V31A MCC: 3006 Wednesday 0800h

The Origins of Hot Spots, LIPs, Seamount Chains, and Volcanic Ridges IV *(joint with OS, T)*

Presiding: **G R Foulger,** University of Durham**; D C Presnall,** Carnegie Institution of Washington

V31A-01 0805h INVITED

The Plate Paradigm; the Standard Model *Reductio ad Absurdum*

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Midplate volcanism, volcanic chains, diffuse boundaries and variable chemistry basalts are usually considered to be outside the plate tectonic hypothesis and to need separate explanations. This is true only for the instantaneous, steady state, kinematic and hard plate versions of the hypothesis. In the more general plate paradigm (with fewer restrictive adjectives), melting anomalies', seamount chains, and LIPs are by-products of plate tectonics. This assumes that the shallow mantle is close to the (variable) melting point and that athermal and episodic processes are important. Cooling of the surface generates forces that drive, break and reorganize plates; global reorganizations (including new plate boundaries) are intrinsic; regions of intense, long-lived magmatism and shallow tensile stress are (usually but not always) plate boundaries. Plates are regions of lateral compression. Plate boundaries have shallow extensional or strike-slip earthquakes; where the mantle is near the melting point the buoyancy of magma generates dikes and volcanoes. When compressional forces dominate, upwelling magmas pond beneath the plate until released by extensional stresses. Large melting anomalies are episodic and associated with changes in plate stress and new plate boundaries (often triple-junctions). Incipient boundaries can be extensional and volcanic, as can abandoned ones. Ridges, island arcs, seamount fields and chains, and reactivated and incipient boundaries , are part of a single process. The plate paradigm thereby reverses the assumptions of current geodynamic and geochemical reservoir models : Locations of volcanoes are controlled by lithospheric stress and fabric (not mantle temperature).The volumes of magma are controlled by lithospheric extension and shallow mantle fertility (not by conditions at the core mantle boundary).The stress-, fertility- and thermal-states are controlled by plate tectonics and upper mantle recycling (not by infusions from the deep mantle).The upper mantle has variable chemistry, melting point, potential temperature and is perisolidus everywhere (not just under hotspots). The upper mantle is not dry, refractory, isothermal , uniform, or well-stirred . The ends of volcanic chains are not fixed' . One even reverses the motivating question, why are there not volcanoes everywhere (instead of why are there volcanoes some places)? Non-fixity, aberrant ages and directions, absence of uplift and thermal rejuvenation, low heat flow, normal' magma temperatures, distributed volcanism, and seamount chemistry are not anomalies' as they are in hotspot theory. The associations of LIPs with suture belts and cratons are no longer coincidences. Predictions: Midplate volcanism implies extensional stress, not necessarily high heat flow, uplift or thermally thinned plate. It need not be age-progressive, parallel or in chains. Basalts are variable in chemistry (central limit theorem) and involve the same recycled components . Recycled oceanic crust and gabbro cumulates are variably distributed in the shallow mantle . The scale of chemical heterogeneity corresponds to the scale of recycled components (crust, sediments, lithosphere) and arc segments. Volcanic chains are stress gages, not motion detectors. If the shallow mantle is perisolidus (near the melting point) then even the deepest slowest ridges will be magmatic; melting will occur under thick plates (not likely in thermal theories). Ponding and underplating should be common. In contrast to thermal theories, volcanism can initiate and terminate abruptly. The technique of testing a hypothesis by assuming the opposite, is *reductio ad absurdum*. A simpler more powerful theory emerges when we drop the adjectives and reverse the assumptions.

V31A-02 0825h

"Hotspots" and the opening and closure of oceans

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A model for "hotspot" volcanism based on endgames of plate tectonic processes is maturing. As ocean basins close and continents collide, latest-subducting slab equal in length, at least, to the thickness of the colliding continental crust and lithosphere, is trapped in the suture. This includes overlying sea-floor sediments and back-arc basins. Young oceanic plate is relatively hot and buoyant, and thus does not sink to great depths into the mantle. Some even obducts and underplates. As a result, eclogitised or metasomatized slabs of subducted oceanic upper and lower crust (including both igneous & cumulate) may also be abandoned, after closure, in the upper mantle below the lithosphere of the sutured continents. Sutures are reactivated and exhumed when continents rift and new oceans open. Continental flood basalts and seaward-dipping reflectors are associated with the edges of thick Archean cratons and mobile belts. This "hotspot" volcanism, produces large volumes of melt, some of which has ocean-island basalt (OIB) geochemistry. The transient large melting rate can be explained by the melting of oceanic crust from subducted slabs in the sutures, which is more fusible than mantle peridotite. OIB geochemistry can be explained by large-degree melting of components of old, eclogitised subducted oceanic crust, including slab sediments. Where rifting occurs longitudinally along a suture, the availability of eclogite may increase melt volumes for the first few Myr after opening. Where a new rift crosses a suture transversely, enhanced melt volumes and OIB geochemistry may persist for longer. This raises interesting questions regarding the geometry of rifted continental edges, possible recirculating of continental mantle lithosphere and the depth to which mantle material is transported with overlying continents over periods of hundreds of Myr. Many primary "hotspots", particularly at the edges of cratons and continents may be readily explained by this model. Abandoned oceanic slabs may be widespread in the upper mantle. Fertility and fusibility variations may explain "hotspot" magmatism better than temperature variations.

URL: http://www.mantleplumes.org

V31A-03 0840h

Modeling Mantle Melting During Continental Breakup: Implications for Anomalous Volcanic Productivity at Rifted Margins

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Mid-ocean ridge accretion generates remarkably uniform crust, placing a powerful constraint on the state of the upper mantle. Models invoked to explain melt anomalies associated with volcanic rifted margins and other large igneous provinces must be consistent with what is known based on mid-ocean ridge studies. A successful model of volcanic margin formation should be able to produce a single transient pulse of excess magmatism followed by steady-state plate driven oceanic crustal accretion. To assess under what conditions buoyantly driven upwelling or small-scale convection at rifted plate boundaries is important, we employ a fluid-dynamical model with non-Newtonian viscosity that includes the feedback from melting on the physical properties of the mantle. Melting affects both the buoyancy and viscosity of the mantle, and may facilitate a transition to other creep mechanisms by enhancing grain boundary sliding. The model shows that some small-scale convection can occur. However, models that evolve into steady-state oceanic accretion show only modest excess melt productivity . In general, models that generate high magmatic productivity at breakup require a viscosity and density structure that also leads to excessive time dependence and/or anomalously high productivity long after breakup. Assuming an abrupt change in lithospheric thickness to enhance convective instabilities does not fundamentally alter this conclusion. In models that include a dehydration induced viscosity increase, the problem is exacerbated by suppressing buoyant upwelling above the depth to the dry solidus thereby restricting shallow flow to plate drive upwelling. The model can be used to quantify the spatial and temporal scales of anomalous volcanism associated with continental breakup under a variety of different assumptions about the viscosity and density structure of the upper mantle. To explain the large (factor of two greater than steady-state), short lived (10 m.y.) pulse of breakup volcanism observed along SE Greenland, an exhaustible layer of anomalous material beneath the lithosphere seems required. Determining the source of this layer and establishing whether it is a chemical or thermal anomaly are needed to fully understand the North Atlantic igneous province.

V31A-04 0855h

Metasomatic Control of Trace Element Ratios in Lithospheric Mantle: New Interpretation of OIB Isotopic Variations

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Metasomatized lherzolites from the deep portions of recycled oceanic lithosphere, rather than subducted oceanic crust, may be the principal component of OIB sources [1]. However, the exact chemical and physical nature of this metasomatic process is unclear. In particular, it is uncertain how metasomatism produces chemical variations in recycled lherzolite that reflect the different OIB isotopic "signatures". Chemical variations observed in Cantal basalt (France), interpreted as the result of a lithospheric metasomatic mechanism, provide important new constraints on the nature of this metasomatic process. The basalts, erupted between 13 and 3 My ago in the Cantal alkali massif, show an unusual increase in Nb/Th and Ce/Pb ratios from 10.5 and 23 respectively in the first emitted basalt to 18.7 and 44 in the last. The range in Nb/Th (10.5 to 18.7) is practically as large as that found in picrites and tholeiites from all major oceanic islands (8 to 20). These basalts are homogeneous with respect to their Sr, Nd, Pb isotopic composition, ruling out variable sediment contamination of their mantle sources. We postulate that the Nb/Th and Ce/Pb variations are the result of a metasomatic process, called "percolative fractional crystallization" (PFC) [2] which produced veins within the lithospheric mantle. A product of the PFC mechanism is observed in Cantal basalts erupted after 9.5 My ago as the appearance of green-core pyroxene xenocrysts (GCPX). The formation of this GCPX, observed worldwide, is related to the crystallization and fractionation of apatite, ilmenite, amphibole and rutile, during the percolation and differentiation within upper-mantle of an initial basaltic liquid. In this model, compositional variations between the first and the last erupted basalt are explained by an evolution of vein composition present at the depth of melting in the vein-plus enclosing mantle source. These new data indicate that there is a "short-term" mineralogic control on Nb/Th and Ce/Pb ratios through a vein-plus-enclosing mantle source model. This differs from previous models for variations in these ratios being related to the "long term" extraction of continental crust from the mantle and the extent of sediment recycling and mixing in the mantle. Reconstruction of lithospheric sources from the different basalt compositions indicates significant heterogeneities in Th/Pb, U/Pb and Sm/Nd resulting from the metasomatic process. If this type of metasomatised lithosphere was subducted and isolated during a long period of time (1-2 Ga), the chemical variations would create Nd and Pb isotopic variations in the different part of this lithosphere similar to isotopic range observed in some oceanic islands. Moreover, these isotopic variations would be correlated with trace element ratio variations commonly interpreted as the product of mixing between different end-member mantle components (HIMU and EM). This suggest that isotopic and trace element variations observed in basalts from individual oceanic islands may more likely be the result of melting metasomatized subducted oceanic lithosphere rather than from a mixture of chemically distinct mantle sources that formed and evolved independently from one another. [1] Y. Nui, M. O'Hara. (2003) J. Geophys. Res.,108, B4, 2209. [2] B. Harte, R. H. Hunter, P. D. Kinny. (1993) Philos. Trans. R. Soc. London, 342, 1-21.

V31A-05 0910h

Was Shatsky Rise Formed by a Plume Head or Plate Boundary Processes?

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Shatsky Rise is a large oceanic plateau located about 1600 km east of Japan, in the NW Pacific Ocean. It is a basaltic mountain range with an area nearly equal to Japan or California, qualifying it as one of the globe's larger LIPs. Existing geologic and geophysical data are consistent with formation by a starting plume head, yet coincidences with spreading ridge tectonics

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suggest otherwise. Most knowledge of Shatsky Rise tectonics comes from magnetic lineations mapped around and within the rise. They show that the rise sits along the track of the Pacific-Farallon-Izanagi (PFI) triple junction from M21 to M3 time (147-125 Ma) and consists of three large volcanoes, separated by minimally-disturbed lithosphere, and a linear volcanic ridge. All volcanic edifices appear to be the same age as the lithosphere upon which they sit, implying progressive volcanism becoming younger to the northeast. The largest volcanic edifice, with a volume of 2.7×10^6 km^3, erupted rapidly, as shown by its consistent reversed magnetic polarity and the near coincidence of dates from basalts cored on its upper flanks with the age of the lithosphere. Shallow water fossils from the upper reaches of this volcano imply its summit was above sea level. Magnetic lineations indicate that the triple junction jumped at least nine times, with larger jumps taking it to positions at the edges of the volcanic edifices and implying a connection between volcanism and ridge jumps. Furthermore, the triple junction migrated in a direction and with a velocity inconsistent with a single, stable configuration, as if its behavior were perturbed by factors other than plate velocities. These observations fit reasonably well with predictions of the plume or plume head hypothesis: (1) rapid and voluminous initial eruptions, (2) the volcano grew above sea level (dynamic uplift), (3) massive plume head eruptions transitioned to lesser-flux plume tail, and (4) extra heat and uplift from the plume caused the triple junction to jump repeatedly to the plume site. In addition, the trends of Shatsky and Hess rises are similar to that of the Mid-Pacific Mountains, implying all were formed by motion of the Pacific plate over mantle hotspots. Other observations fit the plume hypothesis less well. Geochemical and isotopic data mostly show MORB-like signatures, arguing against a plume source unless it was diluted or swamped by sub-ridge melting. More troublesome, however, is the affinity of Pacific plate plateaus for triple junctions. Shatsky Rise formed at a triple junction, beginning at the time of a plate reorganization that formed one or two microplates. Hess Rise and another microplate probably formed at the location of a later PFI triple junction jump. Furthermore, the Mid-Pacific Mountains, Magellan Rise, Manihiki Rise, and two additional microplates seem to have formed along the track of the Pacific-Farallon-Phoenix triple junction and the tracks of the two triple junctions have different trends (i.e., cannot be explained by motion over fixed hotspots). This coincidence of ridges and triple junctions only makes sense if plate boundary processes give rise to the plateau volcanism. In summary, Shatsky Rise has characteristics that fit formation either by plume or plate boundary processes, but new data are required to decide which. What's more, the connection between plumes, microplates, and triple junctions is unclear and seems fertile ground for further study.

V31A-06 0930h

A Cenozoic Alkaline Magmatic Province in the SW Pacific Without Rift or Plume Origin

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A large-scale, long-lived (ca. 55 Ma) alkaline magmatic province occupies discontinuous portions of the SW Pacific region including eastern Australia, New Zealand, west Antarctica and the oceanic plates between. Although this province, here named Pacific SW Alkaline Province (PSWAP), is aerially extensive, estimates of the total volume of upper crustal igneous rocks and the magma production rates are rather low. Comparison of the location of magmatic centers and seismic shear wave perturbation models shows that the PSWAP is largely limited to lithosphere less than 80 km thick underlain by distinct low seismic velocity anomalies extending to 200 km depth. Geochemical studies show that the magmatism is largely a result of small degrees of melting of a source enriched in incompatible elements relative to primitive upper mantle. Metasomatic enrichment of the upper mantle, including infiltration of volatile-rich fluids and melts into the overlying lithosphere, may explain the regional geochemical as well as low seismic velocity signatures. Metasomatism most likely occurred during Paleozoic-Mesozoic subduction along the Pacific margin of Gondwana and Jurassic plume-related activity. Models to explain the magmatism in separate parts of PSWAP include adiabatic decompressive melting due to rifting and strike-slip faulting, mantle plumes, or hundreds of hot spots, but all of these associations have flaws. Hot spot formation and associated magmatism have also been linked to faults and propagating fractures in geodynamic models of extending lithosphere above regions where upper mantle has been shielded from the cooling effects of subducting slabs. In addition, boundaries between thick cratons and thin lithosphere (such as in eastern Australia and West Antarctica) may drive small-scale convection, bringing hot sub-cratonic mantle toward thinner lithosphere with eruption occurring during extension- often during major plate reorganizations. But the Cretaceous break-up of Gondwana that rifted Australia and the New Zealand-Campbell Plateau region from Antarctica, regional extension of lithosphere over metasomatized mantle did not cause widespread magmatism as predicted by these models. Although the PSWAP magmatism has been linked broadly to tensional stress-fields, these are not requirements as evidenced by Australian volcanism under mildly compressional stress-fields. Therefore, extension probably did not trigger Cenozoic magmatism in PSWAP. A regional Cenozoic heating event may be more likely. We propose a new model that links sudden detachment and sinking of subducted slabs into the lower mantle beneath the PSWAP in the early Cenozoic, with vertical and lateral flow that triggered melting of metasomatized upper mantle. Small batches of magma leak through pre-existing faults and fractures in most regions, but larger volumes erupt in areas with moderate extension.

V31A-07 0945h

Could Low Thermal Diffusivity Provide Runaway Melting in The Upper Mantle?

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Melting in the mantle has been attributed to thermal feedback associated with the temperature dependence of viscosity during deformation (Shaw, 1969, J. Petrol.). Visco-elastic heating has been explored in various geodynamics studies. In particular, Branlund et al. (2000, EPSL) found that a non-linear decrease of thermal diffusivity (D) with temperature (T) would enhance shear zone thinning and speed-up instabilities. Their result suggests that thermal feedback enhances melting in the uppermost mantle, without viscous heating, if considerable non-linearities exist in D(T) at the onset of melting. In fact, extreme non-linearities are indicated by theory and measurements. (1) Measurements of D of volcanic olivine-melilitite (Buettner et al. 1998, J. Volc. Geotherm. Res.) show large non-linearities in D(T) due to pre-melting effects, and a discontinuous decrease in D upon melting. This behavior should be general, because increasing disorder reduces D (e.g., Giesting and Hofmeister, 2002, Phys. Rev. B). (2) Our laser-flash measurements of various glasses show that D depends non-linearly on T. Melts will behave similarly. To quantify the function we are applying the melting experiments of Buettner et al. to Icelandic lavas and other relevant materials. In our runaway model, melting under ridges or hotspots does not define a magma chamber, but rather occurs on grain boundaries of the solid phases. A small amount of melting decreases D precipitously and raises the temperature which induces more melting. This phenomena is confined to low pressures (since D increases with P) and T below 2000 K (wherein radiative effects are unimportant), and can occur in a low temperature gradient. Thus, production of magmas at hot spots need not require a deep-seated mantle plume.

V31B MCC: 3008 Wednesday 0800h

Messages from the Underworld: Linking Geophysical Signals to Magmatic and Hydrothermal Processes I *(joint with S)*

Presiding: **J B Lowenstern,** U.S. Geological Survey**; J W Neuberg,** School of Earth Sciences, University of Leeds

V31B-01 0800h

A Trigger Mechanism for Volcanic Low-Frequency Seismic Events on Montserrat

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Seismic observations of low-frequency earthquake swarms on Montserrat point to a non-destructive, repeatable source mechanism in a confined area inside or near the conduit. While the seismic wave propagation pattern of the subsequent resonance in and around the conduit is well studied, the trigger mechanism has remained elusive. In this contribution we suggest a trigger mechanism based on new field evidence for fracture and healing of magma in volcanic conduits, together with seismic observations from Montserrat and finite element modelling of magma deformation during conduit flow. As a seismic trigger we suggest a stick-slip motion of highly-viscous magma in the glass transition, that periodically generates networks of seismogenic shear fractures a few metres in length. These fractures are rapidly filled by fine-grained material [cataclasite] that is generated by friction processes on the fracture surfaces, such as corner abrasion, and is locally redeposited by gas flowing within the fracture system. Filled fractures are then swiftly healed as reloading leads to annealing and a return to cohesive viscous deformation. Such a fast healing process, probably on the order of tens of seconds, leads to a repeatable trigger mechanism. Due to a strong lateral viscosity gradient in the conduit, highly-viscous magma near the conduit walls, which can exhibit brittle behaviour, co-exists with low-viscosity, fluid magma in the conduit centre; such that brittle failure provides the seismic trigger mechanism while the fluid part can still act as a seismic resonator.

V31B-02 0815h

Magmatic Dike Resonances Inferred From Very-Long-Period Signals

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Hachijo Island is a volcanic island located 280 km south of Tokyo. Renewed activity began on 13 August 2002, when a swarm of volcano-tectonic (VT) earthquakes accompanied by deformation of the volcano was detected. On 20 August, when the VT seismicity was almost waned, a swarm of very-long-period (VLP) events began beneath the island. The VLP signals show simple decaying harmonic oscillations with periods near 10 seconds and lasting for about 300 seconds. We analyze the waveforms of the VLP signals on 4 September. These were observed by two permanent and three temporary broadband seismic stations on this island. Spectral analysis of the decaying harmonic oscillations in the tail of the VLP waveforms identifies two clear peaks at the periods of 7.3 and 11.4 s with quality factors (Q) of about 30. The source mechanism analysis of the VLP signals shows that the moment-tensor solution is dominated by volumetric change components with oscillatory signatures, indicating the resonance of a vertical crack at a depth of 5 km below the northern flank of Mt. Hachijo Fuji. We perform numerical simulations based on a fluid-filled crack model, and find that the basalt-steam mixture with gas-volume fraction around 20 % produces the crack resonance with Q around 30. We further find that the frequency ratio for two longitudinal modes with the wavelengths of 2L/7 and 2L/9, where L is the length of the crack, is similar to the observed frequency ratio. We calculate the synthetic waveform generated by the excitation of a vertical crack containing the basalt-steam mixture, which reproduces the feature of the observed VLP waveform. We may therefore reasonably interpret that the VLP signals originate in the resonance of a dike filled with a basalt-gas mixture, which may be the result of magma intrusion beneath this island as evidenced by the VT earthquake swarm and deformation of the island. The VLP activity continued for about 8 months between August, 2002 and April, 2003. The observed two peaks at around 7 and 11 s were stably observed during this period, although the frequencies showed a slight increasing trend within 5 % change since January, 2003. This suggests that the dike system stably existed beneath Hachijo Island during this interval. The stable existence of the dike system may not be explained by a simple magma cooling process, and implies the magma circulation between the dike and a possible magma chamber beneath the Island.