather than mantle plumes. Every concession to source heterogeneity (enriched, volatile-charged, pyroxenitic, or eclogitic components in the source) reduces the likelihood that average primitive magmas have a high potential temperature that can only be explained by a mantle plume.

The term "ocean-island basalt" (OIB) is a misnomer, since geochemically similar lavas occur on many thousands of widely dispersed seamounts and submarine volcanic ridges, and even in small percentages on the crests of spreading ridges. Many seamounts and islands in the Pacific could not have formed above narrow vertical mantle conduit systems, whether fixed or moving, and indeed the few strongly co-linear age-progressive chains are only prominent during the last third of the history of the Pacific plate. The majority of places have widely distributed volcanoes, cross-trend ridges, and/or repetitions of volcanism over wide regions that have spanned several tens of million years; these favor persistent tapping of a widely-distributed enriched and shallow asthenospheric layer rather than numerous narrow mantle plumes that originated deep in the mantle. The layer appears to accumulate over time from aggregation of dispersed or strongly concentrated enriched materials in the asthenosphere. The lithosphere acts as a permeability barrier to the ascent of buoyant material derived from such sources. Thus seamounts on older lithosphere tend to be more consistently and strongly enriched than those near the ridge axis. The thickness and composition of the layer likely derive from the arrangement and concentration of low-density materials implanted in the depleted upper mantle during ancient episodes of subduction. Xenoliths show that the lithosphere itself can become infused with enriched veins and cumulates charged with volatile-rich inclusions, which in turn can be carried away for long distances, and even to subduction, by plate motion. Shallow contractive and tectonic forces transmitted across the Pacific plate from subduction boundaries plus buoyancy forces from the irregular enriched layer determine where mid-plate fissure systems develop and volcanism occurs. These have changed as the Pacific plate has grown and become more strongly directed in its direction and rate of subduction over the past 160 million years.

The Dongargarh Group: A Large Igneous Province at the Archean-Proterozoic Transition in India

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The palaeoproterozoic (~2.5 Ga) Dongargarh Group in the Central Indian Craton is a continuous ~10 km.thick volcano-sedimentary sequence with large and sub-equal volumes of coeval mafic and felsic lavas occurring in a bimodal distribution for a length of ~250 km and width of ~90 km. The rocks are weakly deformed into a regional syncline and metamorphosed at low-grade green schist facies.The felsic rocks (Bijli Rhyolite) occur at the base of the succession.The mafic volcanism is pulsatory,and mainly represented by the Pitepani (PV) and Sitagota Volcanics (SV) successively towards top. The minor andesitic Mangikhuta Volcanics (MV) denote the terminal volcanicity.The SV is thicker (~3 km) than PV (~1 km) and MV(<1 km).The high-Mg basalts–Fe-rich tholeiites assemblage with common intrinsic geochemical characteristics form the PV and SV,and are repeated in the succession. Because of the great volumes of coeval mafic and felsic lavas,pulsatory eruptions of high-Mg basalts/basaltic komatiites and CFB-type tholeiitic basalts with melts volume in second pulse exceeding that of the first,dominance of thick tholeiites over komatiites in the sequence, the Dongargarh Group may be characterized as a large igneous province,one of the few of its kind known at or near the Archean-Proterozoic (A-P) transition.

The rhyolites have high silica, high alkali, FeO/MgO, Ga/Al, REE, and low CaO,Sr.The high-Mg basalts in the PV (P1) and SV (S1) have MgO (7.5-10.5 wt%) at SiO2 (50-54 wt%), with TiO2(~0.5 wt%), Ni (~200 ppm) and Cr (>300 ppm), chondritic Al2O3/TiO2 (20-25) and CaO/Al2O3 (~0.8), and nearly flat HREE (10xchondritic), and are of Munro-type komatiite affinity. The S1 rocks occasionally show pyroxene-spinifex texture. The P1 and S1 have elevated FeOt than the peridotite mantle (9.5 wt% vs.8 wt%).The S1, however, show depletion in incompatible elements (e.g.,Rb,Sr,Ba,La) compared to P1. The tholeiites in the PV (P2) and SV (S2), on the other hand, have MgO (5-6 wt%) at SiO2 (47-48 wt%),with TiO (~1 wt%), Ni (<100ppm) and Cr (100ppm), flat HREE (20xchondritic), sub-chondritic Al2O3/TiO2 (10-15), and CaO/Al2O3 (<0.7). The P2 and S2 have FeOt (13-14 wt%).

The olivine fractionation from a komatiitic parental melts,and interaction with bulk Bijli melts gave rise to the high-Mg basalts, with decline in both olivine fractionation and rhyolite contributions in the second pulse (S1). The P2 and S2 are possibly related to parental picro-tholeiites by olivine and/or pyroxene fractionations. The komatiitic melts may have been derived from Fe-rich peridotite and/or harzburgite at 3-4 GPa.The picro- holeiites were generated at 1-2 Gpa from a source with variable but elevated FeOt/MgO than that of komatiite.The upper andesites are related to the CFB-type tholeiites by 50% fractionation. The high temperature Bijli melts (950°c) is hybrid having crustal as well as material contributions from high-Mg basalts.The pulsatory eruptions of high-Mg basalts and tholeiites in the belt could reasonably be explained in terms of anomalously hot plume head melting in an extensional environment. Direct involvement of Fe-rich deeper mantle in production of juvenile crust was important at the A-P transition in Central India, similar to many cratons in the erstwhile Gondwanaland.

Statistical Comparison of 3He/4He Distributions in Mid-Ocean Ridge and Ocean Island Basalts

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Helium isotope variations in mantle-derived materials provide a central constraint on models of mantle structure and evolution. Mid-ocean ridge basalts (MORB), generally interpreted to be derived from the upper mantle, are typically described as clustering around a 3He/4He value of 8 RA, representing a mixture of radiogenic He (<0.01 RA) and He initially trapped within the Earth (120 RA). Ocean island basalts (OIB) from a variety of hotspot locations (in particular Hawaii, Iceland, Samoa and Galapagos) exhibit values ranging up to ~50 RA, and this has been widely interpreted as evidence for a mantle source having a much higher 3He/(U+Th) ratio over Earth history. This in turn suggests isolation from the main convective flow, likely deeper within the Earth. However, several recent studies claim that both OIB and MORB have similar average values for 3He/4He. This, in turn, could indicate derivation from a common, heterogeneous reservoir, with OIB exhibiting a larger spread due to more limited averaging of small-scale mantle domains by the melt generation process.

We have made a comprehensive compilation of all the published He isotope data for MORB and OIB. MORB values do cluster around 8 RA (e.g., the median value for all ocean basins is 8.1 RA). A minority of moderately high 3He/4He (up to 14.2 RA) exist, usually in MORB from spreading ridges near ocean islands or bathymetric highs. OIB 3He/4He range from somewhat below the MORB range to 50 RA. An undeniable feature of the OIB data is that while there is a concentration of values lower than MORB, there is a preponderance of values well above the MORB range. This is true regardless of how the data are weighted, whether equally, by hotspot size, or by region. In particular, both large and small hotspots have high 3He/4He, making it unlikely that the MORB-OIB distinction can be explained by differences in depth or extent of melting. The most plausible explanation is that the mantle source of OIB with high 3He/4He is distinct from the mantle source of MORB.

Applicability of Large Magma Chambers to Deccan Volcanism: A Numerical Study

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Deccan Volcanic Province (DVP) is one of the largest continental flood basalt (CFB) provinces. One of the most important questions connected with the CFBs is to understand the enormous volume of volcanism. Explanations for such massive scale of magmatism over apparently short duration of time have been sought over the years through various proposed processes. However, a lot more information is required to understand the dynamics involved in such complex phenomenon.

We suggest a mechanism through which large volumes of magma, sufficient to generate DVP, can be stored at shallow crustal depths and can be erupted in relatively short duration of time. This concept is based on the physical and thermodynamic properties of accumulated magma in an extensional environment leading to continental rifting. Our model is derived from the published numerical data, dealing with the possibilities of immense amount of magma generation and storage. Further, the model incorporates the geological/geochemical characteristics of the DVP to assess the applicability of these numerical models on this CFB.

Experimental Constraints on the Role of Garnet Pyroxenite in the Genesis of High-Fe Mantle Plume Derived Melts

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The anhydrous phase relations of a primitive, ferropicrite lava from the base of the Early Cretaceous Parana´ Etendeka continental flood basalt province have been determined between 1 atm and 7 GPa. The sample has high contents of MgO (14.9 wt %), FeO* (14.9 wt %) and Ni (660 ppm). Olivine phenocrysts have maximum Fo contents of 85 and are in equilibrium with the bulk rock, assuming a K Ol_liquid (Fe/Mg) of 0.32. A comparison of our results with previous experimental studies of high-Mg rocks shows that the high FeO content of the ferropicrite causes an expansion of the liquidus crystallization field of garnet and clinopyroxene relative to olivine; orthopyroxene was not observed in any of our experiments. The high FeO content also decreases solidus temperatures. Phase relations indicate that the ferropicrite melt last equilibrated either at ca.2.2 GPa with an olivine clinopyroxene residue, or at ca. 5 GPa with a garnet clinopyroxene residue. The low bulk-rock Al2O3 content (9 wt %) and high [Gd/Yb]n ratio (3.1) are consistent with the presence of residual garnet in the ferropicrite melt source and favour high-pressure melting of a garnet pyroxenite source. The garnet pyroxenite may represent subducted oceanic lithosphere entrained by the upwelling Tristan starting mantle plume head. During adiabatic decompression, intersection of the garnet pyroxenite solidus at ca. 5 GPa would occur at a mantle potential temperature of 1550 C and yield a ferropicrite primary magma. Subsequent melting of the surrounding peridotite at ca. 4.5 GPa may be restricted by the thickness of the overlying sub-continental lithosphere, such that dilution of the garnet pyroxenite melt component would be significantly less than in intra-oceanic plate settings (where the lithosphere is thinner). This model may explain the limited occurrence of ferropicrites at the base of continental flood basalt sequences and their apparent absence in ocean-island basalt successions.