Penrose Conference

Plume IV: Beyond the Plume Hypothesis

Tests of the plume paradigm and alternatives

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Can “hot spots” – regions of anomalous volcanism – be explained by mechanisms other than deep thermal upwellings? This question was the subject of a week-long debate at the Penrose Conference, *Plume IV: Beyond the Plume Hypothesis*, held August 25-29, 2003 in Hveragerdi, Iceland. Over 60 geologists, geophysicists, and geochemists from 12 nations gathered to brainstorm the fundamental evidence that constrains the origins of volcanism. Seismology, convection modeling, heat flow, geothermometry, petrology, geochemistry, radiometric dating, kinematics, morphology and basic geology were all considered. This meeting was the most significant gathering ever held of scientists working on alternative mechanisms for anomalous volcanic regions. More such meetings will follow.

Seismology presented included wave propagation, tomography, anisotropy, and a summary of what seismology can and cannot tell us. Contrary to general assumptions, seismic wave speeds beneath Hawaii are relatively high (*Julian*). Whole-mantle tomography favors strong impedence of flow across the 660-km discontinuity and a relatively homogenous middle mantle (*Dziewonski*). Tomographic evidence for slab penetration to the core-mantle boundary is sparse and detailed scrutiny reveals problems with these interpretations of the most likely images. Anisotropy can reveal the orientation of flow beneath volcanic regions (*Montagner*). Credible images of low-velocity bodies traversing the entire mantle as predicted for hot upwellings from the core-mantle boundary are lacking. Low-velocity bodies extending down to the transition zone have been found beneath a few volcanic areas but similar bodies also underlie long-extinct volcanic areas such as Brazil and the Ontong-Java plateau (*Foulger*). The interpretation of high- and low-velocity anomalies is ambiguous. Melting, mineralogy, composition, anisotropy and temperature variations can all explain seismic wave-speed anomalies, with temperature having a relatively small effect (*Anderson*). A serious problem in many regions is scarcity of ray-path data resulting from the uneven distribution of earthquakes and seismic stations, especially in the Pacific ocean (*Dziewonski*). This situation could improve if large numbers of ocean-bottom seismometers are deployed (*Montagner*).

Modeling can explore whether convection within the Earth is layered or whole-mantle and whether thermal plumes are likely to form (*Ihinger, King*). Early, simple investigations involving tanks of liquids or numerical models have been influential in shaping popular concepts of plumes. However, Earth is radically different from a tank of liquid, and is not reliably modeled using mathematical approximations such as ignoring the temperature and pressure dependence of rheology, thermal conductivity and the coefficient of thermal expansion (*Anderson*). The most sophisticated lower-mantle models to date predict few, vast, sluggish upwellings in the lower mantle, not many localised plumes, and these models still neglect critical factors such as temperature-dependent viscosity (*King*). The Earth is probably chemically layered as suggested, for example, by dynamic topography, different grain sizes in the upper and lower mantles and seismic velocities in the transition zone (*Anderson, Hofmeister*).

It is generally assumed that "hot spots" are hot. They are hot in the sense that volcanic activity occurs at the surface, but the important point is the relative potential temperature of the mantle beneath. Three sessions focused this critical issue. Marine heat flow measurements provide little evidence for enhanced heat flow around "hot spots". Two spectacular examples of this are Hawaii and Iceland where heat flow measurements provide no evidence for elevated sub-lithospheric temperatures. Such findings are typical of "hot spots" (*C. Stein*).

Experimental studies consistently indicate low solidus temperatures for mantle materials containing likely amounts of water or carbon and suggest that the seismic low-velocity zone beneath oceans may result from incipient melt since volatiles lower the solidus temperature in adiabatically ascending mantle material (*Green, Presnall*). Thus, either mantle composition or potential temperature is mapped by the low-velocity zone. Subduction re-introduces materials more fusible than peridotite such as recycled ocean crust into the mantle (*Green*). The existence or otherwise of picritic magmas in both MOR and "hot spot" locations is a critical issue, as the temperatures of primitive magmas are the most direct evidence of mantle potential temperatures (*Green, Presnall*). Parental picritic magmas were proposed in both Hawaiian and MOR settings (N-MORB and E-MORB) leading to the inference of similar mantle potential temperatures (*Green*). Liquidus spinels and harzburgite-residue trends for Hawaiian picrites indicate a more refractory (in major elements) but refertilized (incompatible elements) source, and more refractory residue, than MORB. The role of picrites in MOR settings was challenged and parental MOR magmas comprising olivine tholeiites at ~150°C below the potential temperature of Hawaiian picrites was advocated (*Fitton, Gudfinnsson, Presnall*). "Hot spots" on or adjacent to ridges were considered to be formed at low potential temperatures comparable to those along "normal" ridges (*Presnall*).

Continental breakup and collision – the start and end games of plate tectonics – de-homogenize the shallow Earth. Continental collision traps slabs in and beneath sutured subcontinental lithosphere, where they provide a source of magma both during collision and subsequent continental breakup (*Chalot-Prat, Cigolini, Peccerillo,Finn, Flower, Barry, Fekiacova, Wilson*). Young, thin slabs may be neutrally buoyant in the shallow mantle. The great melt volume of the North Atlantic Volcanic Province and Iceland may result from mantle fertilised with subducted Iapteus crust (*Foulger*). Intense magmatism at the onset of continental breakup may be a result rather than a cause of breakup (*Anderson*). The Central Atlantic Magmatic Province (CAMP) reflects stress patterns related to Pangaean rifting, and requires a widespread mantle source and extraction of melt from different depths (*Mangas, McHone*). It is best explained by distributed, shallow, small-scale convection. The intense volcanism associated with the breakup of the South Atlantic persisted at some locations *e.g.*, the Walvis and Rio Grande ridges, where recent, detailed gravity data suggest control by variable lithospheric stress. This may arise from large-scale internal deformation and stress redistribution within the African plate, resulting from changes in its plate-tectonic boundary conditions (*Wilson*). Transform zones (*Beutel*) and also normal ridges (*Bonatti, Chalot-Prat*) are important both in controlling stress and facilitating mantle melting and the ascent of this melt to the surface.

Extraterrestrial volcanism can potentially increase our understanding of volcanism on Earth. Venus has no plate tectonics, and its heat budget and thermal history are poorly constrained (*Smrekar, Stofan*). Volcanism may have been localized in part by distributed rifting (*Jurdy*). The large (> 2,000 km) rimmed circular structures may also be impact craters dating from the main accretion of the planet, before 3.9 Ga (*Hamilton*).

Geochemistry, including Sr-, Nd-, Pb-, and He- isotopes, cannot be used to estimate a depth of origin or volume of mantle sources. Connections have been made between He isotopes and FOZO or C in oceanic island isotopic systematics but there is no requirement that FOZO and other enriched components (EM1, EM2, HIMU) must come from the deep mantle (*Natland, Peccerillo, Smith*). Enriched basalts are widely distributed over thousands of seamounts, and are not confined to tops of islands in linear chains. Plume sources cannot explain them all. Os isotopes have been interpreted to indicate a core component but they could reflect instead a metamorphic or pyroxenitic component (*Anderson, Smith, Walker*). W-Hf isotopic systematics may soon offer a means of testing whether a signal from the core-mantle boundary ever reaches Earth's surface (*Anderson*).

Field associations suggest a heterogeneous upper mantle over which ridges migrate (*Bonatti, Dick, Natland*). The upper mantle appears to contain variably fertile to barren lherzolite and harzburgite, on scales varying from hand-specimen-sized domains to subducted slabs of partly altered, eclogitized ocean crust (*Natland*). Also present is abyssal peridotite, pyroxenite produced by reaction between peridotite and migrating melts, and former terrigenous and marine sediment carrying quartz, water, and carbonate. Blocks of continental lithosphere, isolated during continental rifting, lie in the middle of oceans. Subcontinental mantle may be incorporated in basaltic magma generated in new ocean basins (*Natland, Smith*). The scale of heterogeneity produced at spreading ridges is re-introduced into the mantle at subduction zones, with sedimentary components added. Isotopic variability testifies that melting domains beneath islands and ridges cannot be represented by a single mantle lithology, but that source materials that formerly interacted with the atmosphere and hydrosphere are present.

Melting models based on homogeneous peridotite that vary only the extent of partial melting and mantle temperature are too simple. Iceland, for example, is compositionally anomalous in so many respects that an unusually fertile mantle source, perhaps including substantial eclogite that was originally ocean crust, may be required and be able to explain both the geochemistry and the crustal thickness there (*Foulger, Natland*). The interpretation of the Icelandic seismic crust in terms of melt thickness is still unclear (*Björnsson, Foulger*). The scarcity of evidence for excessive mantle potential temperatures (*Green, Gudfinnsson, Presnall, C. Stein*) encourages consideration of source variability (*Natland*). Models that involve fertile, fusible patches and lithospheric stress may provide viable alternatives to localized high temperature for many volcanic regions.

The ideal of truly rigid tectonic plates breaks down in reality. Plates move coherently but are not completely rigid, and cracks and volcanic chains can form (*Anderson, Natland, Smith, Winterer*). The Pacific plate may be affected by changes in subduction geometry which change plate-wide stress. Can such stresses produce propagating lithospheric fractures along which basaltic magma erupts? Mesozoic Pacific volcanoes are widely scattered and do not form linear chains. As continental collisions accompanied the close of Tethys in the Eocene (*Flower*), the western Pacific plate became largely bordered with subduction zones and much subsequent seamount and island volcanism on the plate has been linear, age progressive, and parallel. The Emperor-Hawaiian bend does not record a substantial change in direction of the Pacific plate, as may be seen from the continuity of spreading patterns and transform zones of the same age (*Hamilton*) but may represent a change in the orientation of stress imposed on the plate from its edges. Scattered Pacific magmatism could be related to shear heating generated by the so-called westward drift of the lithosphere (*Doglioni*).

Various aspects of volcanism in the Pacific appear to require new models. Linear chains, especially where not time-progressive, suggest tears in the plate or eruption along pre-existing structures (*Geist, Harpp, O'Connor*). The most credible non-thermal model for the Emperor-Hawaiian chain is a propagating crack related to stress in the plate. Much plateau formation was associated with triple junctions (*Smith*). Finite-element modeling of ridge-transform junctions reveals an intrinsic pattern of extensional stress that encourages volcanism (*Beutel*). In the south-west Pacific, the small magma volumes, lack of rifting and uplift, and broad areal distribution could be explained by episodic plate reorganization and recycling of metasomatized lithosphere from subducted slabs (*Finn*).

The Ontong Java plateau, Shatsky Rise, Kerguelen plateau, Deccan Traps and Bushveld complex are Large Igneous Provinces (LIPs) that represent volumes of magma so huge and eruption rates so rapid that they are difficult to explain by any process. The uniformity and major element geochemistry of Ontong Java plateau basalts was cited as supporting a plume origin and ruling out the involvement of eclogite (*Fitton*). The lack of evidence for precursory uplift, and the existence of magnetic stripes across the plateau remain unsolved problems in this model, as is the lack of evidence for fertility in models based on source heterogeneity. Sublithospheric ponding of magmas prior to eruption of LIPs may be required to explain the huge volumes, eruption rates and compositional homogeneity (*Anderson, Foulger*).

The Shatsky Rise is shown by magnetic stripes to have formed at a migrating triple junction (*Sager*). The Kerguelen plateau contains a continental crustal component and had a long duration of emplacement compared with some other LIPs (*Pringle*). A model presented for the Deccan Traps proposed a source in recycled eclogite trapped in ancient sutures. Evidence for high temperatures is lacking in the petrology and there was no precursory uplift (*Sheth*), features that are shared by the continental Columbia River Basalts, which formed in a back-arc environment (*Christiansen*). A multiple bolide impact origin for the Bushveld Complex is supported by evidence for ultra-high temperature debris flows and intense deformation there (*Elston*). The absence of LIPs at the ends of many linear volcanic chains e.g., the Emperor chain, and the lack of linear chains emanating from many LIPs, e.g., the Ontong Java plateau, brings into question the traditional "plume head – plume tail" model. The classic example of a plume head-tail, the Deccan Traps – Chagos – Laccadive Ridge – Reunion Island, was questioned, and the Chagos – Laccadive Ridge ascribed to melting and melt focusing along a southward propagating fracture in the Indian plate (*Sheth*).

An exciting diversity of ideas and concepts was presented at the conference, along with a healthy infusion of skepticism and challenges. In volcanic regions where evidence for a thermal origin is lacking, source fertility, volatiles, recycling of subducted slabs or continental lithosphere, intraplate deformation along faults, rifts and sutures, stress variations and bolide impacts are promising avenues to consider. These models require re-evaluation of other aspects of our planet, such as the interpretation of seismic anomalies, convection, the longevity of shallow heterogeneities, the importance of lithospheric stress and structure, the origin of geochemical tracers, the fate of subducted slabs and the melt-retention capabilities of the mantle. Critical data such as seismic measurements from the oceans, heat flow, radiometric dates and petrological laboratory data are required. Methodologies such as geothermometry, and thermodynamic modeling of mantle convection are still too primitive to answer the critical questions. Much work remains to be done.

This Penrose conference brought together for the first time scientists who still seek to understand the fundamental origins of volcanic regions. The full range of ambient ideas in this embryonic field was laid out, brainstormed, criticised and challenged. The problems, needs and tasks ahead were brought into focus. We are at the start of a long and exciting journey.

Participants were: *Don Anderson, Tiffany Barry, Erin Beutel, Axel Bjornsson, Enrico Bonatti, Francoise Chalot-Prat, Richard Chamberlin, Bob Christiansen, Corrado Cigolini, Marc Davies, Henry Dick, Carlo Doglioni, Adam Dziewonski, Wolfgang Elston, Zuzana Fekiacova, Carol Finn, Godfrey Fitton, Martin Flower, Gillian Foulger, Bjarni Gautason, Dennis Geist, David Green, Gudmundur Gudfinnsson, Giuseppe Guzzetta, Warren Hamilton, Karen Harpp, Anne Hofmeister, Dorthe Holm, Fredrik Holm, Gregory Huffman, Phillip Ihinger, Sveinn Jakobsson, Leonard Johnson, Bruce Julian, Donna Jurdy, Scott King, Vlad Manea, Marina Manea, Jose Mangas, Greg McHone, Jean-Paul Montagner, James Natland, John O'Connor, Angelo Peccerillo, Emma Perez-Chacon, Brian Pope, Malcolm Pringle, Dean Presnall, Will Sager, Hetu Sheth, Olgeir Sigmarsson, Alan Smith, Suzanne Smrekar, Carol Stein, Seth Stein, Ellen Stofan, Richard Walker, Phil Wannamaker, Dayanthie Weeraratne, Marjorie Wilson, Jerry Winterer and Don Wright.*

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