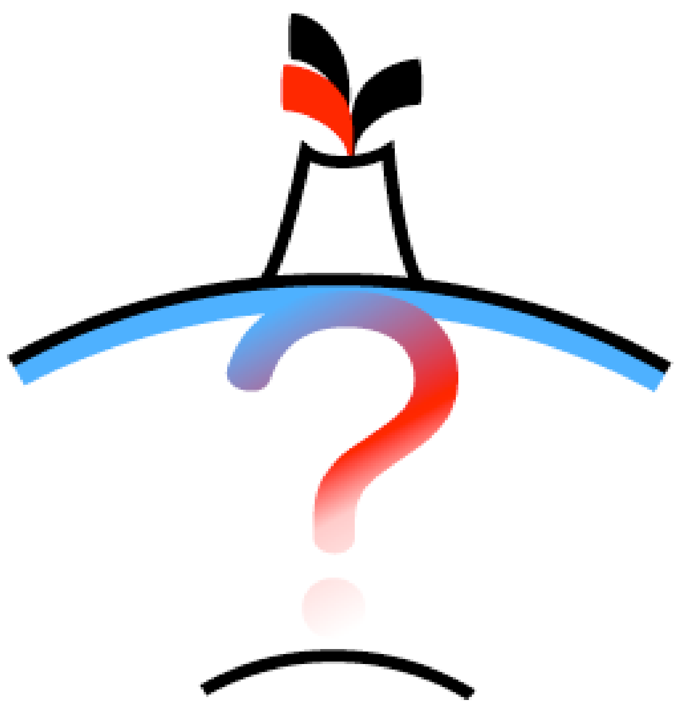
THE GEOLOGICAL SOCIETY
OF AMERICA

Penrose Conference

Plume IV:
Beyond the Plume Hypothesis

Testing the plume paradigm and alternatives

The Hotspot Handbook



August 25th – 29th, 2003
Hveragerdi, Iceland

http://www.mantleplumes.org/

Thanks is extended to the Geological Society of America for sponsoring this Penrose conference, and to the National Science Foundation (NSF), the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI), and the Geological Society of London for financial support.

THE PLUME PARADIGM

The plume and the plate hypotheses are two of the most elegant ideas of global Earth science. There is a remarkable simplicity and symmetry between them and both are involved in the Standard Model of global geodynamics. Plumes were devised to explain features, such as age-progressive volcanic chains and continental breakup, which did not seem to be a part of rigid plate tectonics. Plate tectonics is the result of cooling of the Earth's surface and plumes are the result of heat transfer from the core to the base of the mantle. Pots on stoves have thermal boundary layers (TBLs) at the top and the bottom. Bottom heating and top cooling play comparable roles. Accidental perturbations in the thickness of either TBL will organize the flow in the fluid in the pot. The two modes of mantle geodynamics are usually treated separately. Ideal plumes are independent of plate tectonics and mantle convection.

The mantle is not a pot on a stove, however. Sphericity, pressure and continents break the symmetry. Material properties depend on temperature and pressure. The mantle is heated from within and contains, and loses, fossil heat. Stress plays a dominant role in plate tectonics. The concepts of rigid or elastic plates are fine for certain problems in global geodesy, plate kinematics and local bending but cannot apply as a general rule. The concept of strength has limited validity for objects as large as plates. Plate tectonics, as often described, is a rigid plate and kinematic theory. More generally, plate theory involves recycling, insulation, slab cooling and a template for mantle convection. Plates and slabs introduce chemical and thermal heterogeneity and structure into the mantle. Plates and plate boundaries are ephemeral. Long linear or arcuate volcanic features are related to stress and relative motions between plates. In the plume paradigm these types of features are attributed to high temperatures and relative motion of the plates over the mantle, rather than to stress or to incipient plate boundaries.

Plume models assume, as the normal condition, an isothermal subsolidus and homogeneous upper mantle which is either static or vigorously convecting (the "convecting mantle"). Variations in bathymetry and melt volume are attributed to core heat. Plume hypotheses are primarily fluid dynamic and thermal theories. Focusing, small-scale convection, fertility, ponding and passive upwellings associated with lithospheric architecture and extension can also create melting anomalies. These are athermal mechanisms. Can they be distinguished? Pressure is an essential parameter in convection and plume simulations but is not involved in laboratory and most computer modeling. Fluid dynamic modeling has not duplicated plate or plume tectonics. Plates are shaped and driven by Mother Nature and plumes are put in as initial singularities, or injections. Neither forms naturally. What is missing?

A good scientific hypothesis gets stronger as it is probed, questioned and tested. In particular, the assumptions behind paradigms must be constantly challenged. Paradoxes must be identified, for therein lie new ideas. Assumptions must be made to get any hypothesis started, but sometimes continued progress can only be made by looking for and dropping unfruitful assumptions. Rigidity, fixity, parallelism, homogeneity, steady-state, uniformitarianism, symmetry and incompressibility are some of the assumptions underlying current models.

Penrose meetings have been important in the development of both the plume and plate paradigms and offer an ideal forum for identifying the strengths and weaknesses of conventional wisdom. Perhaps a unifying, or at least, a self-consistent, theory will emerge.

The conveners, *Plume IV: Beyond the Plume hypothesis*

	Monday		Tuesday		Wednesday		Thursday		Friday	
8:30 - 8:40	*Opening address*	*Foulger*	*Announcements*	*Foulger*	*Announcements*	*Foulger*	*Announcements*	*Foulger*	*Announcements*	*Foulger*
8:40 - 9:25 **9:25-10:10**	*I. What is a plume? What is a hotspot?*	*Anderson Foulger*	*V. Opening ocean*	*Foulger McHone*	*VIII. Petrology & temperature I*	*Presnall Green*	Fieldtrip: Hengill triple junction, Thingvellir, Geysir & Gullfoss	*Foulger Bjornsson*	*XIII. Hotspots, kinematics & dynamics*	*Doglioni Winterer*
10:10-10:30	coffee		coffee		coffee				coffee	
10:30-11:15 **11:15-12:00**	*II. Seismology & hot spots*	*Julian Montagner*	*VI. Continental*	*Chalot-Prat Christiansen*	*IX. Petrology & temperature II*	*Green Presnall*			*XIV. Cracks & tracks*	*Smith Finn*
12:00 - 1:00	lunch		lunch		lunch				lunch	
1:00-1:30	posters		Fieldtrip: Reykjanes Peninsula	*Jakobsson Foulger*	posters				posters	
1:30-2:15 **2:15-3:00**	*III. The big, deep picture*	*King Anderson*			*X. Geochem & Petrology I*	*Natland Dick*			*XV. Large igneous provinces*	*Sager Sheth*
3:00-3:30	tea				tea				tea	
3:30-4:15 **4:15-5:00**	*IV. Temperature, heat & magma*	*Stein Gudfinnsson*			*XI. Geochem & Petrology II*	*Dick Natland*			*XVI. Synthesis*	*Anderson Wilson*
6:00-7:00	informal discussion				informal discussion				informal discussion	
7:00-8:00	dinner		dinner		dinner		dinner		dinner	
8:00 - 9:00	*Lecture: Iceland*	*Bjornsson*	*VII. Extraterrestrial*	*Hamilton Jurdy*			*XII. Plate Tectonic End Games*	*Flower Elston*		

Session/Moderators/Key Questions

10-15 min keynote talks

Primary potential 2-3 min talkers

I. Overview: What is a plume? What is a hotspot?

Definitions, rules of the game, options, active vs. passive, lithosphere vs. asthenosphere, near-surface or deep, point sources of pollution vs. distributed, stress vs. temperature, cracks vs. tracks, global/regional vs. local, pressure effects, self-organization, central limit theorem, paradoxes, problems, predictions.

Moderators: Don L. Anderson, Gillian R. Foulger

- Rules of the game
- What is a plume?
- Initial & boundary conditions
- Assumptions
- What is plate tectonics (& implications)?
- Roles of T, P and composition.
- Sampling vs. reservoirs
- What drives what?

1. Don L. Anderson: Introduction

Introductions & overview; Where are we? What do we hope to learn? What are the issues, questions, paradoxes and bottom lines? By:

- *Enrico Bonatti*
- *Henry Dick*
- *Carlo Doglioni*
- *Adam Dziewonski*
- *Carol Finn*
- *Martin Flower*
- *David Green*
- *Warren Hamilton*
- *Anne Hofmeister*
- *Pino Guzzetta*
- *Scott King*
- *Greg McHone*
- *Jim Natland*
- *Dean Presnall*
- *Carol Stein*
- *Richard Walker*
- *Marge Wilson*
- *Jerry Winterer*

II. What does seismology say about hot spots?

Seismology is the highest-resolution technique for studying the deep structure of the Earth. This session reviews the current state of seismic imaging of the mantle and the question of what constraints seismology can place on the physical and chemical structures and processes beneath hot spots

Moderators: Bruce Julian, Jean-Paul Montagner

- What can seismology resolve? How small? How deep?
- What do seismic-wave speeds mean? Is red really hot and blue cold?
- What can we expect in the future? Bananas? Doughnuts? Flow fields?

1. **Adam Dziewonski**: Global seismic tomography: What we really can say and what we make up
2. **Jean-Paul Montagner**: Plume-lithosphere interactions: Cases of Afar (Africa), and Pacific hotspots

- *Don Anderson*
- *Axel Bjornsson*
- *Gillian Foulger*
- *Anne Hofmeister*
- *Phillip Ihinger:* Whole Earth convection models
- *Scott King*
- *Seth Stein*

III. The big, deep picture

Much of our physical intuition regarding convection has come from Rayleigh-Benard type convection (constant physical properties, simplistic equation of state) or tank experiments (e.g., Griffiths and Campbell). In these experiments, there are no cratons, no plates, no mid-ocean ridges, no phase changes, no layering, no depth-dependent properties and no plate-scale flow. Have these simplifications led us down the wrong path? How does the near-surface (cratons, plates, ridges, edges, melting) impact the deep mantle? What do we learn from tomography? Why are there global plate reorganizations, and how do they work?

Moderators: Scott King, Don L. Anderson

- Does pressure reverse our intuition about convection?
- Is the mantle active or does it do what the plates tell it to?
- Is tomography a temperature or a petrology (composition, anisotropy, phase changes, flow) tool?
- What do we learn from global plate reorganizations?

1. **Scott King**: Plume Convection: What happens when you add all that icky stuff?
2. **Don Anderson**
3. **Anne Hofmeister**

- *Carlo Doglioni*
- *Adam Dziewonski*
- *Pino Guzzetta*
- *Phillip Ihinger:* Whole Earth convection models
- *Jean-Paul Montagner*
- *Alan Smith*
- *Phil Wannamaker*

IV. Temperature, heat & magma

Geophysical constraints on models of hotspot/swell formation including heat flow, topography, and the assumptions about the volcanic age along island/seamount chains.

Moderators: Carol Stein, Gudmundur Gudfinnsson

- What does heat flow tell us about hot spots/plumes?
- What do depths tell us about hot spots/plumes?
- What does volcanic age progression along island/seamount chains tell us about the interaction of the upwelling hot mantle material and the lithosphere?

1. **Carol Stein**: Spots yes, hot barely or not
2. **John M. O'Connor**: What can long-lived seamount chains reveal about the origin of hotspots?
3. **Enrico Bonatti**: Mantle thermal structure below ridges: space and temporal variations

- *Don Anderson*
- *Françoise Chalot-Prat*
- *Giuseppe Guzzetta*
- *Warren Hamilton*
- *Anne M. Hofmeister*
- *Phillip Ihinger*
- *Vlad Manea*
- *John O'Connor*
- *Hannah L. Redmond*
- *Suzanne Smrekar*
- *Seth Stein*
- *Ellen Stofan*
- *Peter Vogt*
- *Phil Wannamaker*
- *Dayanthie Weeraratne*

V. Opening of an ocean

The opening of the Atlantic ocean was accompanied by intense volcanism along much of the new seaboard. This persisted at several locations giving rise to a chain of volcanic anomalies along the mid-Atlantic ridge. These are traditionally attributed to localised high temperatures, but what evidence is there for this, and can an athermal model stand?

Moderators: Gillian R. Foulger, Greg McHone

- Can volcanism in the Atlantic ocean be explained by variations in mantle fertility and deformation?
- What are the implications of this view?
- What are the main problems with this theory?
- How can they be addressed?

1. **Gillian R. Foulger**: A shallow model for north Atlantic volcanism
2. **Greg McHone**: Volcanic features of the central Atlantic ocean: tectonic and magmatic models
3. **Marge Wilson**: Understanding the 135 Myr record of magmatism in the South Atlantic: Plumes, plate tectonics and propagating fractures

- *Enrico Bonatti*
- *Axel Bjornsson*
- *Don DePaolo*
- *Henry Dick*
- *Godfrey Fitton*
- *Martin Flower*
- *Bjarni Gautason*
- *Warren Hamilton*
- *Sveinn P. Jakobsson*
- *Jose Mangas*
- *Hetu Sheth*
- *Olgeir Sigmarsson*
- *Alan Smith*
- *Reidar Trønnes*
- *Peter Vogt*

VI. Continental volcanism & lithospheric tectonics

The compositions and tectonic associations of continental intraplate magmatism are highly varied, and these factors are not always clearly linked. Both continental flood basalts and anorogenic magmatic suites with major silicic components can reflect significant crustal interactions but are nevertheless generated and sustained by melting in the upper mantle. The alkaline mafic magmas common in intraplate settings are often considered to be "hotspot-related", but they may erupt synchronously with calc-alkaline magmas – either syn-subduction or post-collisional. Rift-related continental mafic magmas may be either calc-alkaline or alkaline, depending at least in part on whether rifting occurred a few thousands to millions of years or hundreds of millions of years after continental-plate collision.

Are these and similar problems better explained by the mantle-plume models commonly invoked for them? Alternatively, do many of these magmas reflect varied source compositions, whereas causes of partial melting and magma emplacement depend on the direct interaction of lithospheric tectonics with deeper upper-mantle processes?

Moderators: Francoise Chalot-Prat, Bob Christiansen

- Are continental mafic magmas generated in residual or metasomatized mantle?
- Does mantle fertility reflect the recycling of oceanic or continental crust, or even of previously metasomatized mantle? When do such changes occur relative to magma genesis (importance of the lithospheric plate story before eruptions)?
- What are the causes of subcontinental mantle melting? Are there distinct roles for deep-mantle plumes, convective systems restricted to the upper-mantle, and lithospheric tectonics to both promote melting of fertile mantle and provide magma conduits to the surface?

1. **Angelo Pecerillo**: Ultrapotassic magmatism: Shallow mantle or plume-related process? The case of central Italy
2. **Hetu Sheth**: The Deccan beyond the plume hypothesis
3. **Bob Christiansen**: Structural control and plate-tectonic origin of the Yellowstone melting anomaly

- *Richard Chamberlin*
- *Corrado Cigolini*
- *Wolf Elston*
- *Don DePaolo*
- *Zuzana Fekiacova*
- *Carol Finn:* Cenozoic alkaline magmatism in west Antarctica, east Australia and New Zealand.
- *Martin Flower*
- *Warren Hamilton*
- *Greg Huffman*
- *Vlad Manea:* Mantle wedge flow and thermal models for the central Mexican subduction zone
- *Greg McHone*
- *Alan Smith*
- *Phil Wannamaker*
- *Marge Wilson*
- *Don Wright*

VII. Extraterrestrial

Evidence for plumes on other planets will be considered: Venus and Mars. Venus hosts numerous "coronae", circular features, as well as uplifted regions that may or may not result from plumes on that planet. The huge Tharsis uplift - the largest known - on Mars may have been caused by a single plume active through much of the planet's history. Some features attributed to plumes on Earth could be the result of impacts.

Moderators: Warren Hamilton, Donna Jurdy

- What is the evidence for plumes on Venus and how does it differ from that on Earth?
- What is the evidence for plumes, or possibly a single plume, on Mars?
- Did impacts on Earth cause plumes?

5-min talks:

1. **Hannah Redmond**: Tharsis Rise, Mars, result of a long-lived plume
2. **Suzanne Smrekar**: Upwelling at different scales on Venus
3. **Donna Jurdy**: Coronae as evidence of active upwelling on Venus
4. **Warren Hamilton**: An alternative Venus: Plume-free planet
5. **Wolfgang Elston**: Impacts as a cause for plumes, Bushveld, as an example

- *Ellen Stofan*
- *Don Wright*

VIII & IX What does petrology tell us about potential temperatures?

Hot plumes imply elevated potential temperatures. For about the last 15 years, it has been commonly thought that petrologists were finally beginning to develop an ability to determine this difficult parameter. However, in the last two years, major differences of opinion have developed that have reopened this issue at a very fundamental level. This session will examine the current status of this subject and discuss future directions.

Moderators: Dean Presnall, David Green

- High vs. low vs. strongly variable potential temperatures
- Picrites vs. picrites
- MORB vs. "hot spot" basalt chemistry
- Can major-elements of basalts constrain potential temperatures?
- Mantle heterogeneity vs. variable potential temperature
- Mantle heterogeneity vs. basalt chemistry
- Volatiles and melting curves
- What are the "primary" magmas at "hot spots" vs ridges?
- Where is the bottom of the seismic low-velocity zone?
- Long, short, or variable melting columns?

1. **Dean C. Presnall**: Phase equilibrium/seismic constraints on potential temperatures
2. **David H. Green**: Potential temperatures and primary magmas in MOR setting and comparison with Hawaii
3. **Gudmundur Gudfinnsson**: Contrasting origins of the most magnesian glasses from Iceland and Hawaii

- *Don Anderson*
- *Enrico Bonatti*
- *Corrado Cigolini*
- *Marc Davies*
- *Henry Dick*
- *Adam Dziewonski*
- *Godfrey Fitton*
- *Dennis Geist*
- *Karen Harpp*
- *Kevin Johnson*
- *Jose Mangas*
- *Jim Natland*
- *D. Gopala Rao*
- *Hetu Sheth*
- *Reidar Trønnes*

X & XI Geochemistry & Petrology

The plate-tectonic cycle imparts heterogeneity to the mantle. Plume theory depends strongly on how melt processes sample a heterogeneous mantle. Geochemistry now suggests that most ocean island basalt (OIB) heterogeneity results from sampling of material once in the Earth's crust but that is now in the mantle, having entered there via subduction. The main question posed by OIB geochemistry is how far into the mantle these materials were carried before becoming involved again in volcanism at ridges, LIPs, islands and seamounts? Did they reach the core-mantle boundary, and arise again in plumes, or did they become trapped in the upper mantle for long periods of time before being tapped? How can petrology and geochemistry tell?

Moderators: Jim Natland, Henry Dick

- What are OIBs?
- Is any magma primary?
- Is the mantle a plum pudding? Distribution of enriched components – the statistical upper mantle assemblage
- What are the possible effects of bulk heterogeneity of the mantle on the compositions of basalt?
- Can melt-extraction processes by themselves produce heterogeneity?
- Are any mantle reservoirs truly well mixed? Fertile versus barren peridotite
- What are the roles of "recycled" ocean crust, eclogite and pyroxenite in mantle sources of basalt?
- Can we move beyond alphabet soup? The relationship of trace-elements and isotopes to possible bulk heterogeneity of the mantle
- What are indicators of a very deep mantle source?
- What is the significance of spatial and temporal geochemical variability on islands and island chains?
- Do komatiites indicate plume heads, or something else?
- What is helium trying to tell us?

1. **Jim Natland**: Opening gambit: A perspective on mantle heterogeneity
2. **Henry Dick**: Abyssal peridotites and tholeiites
3. **Don DePaolo**: Geochemical structure of the Hawaiian plume: Results from the Hawaii Scientific Drilling Project

- *Don Anderson*
- *Enrico Bonatti*
- *Françoise Chalot-Prat:* The link between magma genesis and lithospheric tectonics during ocean spreading
- *Corrado Cigolini*
- *Mark Davies*
- *Don DePaolo*
- *Godfrey Fitton*
- *Gillian Foulger*
- *Dennis Geist*
- *David Green*
- *Martin Flower*
- *Warren Hamilton*
- *Phillip Ihinger*
- *Sveinn P. Jakobsson*
- *Dean Presnall*
- *Hetu Sheth*
- *Olgeir Sigmarsson*
- *Alan Smith*
- *Richard Walker*
- *Marjorie Wilson*

XII. Plate Tectonic End Games

While most scientists assume plate mobility is driven by mantle flow, "slab pull", and "lithosphere push" forces, a paradigm shift may be needed given the failure of "jelly sandwich" lithosphere models and increasing indications of plate-induced mantle flow. Plate tectonic "end games" may bear critically on several phenomena - Large Igneous Provinces, back-arc basins, forearcs and ophiolites, and oceanic hotspot trails. Collision-related seafloor spreading changes, accompanied or preceded by new subduction events, are often followed by arc-trench rollback. When subduction initiation precedes a collision, rollback is probably mantle-driven rather than triggered by plate kinematics. Global-scale responses, e.g. to the Africa-Eurasian collision, may also involve far-field mantle flow perturbations. These observations highlight the paradoxes of hot plume models. Links to propagating cracks, mantle thermal and compositional heterogeneities, and shallow perturbations suggest mantle flow is both the cause and effect of plate motions. Upper-mantle anisotropy and variations in asthenospheric Tp support numerical models that can explain continental volcanism, escape tectonics, marginal basin opening, and the genesis of ophiolites as responses to small-scale, plate-induced convection. Thus while global synchronism is an important aspect of plate tectonics, resisting or dissipative stresses, which control the spatial-temporal distribution of volcanic arcs, marginal basins, and mountain belts are subject to rapid changes.

Moderators: Martin Flower, Wolf Elston

- The formation and propagation of back-arc basins - "slab pull", mantle flow, or escape tectonics?
- Large Igneous Provinces - are these linked to cratons and mobile belts?
- Ophiolite genesis at new, hot, plate boundaries - do these reflect lithosphere heterogeneities or collision-related mantle flow fronts?
- Fertile mantle at collision sutures - does this portend large-fraction melting when the Wilson cycle resumes?

1. **Martin Flower**: Mantle melting, stress dissipation, and the Wilson cycle
2. **Wolfgang Elston**: The unique 2.06 Ga Bushveld Complex, South Africa: Result of an impact-induced plume?

- *Don Anderson*
- *Tiffany Barry*
- *Franciose Chalot-Prat*
- *Richard Chamberlain*
- *Bob Christiansen*
- *Corrado Cigolini*
- *Marc Davies*
- *Henry Dick*
- *Carlo Doglioni*
- *Zuzana Fekiacova*
- *Gillian Foulger*
- *Fred Frey*
- *Warren Hamilton*
- *Vlad Manea*
- *Jose Mangas*
- *Greg McHone*
- *Jean-Paul Montagner*
- *Jim Natland*
- *Angelo Peccerillo*
- *Hetu Sheth*
- *Alan Smith*
- *Marge Wilson*

XIII. Hotspots vs. Plate Kinematics and Dynamics

Age progressions, reference frames, westward drift of the lithosphere, mantle and plate kinematics, lithospheric fabric and stress

Moderators: Carlo Doglioni, Jerry Winterer

- What does the age progression of Pacific hotspots tell us about motions & shears in the mantle?
- Do plates & slabs drive themselves or is an independent mantle
- convective source, or something else required?
- What kinematic constraints are there on depths of hotspot and MORB sources?
- Is the westward drift of the lithosphere global or is it only a mean value? What is its origin?
- Is stress, water content, or mantle temperature the dominant parameter in localizing hotspot volcanism?
- What can we really argue about mantle kinematics?
- What are rates of ridge and trench migration, and the minimum
- relative rates of plates? Do these differ from hotspot motions?
- Can/do plate motions and local change rapidly and often?

1. **Phillip D. Ihinger**: Plume magmatism and mantle convection: revising the standard
2. **Carlo Doglioni**: On the westward drift of the lithosphere
3. **James H. Natland**: On changing stress during Pacific plate kinematic evolution

- *Peter R. Vogt:* Sea-floor basement morphology: Distinguishing hotspot effects from plate tectonic effects - Examples from Iceland and the Azores
- *Dayanthie Weeraratne:* An alternative model for the origin of non-hotspot intraplate volcanism in the Pacific
- *Brian Pope:* Is hot spot magmatism, like Hawaii, coming from shallow mantle?
- *Gillian Foulger:* On the apparent eastward migration of the spreading ridge in Iceland
- *Martin Flower:* Collision-induced mantle flow during Tethyan closure: a link between magmatism, lithosphere 'escape', and arc-trench rollback?
- *Phillip Ihinger:* Spatial and temporal geochemical variations along alleged hot-spot tracks
- *Hetu C. Sheth:* The Deccan beyond the plume hypothesis
- *Alan Smith:* The fate of subducted oceanic crust and the sources of intraplate volcanism

XIV. Cracks & tracks

The role of lithospheric architecture (thickness and fabric - cracks, boundaries, sutures) in intra-plate magmatism Pacific, dikes, leaky & incipient plate boundaries, island chains.

Moderators: Alan Smith, Carol Finn

- What are the roles of lithospheric architecture and stress on magmatism?
- What are the links between lithospheric (architecture and stress) and upper and lower mantle processes (that is, dynamic processes, such as upper mantle hot/warm spots, small scale convection, detachment of subducting slabs in the upper and lower mantle, cooling by subduction, chemical modification by subduction, melting at ridges, and plumes, and thermal boundary layers in the lower mantle, etc.) that result in magmatism?
- What are the relations between lithospheric architecture/stress and mantle temperature and chemistry (in particular origin and location of volatiles (CO_2, H_2O + recycled crust, eclogite) that lower melting temp.) and ponding/underplating that allows or increases volumes or rates of magmatism?
- What are the orientation, magnitude and sign of stress required to open pre-existing zones of weakness or break virgin rocks that permit magmatism?
- What are the links between lithospheric fabric and stress and age-progressive volcanism?
- Are there temporal links between the onset, termination, and longevity of regional mid-plate volcanism and plate tectonic events such as regional and global plate reorganizations and conjectured slab detachments?

1. **Alan Smith**: The Regular Distribution of Intraplate Volcanism in the Pacific Basin
2. **Erin Beutel**: Lithospheric stress state responsible for hotspots at ridge-transform intersections?
3. **Carol Finn**: Definition of a Cenozoic alkaline magmatic province in the southwest Pacific mantle domain (W. Antarctica, E. Australia and New Zealand) without rift or plume origin.

- *Enrico Bonatti*
- *Francioise Chalot-Prat*
- *Karen S. Harpp*
- *Phillip Ihinger*
- *Jose Mangas*
- *James Natland*
- *John O'Connor*
- *Dayanthie Weeraratne*
- *Jerry Winterer*

XV. Geodynamic origin of large-volume basaltic provinces & flood basalts

Over the last 10-15 years the plume head hypothesis has become the theory of choice to explain the formation of large LIPs, such as ocean plateaus and continental flood basalts. Data have now been gathered from a number of LIPs and compared with this hypothesis. In this session, we will discuss how well the plume head hypothesis has held up to this scrutiny. We will examine alternate hypotheses that may do a better job of explaining large LIPs. Finally, we will compile the matrix of hypotheses and critical observations needed to test these hypotheses as a guide to future LIP research.

Moderators: Will Sager, Hetu Sheth

- Is the evidence from LIPs consistent with the plume head model?
- How well do non-plume mechanisms work for LIPs?

1. **Fred Frey**: The Kerguelen plume: what we have learned from ~120 Myr of volcanism
2. **Godfrey Fitton**: A plume origin for the OJP?
3. **Will Sager**: Tectonic evolution of the Shatsky Rise: a plateau formed by a plume head or not?

- *Richard Chamberlin*
- *Wolf Elston:* The Bushveld enigma: A catastrophe-triggered complex LIP on a tectonically stable platform.
- *Fred Frey*
- *David Green*
- *Warren Hamilton*
- *Greg McHone*
- *Dean Presnall*
- *Alan Smith*
- *Marge Wilson*

XVI. Synthesis

Moderators: Don L. Anderson, Marge Wilson

- *Everybody*

Organising Committee

Dr. Gillian R. Foulger
University of Durham,
Dept. Geological Sciences,
Science Laboratories,
South Rd., Durham DH1 3LE, U.K.
g.r.foulger@durham.ac.uk

Prof. James H. Natland
Rosenstiel School of Marine & Atmospheric Science,
University of Miami,
4600 Rickenbacker Causeway,
Miami, FL 33149, USA
tel: (305) 361-1819
fax: (305)361-4632
jnatland@msn.com

Prof. Don L. Anderson
Seismological Laboratory,
California Institute of Technology, MC 252-21,
Pasadena, CA 91125, USA
tel: 1 (626) 395 6901
fax: 1 (626) 564 0715
dla@gps.caltech.edu

Meeting support

Ms. Edna Collis
The Geological Society of America,
P.O. Box 9140,
Boulder, CO 80301, USA.
tel: (303) 357 1034
fax: (303) 357-1072

Ms. Dianna L. Gury
Meetings & Exhibits Manager
Quality Business Services
3110 S. Wadsworth Blvd., Suite 307
Denver, CO 80227, USA
tel: 303 914-9647
fax: 303 914-9651
dianna@qbsoffice.com

List of Participants

Prof. Don L. Anderson
Seismological Laboratory
California Institute of Technology, MC 252-21
Pasadena, CA 91125, USA
tel: 1 (626) 395 6901
fax: 1 (626) 564 0715
dla@gps.caltech.edu

Prof. Dereje Ayalew
Addis Ababa University
P.O. Box 1176, Addis Ababa, Ethiopia
tel: (251 1) 553214 or 121474
dereayal@geol.aau.edu.et

Prof. Ken Bailey
Department of Earth Sciences
University of Bristol
Wills Memorial Building
Queen's Road
Bristol, BS8 1RJ, UK
tel: 0117 9545400
fax: 0117 9253385
Ken.Bailey@bristol.ac.uk

Dr. Tiffany Barry
Cardiff University (NIGL/BAS)
BGS, Keyworth,
Nottingham NG12 5GG, U.K.
tel: 44 (0) 115 9363191
tbarry@bgs.ac.uk

Prof. Erin Beutel
College of Charleston
66 George St.
Charleston, SC 29424, USA
tel: (843) 953 5591
fax: (843) 953-5446
beutele@cofc.edu

Prof. Axel Bjornsson
Háskólinn á Akureyri
Sólborg, 600 Akureyri, Iceland
tel: 463.0934
tel: 463.0999
tel: 463.1530 / 561.2430 (home)
ab@unak.is

Prof. Enrico Bonatti
Italian National Research Council (CNR),
Istituto di Geologia Marina
Via P. Gobetti 101, 40129
Bologna, Italy
tel: 39-051-6398935
fax: 39-051-6398939
enrico.bonatti@ismar.cnr.it

Prof. Francoise Chalot-Prat
CNRS/CRPG
Nancy University, BP20,
15 rue Notre Dame des Pauvres
F-54501 Vandoeuvre les Nancy, France
tel: 33 (0)3 83 59 42 48
fax: 33 (0)3 83 51 17 98
chalot@crpg.cnrs-nancy.fr

Dr. Richard Chamberlin
New Mexico Bureau of Geology & Mineral Resources
801 Leroy Place, Socorro, NM 87801-4769
tel: 505/835-5310
fax: 505/835-6333
richard@gis.nmt.edu

Dr. Bob Christiansen
U.S. Geological Survey
345 Middlefield Rd., MS 910
Menlo Park, CA 94025, USA
tel: 650 329 5201
fax: 650 329 5203
rchris@usgs.gov

Prof. Corrado Cigolini
Department of Mineralogy & Petrology (DSMP),
University of Torino,
Torino, Italy
corrado.cigolini@unito.it

Dr. Marc Davies
Dept Earth Sciences,
The Open University,
Walton Hall,
Milton Keynes, MK7 6AA, UK
tel: 01908 655 947
marc.davies@open.ac.uk

Prof. Donald DePaolo
Earth and Planetary Science Department
MC4767, University of California
Berkeley, CA 94720-4767, USA
tel: 510/643-5064
fax: 510/ 642-9520
depaolo@eps.berkeley.edu

Prof. Henry Dick
McLean Lab, MS#8
Woods Hole Oceanographic Inst
Woods Hole,
MA 02543-1539, USA
tel: (508) 289-2590
hdick@whoi.edu

Prof. Carlo Doglioni
Dipartimento di Scienze della Terra,
Università La Sapienza
P.le A. Moro 5,
Box 11, 00185 Roma, Italy
tel: (39)-06-4991-4549
carlo.doglioni@uniroma1.it

Prof. Adam Dziewonski
Dept. of Earth and Planetary Sciences
20 Oxford Street
Cambridge, MA 02138
tel: (617) 495-9517
fax: (617) 495-8839
dziewons@seismology.harvard.edu

Prof. Wolfgang Elston
Dept Earth and Planetary Sciences
University of New Mexico
Albuquerque, NM 87131-1116
home: (505) 255-9170
work: (505) 277-5339
fax: (505) 277-8843
weelston@earthlink.net

Dr. Zuzana Fekiacova
Institut für Geowissenschaften,
Universität Mainz
Abt. Geologie, Becherweg 21,
55099 Mainz, Germany
tel: (0049) 6131 39 23 798
fekiacov@mail.uni-mainz.de

Prof. Carol Finn
U.S. Geological Survey
P.O. Box 25046, MS 964, Bldg. 20
Denver Federal Center
Denver, CO 80225, USA
tel: 303-236-1345
fax: 303-236-1425
cfinn@usgs.gov

Prof. Godfrey Fitton
School of Geosciences
The University of Edinburgh
Grant Institute, West Mains Road
Edinburgh EH9 3JW, U.K.
tel: 0131 650 8529
fax: 0131 668 3184
Godfrey.Fitton@glg.ed.ac.uk

Prof. Martin Flower
Department of Earth & Environmental Sciences
University of Illinois at Chicago
Chicago, Illinois 60607-7059, U.S.A.,
tel: (+1) 312 996-9662
fax: (+1) 312 413-2279
flower@uic.edu

Dr. Gillian R. Foulger
University of Durham,
Dept. Geological Sciences,
Science Laboratories,
South Rd., Durham DH1 3LE, U.K.
g.r.foulger@durham.ac.uk

Prof. Fred Frey
Dept Earth, Atmospheric & Planetary Sciences
54-1226 EAPS , Mass Inst Tech
Cambridge Ma 02139 , USA
tel: 617 253 2818
fafrey@mit.edu

Dr. Bjarni Gautason
Orkustofnun & University of Akureyri
Rangarvellir,
P.O.Box 30, 602 Akureyri, Iceland
tel: 354-460-1382
fax: 354-460-1381
bg@os.is

Prof. Dennis Geist
Dept Geological Sciences
University of Idaho
Moscow ID 83844, USA
tel: 208-885-6491
fax: 208-885-5724
dgeist@uidaho.edu

Dr. Steven Golden
Institut für Meteorologie und Geophysik,
Johann Wolfgang Goethe-Universität
Feldbergstr. 47,
60323 Frankfurt am Main, Germany
tel: +49-(0)69-798-24909
golden@geophysik.uni-frankfurt.de

Prof. David Green
Research School of Earth Sciences
Australian National University
0200, Canberra, Australia
tel: 61 2-61252488
david.h.green@anu.edu.au

Dr. Gudmundur Gudfinnsson
Geophysical Laboratory
Carnegie Institution of Washington
5251 Broad Branch Road, N.W.
Washington, DC 20015-1305
tel: (202) 478 8931
fax: (202) 478 8901
g.gudfinnsson@gl.ciw.edu

Prof. Giuseppe Guzzetta
Università di Napoli Federico II
Dip. Di Scienze della Terra,
Centro Direzionale,
Is. A/5 - 80143 Napoli, Italy
tel: +39 081 787 5289
guzzetta@unina.it
rebay@crystal.unipv.it

Prof. Warren Hamilton
Dept. of Geophysics,
Colorado School of Mines,
Golden CO 80401, USA
tel: 303 384 2047
fax: 303 273 3478
whamilto@mines.edu

Prof. Karen Harpp
Dept. of Geology
Colgate University
13 Oak Drive
Hamilton, NY 13346, USA
tel: (315)228-7211
fax: (315)228-7187
kharpp@mail.colgate.edu

Prof. Anne Hofmeister
Dept. Earth & Planetary Sciences,
Washington University
Campus Box 1169
1 Brookings Drive
Saint Louis MO 63130-4899
tel: 314-935-7440
fax: 314-935-7361
hofmeist@levee.wustl.edu

Dr. Dorthe H. Holm
Nordic Volcanological Institute
Grensásvegur 50, 108 Reykjavík, Iceland
tel: +354 525 5484
fax: (+354) 562 9767
dorthe@hi.is

Prof. Lirim Hoxha
Albanian Geological Survey
Rr.e Kavajes N-153, Tirana, Albania
tel: 355 42 35 436
fax: 355 42 29 441
lirimhoxha@yahoo.com

Dr. Gregory Huffman
Department of Earth Sciences,
Laurentian University,
935 Ramsey Lake Road,
Sudbury, Ontario, Canada, P3E 2X2
tel: (705) 671-3418
gw_huffman@nickel.laurentian.ca

Prof. Phillip Ihinger
Univ. Wisconsin Eau Claire
Dept. Geology, 105 Garfield Ave.
Eau Claire, WI 54702-4004, USA
tel: (715) 836-2158
ihinger@uwec.edu

Dr. S. P. Jakobsson
Icelandic Institute of Natural History
Hlemmur 3, IS-105 Reykjavik, Iceland
tel:+354-590-0500
fax:+354-590-0595
sjak@ni.is

Dr. Leonard Johnson
Continental Dynamics Program
Division of Earth Sciences
National Science Foundation
4201 Wilson Blvd., Room 785
Arlington, VA 22230, USA
tel: 703-292-8559
fax: 703-292-9025
lejohnson@nsf.gov

Dr. Bruce Julian
U.S. Geological Survey
345 Middlefield Rd., MS 977
Menlo Park, CA 94025, USA
tel: 650 329 4797
fax: 650 329 5163
julian@usgs.gov

Prof. Donna Jurdy
Northwestern University
Department of Geological Sciences
1850 Campus Drive
Evanston, Illinois 60208-2150, USA
tel: (847) 491-7163
fax: (847) 491-8060
donna@earth.northwestern.edu

Prof. Scott King
Department of Earth and Atmospheric Sciences
Purdue University, 550 Stadium Mall Drive
West Lafayette, IN 47907-2051, USA
tel: 765-494-3696
fax: 765-496-1210
sking@purdue.edu

Dr. Vlad Manea
Instituto de Geofísica UNAM
Circuito de la Inv. Científica s/n
Ciudad Universitaria
04510 México D.F.
tel: (52-55)-5622-4126
fax: (52-55)-5616-2547
vlady@ollin.igeofcu.unam.mx

Dr. Marina Manea
Instituto de Geofisica,
Ciudad Universitaria,
Circuito de la Investigacion Cientifica,
S/N, Mexico D.F., 04510, Mexico
tel: (52-55)-5622-4126
fax: (52-55)-5616-2547
mary@ollin.igeofcu.unam.mx

Prof. Jose Mangas
Departamento de Física.
Facultad de Ciencias del mar.
Universidad de las Palmas de Gran Canaria
Edificio de Ciencias Básicas.
Campus de Tafira. 35017
Las Palmas de Gran Canaria. Spain
tel: (34)928451296
jmangas@dfis.ulpgc.es

Prof. Greg McHone
Department of Geology and Geophysics
University of Connecticut
Storrs, CT 06268, USA
gregmchone@snet.net

Prof. Jean-Paul Montagner
Dept. Sismologie
4 Place Jussieu, case 89
75252- Paris cedex 05, France
tel: 33 1 4427 4896
fax: 33 1 4427 3894
jpm@ipgp.jussieu.fr

Dr. Raffaella Montelli
Dept. Geosciences
Guyot Hall, Princeton University
Princeton NJ 08540, USA
tel: 609 258 5031
fax: 609 258 1671
montelli@Princeton.EDU

Prof. James H. Natland
Rosenstiel School of Marine & Atmospheric Science,
University of Miami,
4600 Rickenbacker Causeway,
Miami, FL 33149, USA
tel: (305) 361-1819
fax: (305)361-4632
jnatland@msn.com

Prof. Yaoling Niu
Department of Geociences
University of Houston
Houston, TX 77204, USA
tel: 1-713-743-9312
fax: 1-713-748-7906
yniu@mail.uh.edu

Prof. Amos Nur
397 Panama Mall, 317 Mitchell
Stanford University
Stanford, CA 94305-2215, USA
tel: 650 723 9526
fax: 650 723 1188
amos.nur@stanford.edu

Prof. John O'Connor
Institute for Geosciences
Christian-Albrechts University
D-24118 Kiel, Germany
tel: +49 431 37865
joconnor@gpi.uni-kiel.de

Prof. Mike O'Hara
Dept of Earth, Ocean & Planetary Sciences,
Cardiff University, PO Box 914,
Cardiff, CF10 3YE, UK
home tel: 01970 832460
work tel: 029 2087 4488
sglmjo@cf.ac.uk

Prof. Angelo Peccerillo
University of Perugia,
Dipartimento di Scienze della Terra,
Piazza Università 1,
06100 Perugia, Italy
tel: (+39) 0755852608
pecceang@unipg.it

Prof. Emma Perez-Chacon
Universidad de Las Palmas de Gran Canaria,
Departamento de Geografía. Campus Universitario del Obelisco.
C/Pérez del Toro, nº1,
35003 Las Palmas de G.C., Spain
tel: 928-442774
eperez@dgeo.ulpgc.es

Dr. Brian Pope
Saint Louis University
3507 Laclede Ave
St. Louis, MO 63103, USA
tel: (314)307-0650
popebj@slu.edu

Prof. Dean Presnall
Department of Geosciences
University of Texas at Dallas
P.O. Box 830688
Richardson, TX 75083-0688, USA
tel: 972-883-2444
fax: 972-883-2537
presnall@utdallas.edu

Dr. Hannah L. Redmond
Purdue University
550 Stadium Mall Drive
West Lafayette, IN 47907, USA
tel: (765)494-0268
redmondh@purdue.edu

Prof. Will Sager
Texas A&M University
Dept. of Oceanography
College Station, TX 77843-3146, USA
tel: (979)-845-9828
fax (979)-845-6331
wsager@ocean.tamu.edu

Prof. Kamal Sharma
Dept. of Geology,
Government Postgraduate College,
Sirohi (Rajasthan) 307 001, India
tel: +91-02972-221684
sharmasirohi@yahoo.com

Prof. Hetu Sheth
Department of Earth Sciences,
Indian Institute of Technology (IIT) Bombay,
Powai, Bombay 400 076, India
tel: 91-22-25767264 (office)
tel: 91-22-25767251/7251 (switchboard)
fax: 91-22-25767253
fax: 91-22-25723480 (IITB main)
hcsheth@iitb.ac.in

Dr. Olgeir Sigmarsson
Laboratoire Magmas et Volcans
CNRS - Universite Blaise Pascal
5, rue Kessler
63038 Clermont-Ferrand, France
tel: +33 473 346 720
fax: +33 473 346 744
o.sigmarsson@opgc.univ-bpclermont.fr

Prof. John Sinton
University of Hawaii
Department of Geology and Geophysics
1680 East-West Road, Honolulu,
Hawai‘i 96822, USA
tel: 808 956-7751
sinton@hawaii.edu

Dr. Yvonne Smit
Laboratoire Magmas et Volcans
Département des Sciences de la Terre
Université Blaise Pascal
5 Rue Kessler
63038 Clermont-Ferrand, France
tel: 0033-673540251
y.smit@opgc.univ-bpclermont.fr

Dr. Alan Smith
CIE-UNAM,
Temixco.
Morelos, Mexico
as@cie.unam.mx

Dr. Suzanne Smrekar
Jet Propulsion Laboratory
Mail Stop 183-501
4800 Oak Grove Dr.
Pasadena, CA 91109, USA
tel.: (818) 354-4192
fax: (818) 393-5059
ssmrekar@jpl.nasa.gov

Prof. Carol Stein
Dept. of Earth & Environmental Sciences
(m/c 186), University of Illinois at Chicago
845 W. Taylor Street
Chicago, IL 60607-7059, USA
tel: 312-996-9349
fax: 312-413-2279
cstein@uic.edu

Prof. Moti Stein
Geological Survey of Israel,
30 Malkhe Yisrael St.,
95501, Jerusalem, Israel.
tel:972-5314296
fax: 972-2-5380688
motis@vms.huji.ac.il

Prof. Seth Stein
Department of Geological Sciences
Northwestern University,
Evanston, IL 60208, USA
tel: (847) 491-5265
fax: (847) 491-8060
seth@earth.northwestern.edu

Dr. Ellen R. Stofan
Proxemy Research
PO Box 338
Rectortown VA 20140, USA
tel: (540)364-0092,
fax: (540)364-1071
ellen@proxemy.com

Dr. Reidar G. Tronnes
Nordic Volcanological Institute,
University of Iceland
Grensasvegur 50,
IS-108 Reykjavik, Iceland
tel: 354-525-4496
rgt@hi.is

Dr. Peter Vogt
Code 7420, Naval Research Laboratory
4555 Overlook Ave. SW
Washington, DC 20375-5320, USA
vogt@qur.nrl.navy.mil

Dr. Richard Walker
Department of Geology
University of Maryland College Park
College Park, MD 20742, USA
tel: (301) 405-4089
fax: (301) 314-9661
rjwalker@geol.umd.edu

Prof. Phil Wannamaker
Univ. Utah/EGI
423 Wakara Way, Suite 300
Salt Lake City, UT 84108, USA
tel: 801 581 3547
pewanna@egi.utah.edu

Dr. Dayanthie S. Weeraratne
Brown University
P.O. Box 1846
Providence, Rhode Island,
02906, USA
tel: (401)-863-3339
Dayanthie_Weeraratne@brown.edu

Prof. Marjorie Wilson
School of Earth Sciences
Leeds University, Leeds LS2 9JT, UK
tel/fax + 44 (0) 113 343 5236
M.Wilson@earth.leeds.ac.uk

Dr. Alistair Wilson
School of Earth Sciences
Leeds University, Leeds LS2 9JT, UK
tel/fax + 44 (0) 113 343 5236
M.Wilson@earth.leeds.ac.uk

Prof. Jerry Winterer
Geosciences Research Division
Scripps Institution of Oceanography
La Jolla, CA 92092-0220, USA
tel: 858-534-2360
fax: 858-534-0784
jwinterer@ucsd.edu

Prof. Don Wright
Department of Earth Sciences
Room ER4063, Alexander Murray Building
Memorial University of Newfoundland
St. John's, NL, Canada, A1B 3X5
tel: (709) 754-8760 (home)
tel: (709) 737-8142 (work)
n12dmw@mun.ca

Prof. Gezahegn Yirgu
Addis Ababa University
Department of Geology and Geophysics
Addis Ababa University
P.O. Box. 1176 Addis Ababa, Ethiopia
tel: (00251-1) 553214 or 569222
yirgu.g@geol.aau.edu.et

Post-Conference Book

The GSA have agreed to edit a post-Conference book of papers arising. All Conference participants are invited to submit papers for this book, and proposals for additional relevant contributions from non-participants are welcome and will be considered by the Editors. The Editors will be Gillian R. Foulger, James H. Natland, Dean C. Presnall and Don L. Anderson. To date over 30 conference participants have pledged papers.

The target timetable for production and processing of manuscripts is:

Deadline for submissions	January 15th 2004
Reviews returned	April 15th 2004
Revised ms returned to editors	May 30th 2004
Submission to GSA	July 30th 2004

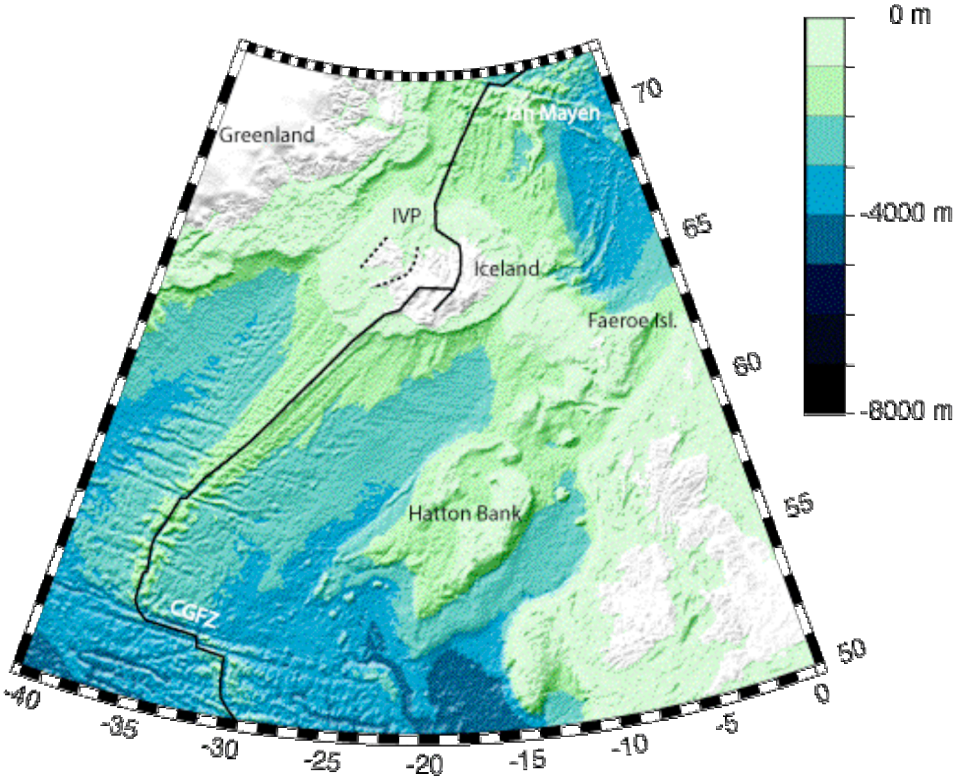
Papers will be reviewed by two reviewers, and the Editors will adjudicate in difficult cases. Authors are encouraged to submit a list of potential reviewers with their manuscripts, including candidates who are not authors of any paper in the volume.

Electronic submission to Gillian R. Foulger at g.r.foulger@durham.ac.uk is preferred. PDF files, Word documents with figures either embedded or separately, and most other formats can be handled. Submissions not in PDF will be translated to this format for distribution to reviewers.

Each paper/chapter should be at or above the standards for papers in GSA Bulletin. More information about GSA books may be found at http://www.geosociety.org/pubs/bookguid.htm

A brief geological tour of Iceland

Iceland lies on the mid-Atlantic ridge between ~ 63˚N and 65˚N, where the full spreading rate is ~ 1.9 cm/year. It is flanked by ridges of thick crust that extend to the adjacent continental blocks of Greenland and the Faeroe islands. These "aseismic ridges", and Iceland itself, are underlain by crust ~ 30 km thick, which indicates that magmatism has been approximately three times that along the mid-ocean ridges to the north and south ever since the north Atlantic opened at ~ 54 Ma. This, and the ocean-island-basalt (OIB) geochemistry of the Iceland region, have traditionally been assumed to result from a mantle plume, but alternative, shallow-sourced models are currently being scrutinised [*Foulger et al.*, 2003].

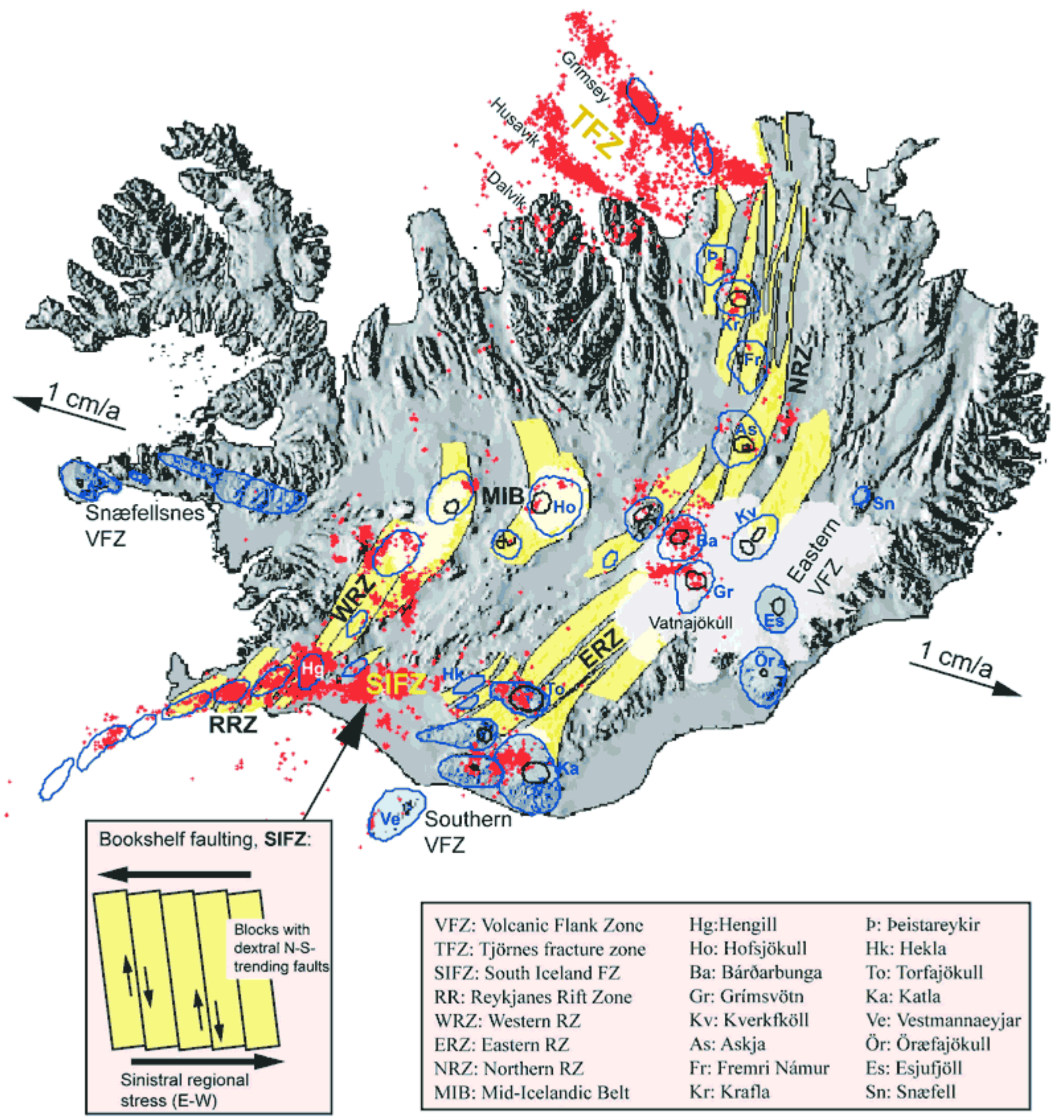


Bathymetry of the area around Iceland.

The initial opening of the north Atlantic at ~ 54 Ma was preceded by Paleocene continental magmatism at 62 – 58 Ma, which produced large volumes of basalts and associated intrusives on Baffin Island, Greenland and the British Isles. Continental breakup, plate separation and incipient ocean crust formation were accompanied by the formation of thick, seaward-dipping reflectors (SDR) along the east Greenland and northwest European margins. Plate boundary configuration in the Iceland region and to the north was subsequently complicated, and involved several migrations of the spreading ridge and spreading about a parallel pair of ridges for much of the time [*Foulger*, 2003]. Such a spreading style is currently ongoing in south Iceland today. The Iceland region meets the definition of a diffuse oceanic plate boundary [*Zatman et al.*, 2001]. In contrast, spreading along the Reykjanes ridge to the south has had a relatively simple history.

Iceland is currently traversed by several 40 – 50 km wide rift zones, the Reykjanes, Western, Eastern and Northern rift zones. These comprise *en-echelon* arrays of spreading segments, most containing a central volcano that may have one or more calderas, acid and intermediate rocks, a high-temperature geothermal area, and a fissure swarm 5 – 15 km wide and up to 200 km long. The Western and Eastern rift zones are subparallel in south Iceland and spreading is distributed across both. A very broad zone of rifting, comprising at least 6 subparallel spreading centers forms the Mid-Iceland Belt that traverses central Iceland. North of this spreading is taken up along only one rift zone – the Northern Rift Zone. The situation in the north may be unusual over the last 26 Myr, as two subparallel rift zones have existed there for much of this time. Extinct rift zones currently lie in north and northwest Iceland.

In addition to the active rift zones, three non-rifting volcanic flank zones (VFZ) are recognised, the Snaefellsnes, Southern and Eastern VFZs. In these, most of the volcanic centers lack well-developed fissure swarms, geothermal activity is generally lower, and volcanism is not accompanied by substantial crustal widening.



Tectonic map of Iceland. Red dots show epicenters of 25,000 earthquakes from 1994 – 2000. Fissure swarms are in yellow. Volcanic centers and calderas are outlined.

There are two complex fracture zones in Iceland that take up transform motion. One lies in south Iceland and connects the southern ends of the Western and Eastern Rift zones (i.e., the Hengill triple junction and Hekla volcano). This zone experiences earthquakes up to magnitude ~ 7.5 on short, north-south orientated faults. Seismic sequences typically occur about once per century, start in the east and propagate west, decreasing in magnitude towards the west. The zone is though to deform in a bookshelf faulting manner on right-lateral faults, such that the whole zone deforms in a left-lateral way as required by large-scale plate motion. Two magnitude 6.6 earthquakes occurred there in the year 2000, and this zone is thus under careful surveillance. The large earthquakes in the year 2000 triggered substantial earthquake activity in the Reykjanes Peninsula. North of Iceland the Northern Rift Zone is connected to the Kolbeinsey Ridge by the offshore Tjornes Fracture Zone which takes up right-lateral transform motion on three subparallel oblique faults.

Iceland contains many remarkable central volcanoes. Hekla (lit. "Hood") erupts frequently and the SiO_2 contents of the eruptives are related to the length of repose since the previous eruption. Torfajokull in the Eastern Rift Zone is exceptionally rich in intermediate rocks and erupts mixed basalt/rhyolite lavas. Katla is remarkable for its seasonal earthquake activity, which occurs primarily in the winter. The cluster of central volcanoes beneath NW Vatnajokull, which include Bardarbunga, Grimsvotn and Kverkfjoll, represent the greatest volcanic activity in Iceland. Kverkfjoll lies on the northern margin of Vatnajokull and has melted remarkable ice caves in the glacier. Grimsvotn contains a subglacial caldera lake which continually fills as a result of melting of the icecap at its base by geothermal heat. Periodically the lake level rises high enough to lift the icecap from bedrock locally and the lake drains, with water flowing beneath the icecap to the south and forming a glacial burst ("jokulhlaup") onto the sandy plains south of Vatnajokull. The subglacial volcano Gjalp, which recently erupted and melted a hole in the icecap, causing an exceptionally large, damaging glacial burst, lies just north of Grimsvotn.

Large earthquakes in Iceland are mostly associated with the two fracture zones, but large numbers of earthquakes also occur within the rift zones [Einarsson, 1991]. On a day-to-day basis, these are of small magnitude and mostly associated with the geothermal areas. They probably result from thermal contraction cracking in the cooling intrusions that comprise the geothermal heat sources. Periodically swarms of earthquakes are associated with spreading episodes along the rift zones.

The mechanism of spreading in Iceland was revealed by an episode in the Krafla spreading segment in the Northern Rift Zone, 1975-1985 [Björnsson, 1985]. The Krafla central volcano became activated and a magma chamber beneath it inflated at a rate of ~ 5 m^3/s for a decade. Periodically the magma chamber failed and magma escaped forming dikes to the north and south along the fissure swarm. These dike injections were accompanied by swarms of earthquakes, but once the magma reached the surface and eruption began, earthquake activity greatly declined. Total lateral crustal extension of ~ 10 m occurred, but no earthquakes were larger than magnitude ~ 4.5. This episode demonstrated that such spreading events could occur along the marine spreading plate boundary undetected by land seismic stations. Following this episode, the most remarkable post-tectonic anelastic deformation field ever observed in the world was measured with GPS. Extension across the fissure zone was several times the average plate rate for about a decade. The viscosity of the asthenosphere under Iceland to calculated to be ~ 10^{19} Pa s [Foulger et al., 1992]. This result was confirmed by study of isostatic rebound of the Vatnajokull icecap during the 20th century [Sigmundsson and Einarsson, 1992].

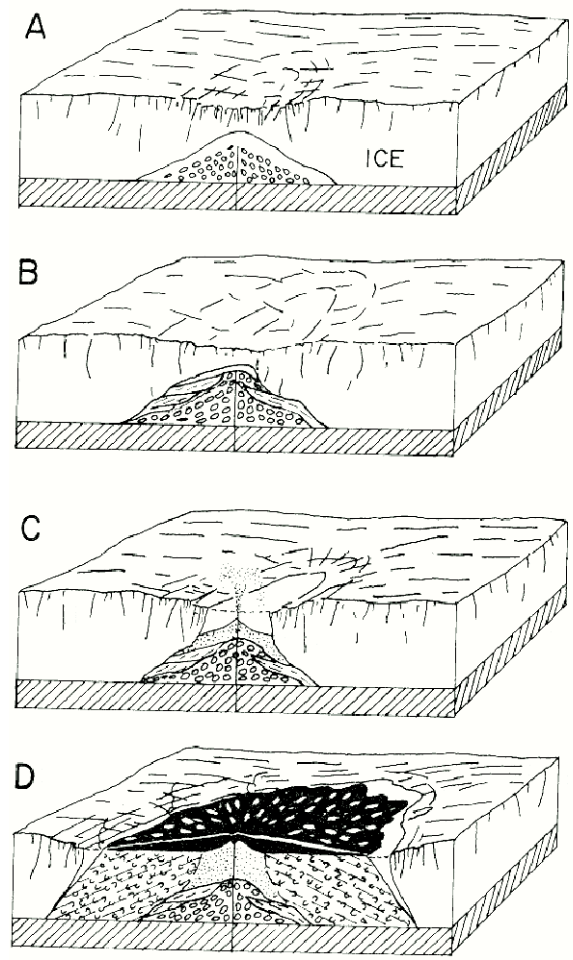
The volcanic systems of the rift zones mainly produce tholeiitic basalts. The major products of the flank volcanic zones are mildly alkaline and transitional (tholeiitic to alkaline) basalts [Saemundsson, 1979].

Fissure eruption in the Krafla fissure swarm

Iceland has been variably covered by ice sheets during the last 3 Ma. Heat transfer to the ice during subglacial volcanism is efficient and magma enters a subaqueous enviromment in the form of water-filled ice cavities or ice-dammed lakes. The character of the eruption products depends on the hydrostatic pressure at the vent and the internal volatile pressure in the magma. Decreasing external pressure leads to a transition from pillow lava via pillow breccia to hyaloclastite tuff. Most Icelandic subglacial volcanic mountains comprise cores of pillow lava, overlain by pillow breccia and hyaloclastite tuff, reflecting decreasing hydrostatic pressure as the mountain grows higher during the eruption. If the vent area becomes subaerial, the volcanism may change to lava eruptions. Icelandic hyaloclastite mountains, capped by subaerial lava flows have generally steep sides and flat tops and are called table mountains.

The landforms developed by subaerial and subglacial volcanism are very different. During subaerial conditions the predominant basaltic eruption products are lava flows from fissure eruptions or gently sloping shield volcanoes. Fissure eruption lavas tend to smooth the topography of the rift zone floor. Some of the postglacial lava flows in Iceland have traveled 50 – 100 km, and some of these flows have traveled outside the rift zones where they originated. The Eldgja (934 – 940 AD) and Laki (1783 – 1784 AD) lava flows are examples, and have volumes of 20 and 14 km^3, respectively. In contrast, subglacial fissure eruptions and subglacial “shield volcanism” produce high and narrow hyaloclastite ridges and steep-sided table mountains. Subglacial volcanism therefore tends to build high topography. The high areas under the major Icelandic glaciers, and especially under Vatnajökull, thus grow more rapidly in elevation compared to the surrounding volcanic zones.

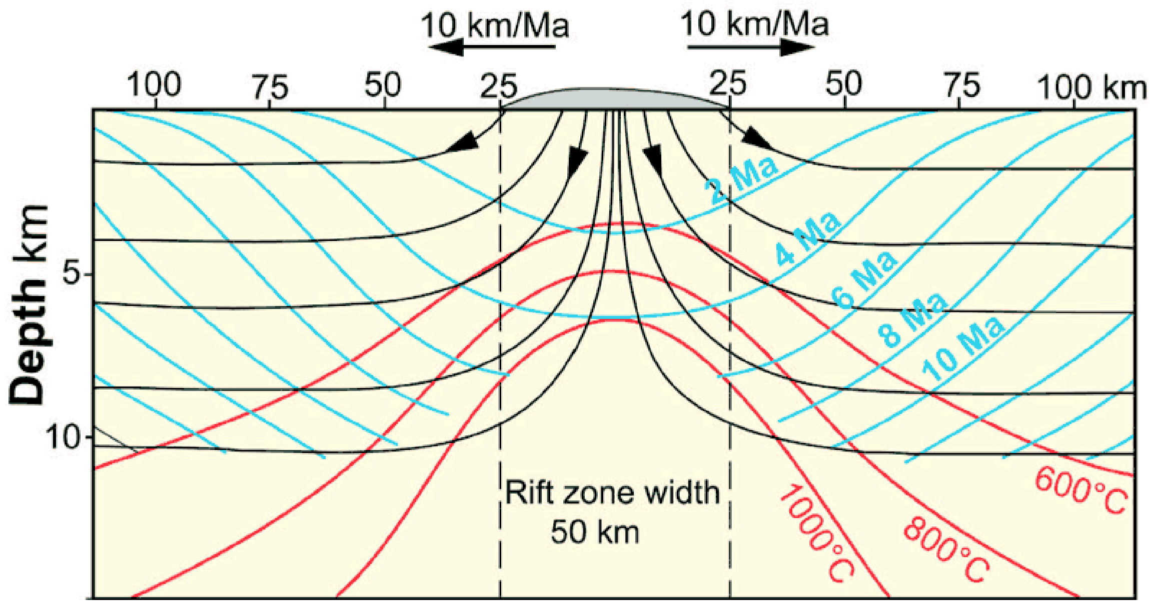
Systematic correlations between major and trace element and radiogenic isotope ratios (Sr, Nd, Hf, Pb, Os isotopes) in Icelandic lavas demonstrate that the mantle source is heterogeneous. The geochemistry of basalts from the nearby ridge segments, Vesteris seamount, the Jan Mayen area, the Early Tertiary successions of Greenland and the British Isles indicate that the upper mantle in much of the NE Atlantic is similar to that beneath Iceland. Maximum $^3He/^4He$ isotope ratios are the highest on Earth, with values of up to 42 Ra reported from Iceland, and > 50 Ra from Baffin Island [Stuart et al., 2003].



Schematic model for the evolution of Icelandic monogenetic table mountains. At high hydrostatic pressure, a core of pillow lava forms above the vent (A). Slumping on the flanks of the pillow lava pile produces pillow breccia (B). Hyaloclastite tuff is erupted when the external hydrostatic pressure is lower (C), and a lava cap progrades across its own delta of fore-set bedded breccias (D). [from Saemundsson, 1979].

The high proportion of rhyolitic extrusives in Iceland is unique in a global oceanic context. The Torfajökull central volcano is the largest rhyolite center in the present-day terrestrial oceanic environment. Rhyolites and other silicic extrusives are confined to the most evolved central volcanoes. Many of these have also erupted large-volume ash-flow deposits, associated with significant caldera collapse. The most common type of basaltic volcanism along the Icelandic rift zones are fissure eruptions fed from a basaltic magma reservoir under a volcanic center. The largest fissure eruptions of 10 – 20 km^3 are generally quite evolved and homogenous, suggesting extensive fractional crystallization and assimilation of hydrothermally altered crust. The most common lava type exposed in the Tertiary volcanic successions of eastern and western Iceland is similarly evolved tholeiitic lavas [Hardarson and Fitton, 1991]. Another important basaltic volcano type is the large shield volcanoes that are scattered along the rift zones. This type appears to be unrelated to the volcanic systems and their fissure swarms. These monogenetic shield volcanoes erupted primitive olivine tholeiitic magmas fed by continuous overflow from summit lava lakes. The eruptions appear to have been nearly continuous, with the entire lifetime of the volcanoes completed within about 100 years. The volumes of some of the early post-glacial shield volcanoes range up to 20 km^3. Many of the table mountains are subglacial analogs of the shield volcanoes.

The rift zones are continually covered by new lava flows and hyaloclastite mountains. The volcanic productivity of the Icelandic rift zones is anomalously high relative to the low half-spreading rate of ~ 1 cm/year. Rapid subsidence of the partially altered and hydrated volcanic pile occurs. Vertical sections through the Tertiary lava pile in glacially eroded valleys and fjords expose the uppermost 1,500 m of extrusive rocks. The lavas dip gently towards the current or extinct rift zones. This regional flexuring and tilting is a result of the continuous loading and subsidence of the rift zone crust. Whereas the loading is most pronounced under the volcanic centers, the average, time integrated (3 – 7 Ma) subsidence is highest along the rift zone axis and decreases towards the rift zone margins.



Simplified model of Icelandic rift zone dynamics [from Palmason, 1973]. The black, blue and red lines are mass trajectories, age contours (Ma) and temperature contours (°C). Partial melting of hydrated mafic lithologies starts at ~ 5 km depth beneath the central part of the rift zone.

Based on these observations and other geophysical constraints, Palmason [1973] developed a dynamic model for the crustal accretion in Iceland. The lava pile subsides and undergoes prograde metamorphism with increasing pressure and temperature to zeolite, greenshist and amphibolite facies and partial melting producing rhyolitic magmas [Oskarsson et al., 1982]. When partial melting occurs along the walls of basaltic magma chambers, the rhyolitic melt fractions mix with the basaltic liquid and promote magma evolution. In other areas rhyolitic melt fractions segregate and give rise to silicic intrusions and extrusions. Such crustal reprocessing occurs only to a very limited extent along the midoceanic spreading ridges.

Acknowledgement: Some of the text and figures are adapted or copied from the guidebook of Trönnes et al. [2003]. GRF thanks R. Trönnes for kindly supplying an electronic version of this guidebook.

References

Björnsson, A., Dynamics of crustal rifting in NE Iceland, *J. geophys. Res.*, **90**, 10,151-10,162, 1985.

Einarsson, P., Earthquakes and present-day tectonism in Iceland, *Tectonophysics*, **189**, 261-279, 1991.

Foulger, G.R., On the apparent eastward migration of the spreading ridge in Iceland, in *Penrose Conference Plume IV: Beyond the Plume Hypothesis*, edited by G.R. Foulger, J.H. Natland, and D.L. Anderson, Geological Society of America, Hveragerdi, Iceland, 2003.

Foulger, G.R., C.-H. Jahn, G. Seeber, P. Einarsson, B.R. Julian, and K. Heki, Post-rifting stress relaxation at the divergent plate boundary in Iceland, *Nature*, **358**, 488-490, 1992.

Foulger, G.R., J.H. Natland, and D.L. Anderson, An alternative model for Iceland & the North Atlantic Igneous Province, in *Penrose Conference Plume IV: Beyond the Plume Hypothesis*, edited by G.R. Foulger, J.H. Natland, and D.L. Anderson, Geological Society of America, Hveragerdi, Iceland, 2003.

Hardarson, B.S., and J.G. Fitton, Increased Mantle Melting beneath Snaefellsjokull Volcano During Late Pleistocene Deglaciation, *Nature*, **353**, 62-64, 1991.

Oskarsson, N., G.E. Sigvaldason, and S. Steinthorsson, A dynamic model of rift zone petrogenesis and the regional petrology of Iceland, *J. Pet. Special Issue*, **23**, 28-74, 1982.

Palmason, G., Kinematics and heat flow in a volcanic rift zone, with application to Iceland, *Geophys. J. R. astr. Soc.*, **33**, 451-481, 1973.

Saemundsson, K., Outline of the geology of Iceland, *Jokull*, **29**, 7-28, 1979.

Sigmundsson, F., and P. Einarsson, Glacio-isostatic crustal movements caused by historical volume change of the Vatnajokull icecap, Iceland, *Geophys. Res. Lett.*, **19**, 2123-2126, 1992.

Stuart, F.M., S. Lass-Evans, J.G. Fitton, and R.M. Ellam, Extreme $^{3}He/^{4}He$ in picritic basalts from Baffin Island: the role of a mixed reservoir in mantle plumes, *Nature*, **in press**, 2003.

Trönnes, R.G., H. Johannesson and S. Planke, South Iceland field trip, June 2002, Guidebook, 2002.

Zatman, S., R.G. Gordon, and M.A. Richards, Analytic models for the dynamics of diffuse oceanic plate boundaries, *Geophys. J. Int.*, **145**, 145-156, 2001.

FIELDTRIPS

Note: The detailed itineraries may alter if required by local conditions at the time.

1. The Reykjanes Peninsula: Tuesday 26th August, 2003

Leaders: Sveinn P. Jakobsson & Gillian R. Foulger

The excursion will focus on Recent volcanism, general petrology and hydrothermal activity.

Hveragerdi – Selvogsheidi – Eldborg – Graenavatn – Krisuvík – Sveifluhals – Ögmundarhraun – Meltunnuklif – Skalamaelifell – Hrolfsvik – Grindavík – Svartsengi – Haleyjabunga – Reykjanes – Langholl – Undirhlidar – Svinahraun – Hveragerdi

Brief description of the Reykjanes Pensinsula

The Reykjanes Peninsula is surfaced by basaltic lava flows dating from the last interglacial period. The Mid-Atlantic Ridge gradually shallows towards Iceland, forming the actively spreading Reykjanes Ridge. Its structural continuation on land is the Reykjanes Peninsula, with Keflavik Airport at its NW corner, and Reykjavik at its NE corner. The Peninsula comprises *en echelon* volcanic systems and fissure swarms, with a narrow (2 to 5 km) seismic zone along the plate boundary between the North American and Eurasian plates. The fissure swarms are oblique to the actual plate boundary and thus extend a few kilometres into the plates on either side.

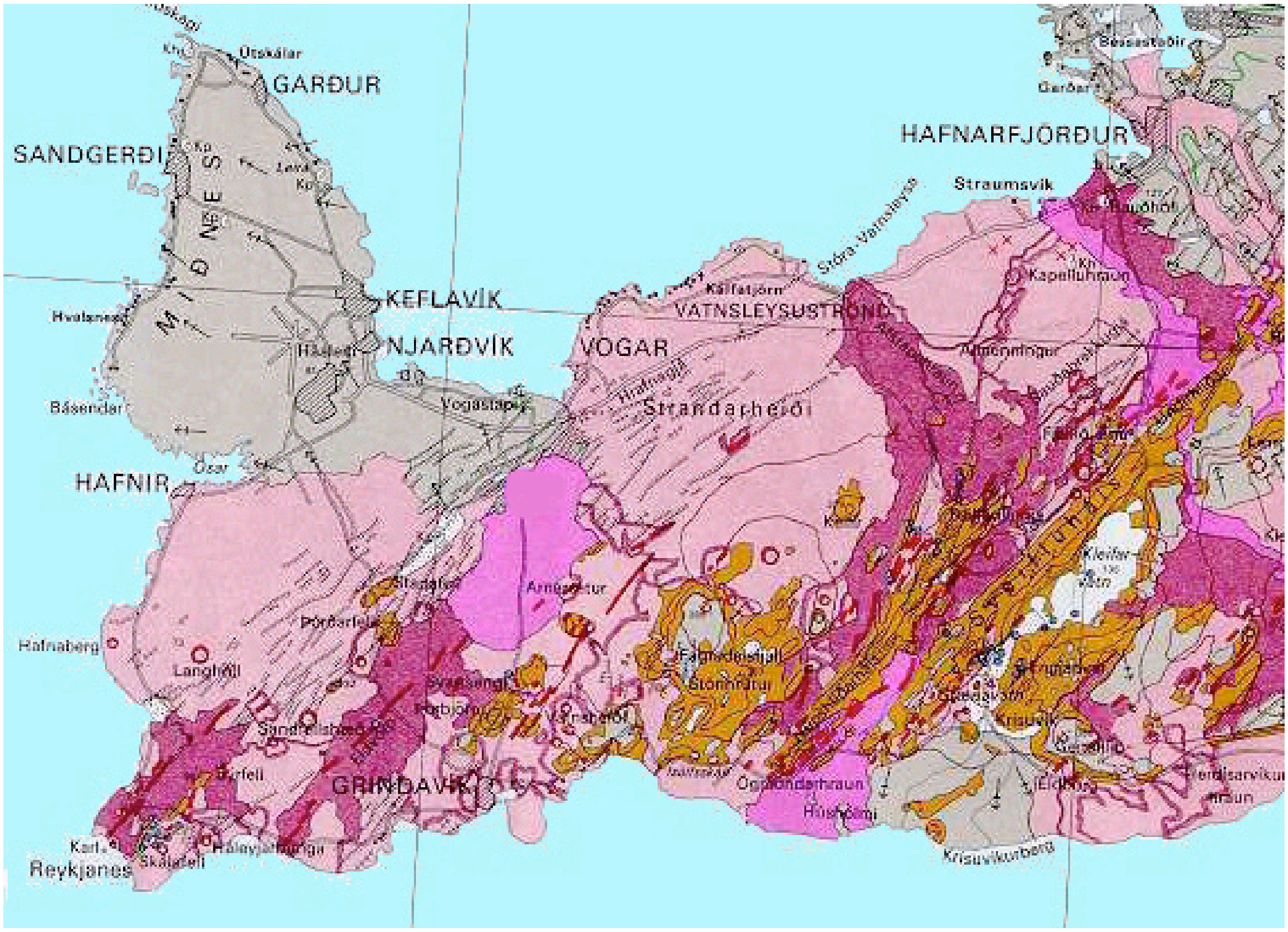
The least compressive stress in the Peninsula is horizontal and trends NW-SE or perpendicular to the boundary, but the maximum compressive stress and strain release varies in direction along the Peninsula. In the SW the Peninusula is characterized by normal faulting, with maximum earthquake magnitudes of 5 to 5.5. In the east the strain release is more strike-slip and maximum magnitudes are up to 6.5. The most recent seismic episodes occurred in 1929-1935 and 1967-73. The latest magmatic episodes occurred in the tenth and eleventh centuries, and the last eruption was in 1340 AD.

Volcanic activity on the Reykjanes Peninsula has been intense in Postglacial times, but has generally been given little attention, because no very recent events have occurred. The number of eruptions is not known but totals a few hundred. The volcanic activity is more or less restricted to the active fissure zones and seems to be periodic. The time lapse between periods is about 1,000 years but each period lasts for about 300 – 400 years. During each period all the fissure swarms are active and the activity starts at one end of the Peninsula and moves to the other. The last period started in the 10th century and lasted to about 1340 AD. The first eruptions took place at the eastern end (in Hellisheidi and Blafjoll) but spread to the west. Eruptions within each volcanic system are thought to behave in a similar manner to those of the Krafla Fires that occurred 1975-1984, i.e. rifting episodes which last for a few years or decades, accompanied by a few or numerous eruptions. At each time only one fissure swarm may be active. The eruptions established from historic accounts, geological mapping and radiocarbon dating are as follows:

950-1000 AD in the Brennisteinsfjoll and Blafjoll swarm
1151 and 1188 AD in the Krisuvik and Trolladyngja swarm
1210-1240 AD in the Reykjanes swarm

1340 AD in the Brennisteinsfjoll swarm

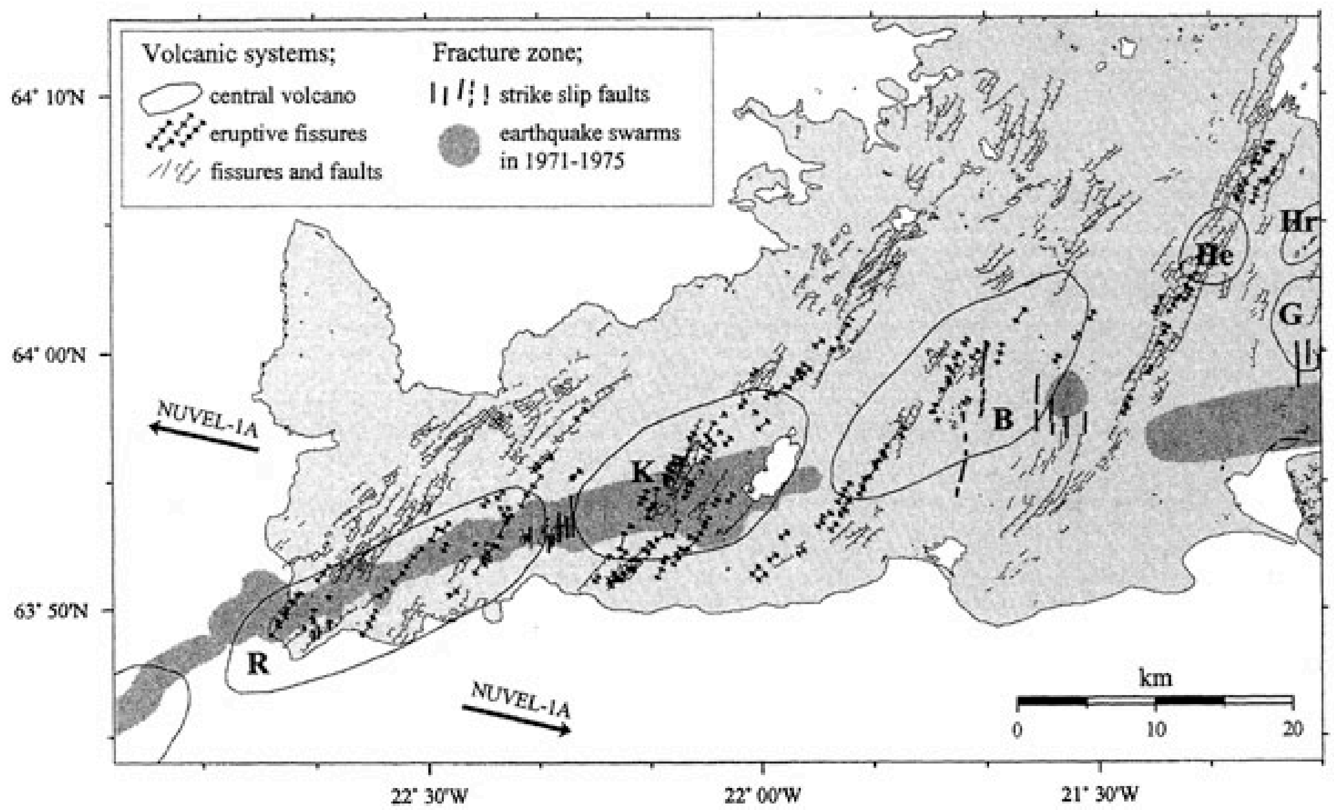
Numerous volcanic eruptions have occurred close offshore on the Reykjanes Ridge throughout the centuries, the last confirmed one in 1926.



Geological map of the Reykjanes Peninsula

The four major fissure swarms are 25 to 50 km in length, have shallow grabens, and are probably the result of repeated dike injection in the crust. There is typically a crater row in the centre of each fissure swarm. Deformation on the Peninsula is of two types: (a) seismic – involving principally brittle failure and earthquakes along a narrow zone, and (b) magmatic, where magma is introduced into the crust. In this case the magmatic fluid causes the crust to fail, and magma propagates laterally and vertically along fractures to form dikes and feed eruptions.

There are additionally N-S trending fissure systems on the Reykjanes Peninsula, which are less obvious than the NE-SW elements. They are shorter (5 to 10 km), and mainly located along the plate boundary. They are collectively arrayed EW and most of the shield volcanoes on the Peninsula also follow this trend. The N-S fractures are believed to be the continuation of the South Iceland Seismic Zone, which will be toured during the 4-day post-Conference fieldtrip.



Tectonic map of the Reykjanes Peninsula showing the en echelon volcanic systems

The majority of the Reykjanes Peninsula is covered by post-glacial basaltic lavas (< 12,000 YBP). The oldest rock formations are interglacial basaltic lavas, composed of very coarse grained basalt lavas that were mainly erupted from shield volcanoes during the last interglacial. The part of the Peninsula which includes Keflavik Airport is composed of interglacial lava flows. They are invariably glaciated, with glacial striae at the surface.

Second in age are hyaloclastites or basaltic subglacial tuffs and pillow lavas, formed by eruptions of basaltic magma beneath the ice cap during the last glacial stage (ca. 120,000 to 12,000 YBP). Because of the presence of ice cover, the eruptives were restricted in their distribution and piled up near and over the vent, as pillow lavas and hyaloclastites. All of the prominent mountains on the Peninsula are subglacial volcanoes formed in this manner, but in some the activity was sufficiently vigorous to build up an edifice above the level of the ice sheet, resulting subaerial lavas which cap these volcanoes and form table mountains.

Subglacial and subaerial (post-glacial) fissure eruptions have formed prominent NE-trending ridges and crater rows that dominate the topography of the Peninsula. Subglacial eruptions produce ridges of hyaloclastite similar to the Axial Volcanic Ridges (AVRs) on the Reykjanes Ridge. A number of table mountains and hyaloclastite cones, products of sub-glacial eruptions from isolated vents, are also present on the Peninsula and closely resemble the small seamounts that have been mapped on the MAR. Early, large-volume post-glacial basaltic and small-volume picritic shield volcanoes have also played a major role in surfacing this ridge segment with voluminous pahoehoe lava flows, which both cover and are covered by the products of fissure eruptions. Shield volcanoes and eruptive fissures have been active on the Peninsula during the Holocene.

The base of the seismogenic zone is ~ 5 - 11 km depth on the Peninsula and most seismicity occurs at depths from 1 - 5 km. A narrow zone of seismicity 2 - 5 km wide, characterized by predominantly strike-slip focal mechanisms and extending the entire length of the peninsula, is identified as the currently active plate boundary. Geodetic measurements show that left-lateral shear is currently occurring along on the Peninsula. Data from Satellite Radar Interferometry indicate that below a depth of 5 km plate motion is accommodated by continuous ductile deformation.

Bibliography

Applegate, B., and A.N. Shor, The northern mid-Atlantic and Reykjanes ridges: Spreading centre morphology between 55˚50'N and 6300'N, J. geophys. Res., 99, 17,935-17,956, 1994.

Clifton, A.E., Laboratory and Field Studies of Fracture Populations Produced by Oblique Rifting, Ph.D. thesis, Rutgers University, New Brunswick, NJ, 2000.

Fisk, M.R., J.-G. Schilling, and H. Sigurdsson, An Experimental Investigation of Iceland and Reykjanes Ridge Tholeiites .1. Phase-Relations, Cont. Min. Pet., 74, 361-374, 1980.

Flower, M.F.J., H.-U. Schmincke, and R.N. Thompson, Phlogopite stability and the $^{87}Sr/^{86}Sr$ step in basalts along Reykjanes Ridge, Nature, 254, 404-406, 1975.

Gee, M.A.M., R.N. Taylor, M.F. Thirlwall, and B.J. Murton, Glacioisostacy controls chemical and isotopic characteristics of tholeiites from the Reykjanes peninsula, SW Iceland, Earth planet. Sci. Lett., 164, 1-5, 1998a.

Gee, M.A.M., M.F. Thirlwall, R.N. Taylor, D. Lowry, and B.J. Murton, Crustal processes: Major controls on Reykjanes Peninsula lava chemistry, SW Iceland, J. Pet., 39, 819-839, 1998b.

Gudmundsson, A., Mechanical Aspects of Postglacial Volcanism and Tectonics of the Reykjanes Peninsula, Southwest Iceland, Journal of Geophysical Research-Solid Earth and Planets, 91, 2711-2721, 1986.

Gudmundsson, A., Geometry, Formation and Development of Tectonic Fractures on the Reykjanes Peninsula, Southwest Iceland, Tectonophysics, 139, 295-308, 1987.

Hreinsdottir, S., P. Einarsson, and F. Sigmundsson, Crustal deformation at the oblique spreading Reykjanes Peninsula, SW Iceland: GPS measurements from 1993 to 1998, Journal of Geophysical Research-Solid Earth, 106, 13803-13816, 2001.

Jakobsson, S.P., J. Jonsson, and F. Shido, Petrology of the Western-Reykjanes-Peninsula, Iceland, J. Pet., 19, 669-705, 1978.

Klein, F.W., P. Einarsson, and M. Wyss, The Reykjanes Peninsula, Iceland, earthquake swarm of September 1972 and its tectonic significance, J. geophys. Res., 82, 865-887, 1977.

Lee, S.M., and R.C. Searle, Crustal magnetization of the Reykjanes Ridge and implications for its along-axis variability and the formation of axial volcanic ridges, Journal of Geophysical Research-Solid Earth, 105, 5907-5930, 2000.

Murton, B.J., and L.M. Parson, Segmentation, volcanism and deformation of oblique spreading centers - a quantitative study of the Reykjanes ridge, Tectonophysics, 222, 237-257, 1993.

Parson, L.M., B.J. Murton, R.C. Searle, D. Booth, J.R. Evans, P. Field, J. Keeton, A. Laughton, E. McAllister, N. Millard, L. Redbourne, I. Rouse, A. Shor, D. Smith, S. Spencer, C. Summerhayes, and C. Walker, En-echelon axial volcanic ridges at the Reykjanes ridge - a life-cycle of volcanism and tectonics, Earth planet. Sci. Lett., 117, 73-87, 1993.

Rowe, E.C., and J.-G. Schilling, Fluorine in Iceland and Reykjanes Ridge Basalts, Nature, 279, 33-37, 1979.

Taylor, R.N., B.J. Murton, and M.F. Thirwall, Petrographic and Geochemical Variation Along the Reykjanes- Ridge, 57-Degrees-N-59-Degrees-N, Journal of the Geological Society, 152, 1031-1037, 1995.

Weir, N.R.W., R.S. White, B. Brandsdottir, P. Einarsson, H. Shimamura, and H. Shiobara, Crustal structure of the northern Reykjanes ridge and Reykjanes peninsula, southwest Iceland, J. geophys. Res., 106, 6347-6368, 2001.
Zindler, A., S.R. Hart, F.A. Frey, and S.P. Jakobsson, Nd and Sr Isotope Ratios and Rare-Earth Element Abundances in Reykjanes Peninsula Basalts - Evidence for Mantle Heterogeneity beneath Iceland, Earth planet. Sci. Lett., 45, 249-262, 1979.
http://www.volcanotours.com/iceland/fieldguide/reykjannes_Peninsula.htm

2. The Hengill triple junction, Thingvellir, Geysir, Gullfoss: Thurs. 28th August, 2003

Leaders: Gillian R. Foulger & Axel Bjornsson

The excursion will focus on the tectonics, geophysics and geothermal activity of the Hengill triple junction, with the afternoon touring Thingvellir, the site of the ancient Icelandic parliament, the Great Geysir and its geysir field, and the Gullfoss waterfall.

Hveragerdi – Kambar – Hveradalur – Pipeline road – Dyradalur – Kyrdalur – Nesjavellir power station – Thingvellir – Geysir – Gullfoss – Hveragerdi

Brief description of the areas to be visited

Geothermal activity in Hveragerdi

The hotsprings of Hveragerdi (lit. “hot spring enclosure”) are fed by hot water that runs from the Grensdalur volcanic area south along fissures. The main fissure has a warm water stream at a depth of 125 m and a temperature of 180°C (356°F). At a depth of 250 m there is another stream that is 10°C cooler.

The geothermal activity is variable, and hot springs migrate about. Once a house was destroyed when a new hot spring developed beneath the living room (“Badstofahver – lit. “living-room hot spring”). The geothermal heat has been utilised, probably since the settlement of Iceland in the 9th century. Traditionally clothes were washed, food was cooked, and bread was baked in steam boxes (hverabraud – lit. “hot spring bread”). Later, pipelines were built from the springs and cisterns installed next to homes.

Some significant dates:

1929	The first establishment of a greenhouse.
1939-41	The first hot water drilling for the use of thermal energy which was used for a laundry for British soldiers during World War II.
1947	The volcanic eruption of Mt. Hekla caused some hot springs to disappear and new ones to be born.
1952	Municipal heating established by drilling eight holes in the geothermal area. Gradually private holes were added and use of the municipal wells diminished.
1970	Drilling by Orkustofnun (the National Energy Authority).

Today, geothermal energy heats 50,000 m^2 of greenhouses, private homes and the swimming pool. Half of the private homes are heated with groundwater that has been heated with steam. Other private homes, industrial sites, commercial establishments and greenhouses are heated directly with steam.

The Hengill ridge-ridge-transform triple junction

The Hengill ridge-ridge-transform triple junction in southeastern Iceland lies where the Reykjanes Peninsula Volcanic Zone, the Western Volcanic Zone, and the South Iceland Seismic Zone meet. The locus of ridge volcanism and spreading within the triple junction has migrated westward by a few kilometers over the last 1 Ma or so, from the Grensdalur system to the Hengill system. The area now comprises a tripartite complex of volcanic systems, the eastern two of which are currently inactive.

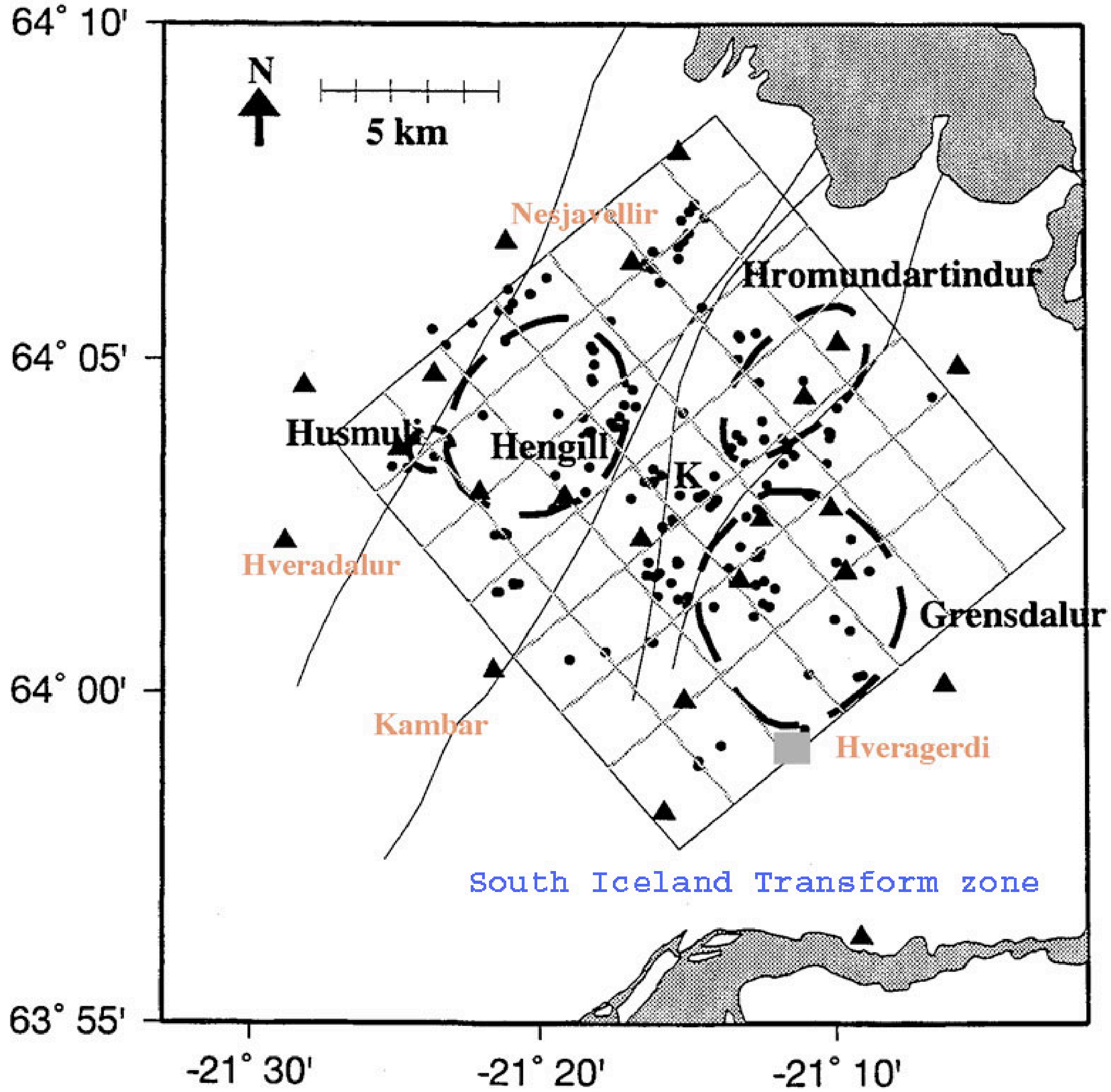
A NNE-striking fissure swarm associated with the Grensdalur volcano was the active spreading center until about 0.3 Ma. Hveragerdi lies at the southern edge of the Grensdalur central volcano and exploits geothermal heat from that system. After spreading ceased along the Grensdalur system, activity migrated west to the Hromundartindur and Hengill systems, a few kilometers to the west. The Hromundartindur system, dominated by the mountain by the same name produced mainly fissure eruptions. It is now almost extinct, having erupted last ~ 10,000 years ago. It did not develop a central volcano to the same degree of maturity as the other two systems.

The Hengill segment is currently the locus of spreading and volcanism, and contains intermediate rocks, suggesting a long-lived magma chamber. It is dominated topographically by Mt. Hengill, which is flanked on the west by a large basalt shield, Húsmuli. The Hengill system has erupted several times since the last glaciation. 200,000 years ago, the Nesjahraun lava field north of Mt. Hengill flowed into Lake Thingvellir. The Hengill area contains widespread geothermal resources that are currently under development for electricity generation and hot water.

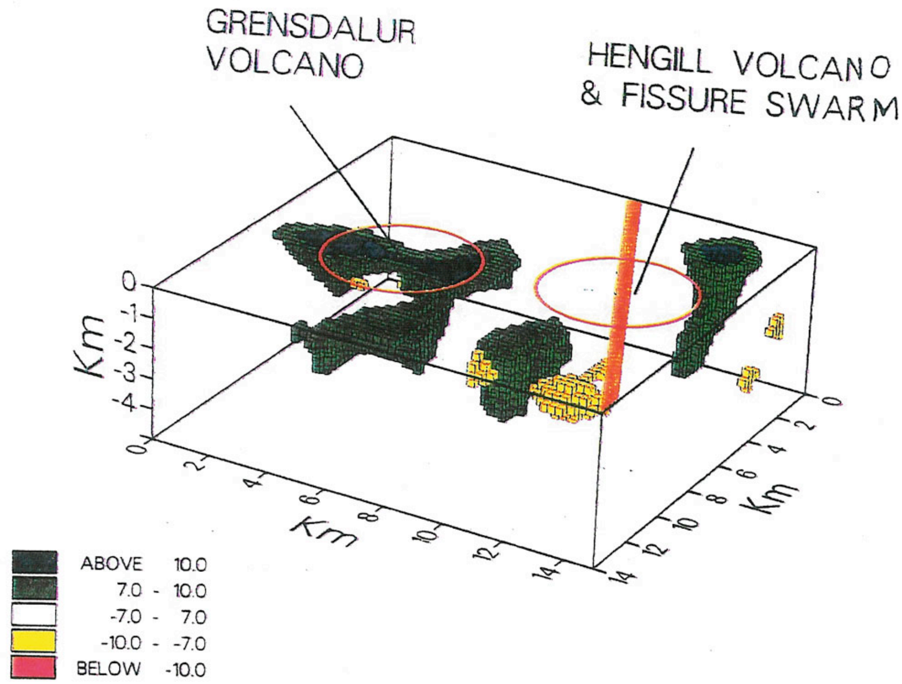
To the south of the Hengill volcanic complex, south of 64˚N, lies the western end of the South Iceland Seismic Zone, an east-west array of north-striking faults that generate earthquakes up to about magnitude 7.

The natural surface heat loss is about 350 MW. The triple junction, in particular the Grensdalur system, is associated with small-magnitude earthquake activity that is curious and unique on a world scale. Small-magnitude seismicity is ongoing on a daily basis at the very high rate of one magnitude 1 earthquake per day. Most earthquakes associated with the volcanic systems are smaller than ~ magnitude 4. They have rare, non-shear mechanisms and are thought to be caused by cooling-contraction cracking in the geothermal heat source, as heat is mined from it and transported to the surface by geothermal fluids. Earthquake monitoring experiments have mapped the seismic volume, and thus the heat source, by locating these earthquakes in three dimensions. This situation is ideal for Local Earthquake Tomography, which has been applied to reveal the three-dimensional structure of the volcanic complex in considerable detail.

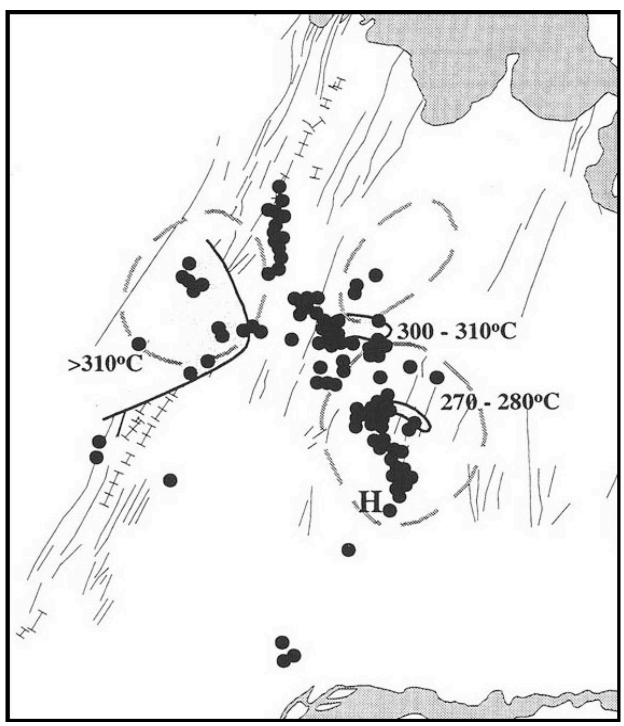
Geothermal activity is associated with all three volcanic systems in the area, and with the transform branch of the triple junction. That associated with the volcanic systems is a so-called “high-temperature” geothermal resource, and is thought to derive its heat from volcanic intrusions. That associated with the transform branch is so-called “low temperature” geothermal heat, and is thought to arise from deep circulation of groundwater in faults. The geothermal heat in Hveragerdi, which is at the southern edge of the Grensdalur central volcano, is the oldest of the high-temperature resources. The most remarkable geothermal features associated with the Hrómundartindur system are CO_2-rich springs on Öldukelsháls (lit. “beer-spring ridge”) which can be reached by a long but magical hike up into the mountains. Geothermal activity associated with the Hengill system is widespread from Nesjavellir north of Mt. Hengill to Hveradalur (lit. “Hot spring valley”) south of it. The source of water is thought to be precipitation falling on the highlands north of Lake Thingvellir that seeps at a depth of 1 – 3 km and flows underground to lower areas.



Volcanic systems of the Hengill ridge-ridge-transform triple junction. Places that will be visited in the fieldtrip are labeled in red. Box shows area tomographically imaged.



Local earthquake tomography image of the Hengill triple junction. Scale indicates wave-speed anomalies in % deviation from the starting model.



The three high-temperature geothermal fields within the volcanic systems of the Hengill triple junction

Geothermal activity at Nesjavellir

Test drilling began at Nesjavellir in 1965 and continued until 1986. Nesjavellir is the focal point for heat extraction to serve Reykjavik because of land ownership issues. Hot water flows from beneath Hengill along the Kyrdalur Ridge to Nesjavellir. The water and steam extracted is used to heat local groundwater from 4 – 5˚C to near-boiling. There are 22 boreholes at Nesjavellir, but five of them are permanently closed. Most of the boreholes are 1-2 km deep and the highest temperature measured is 380°C. Each borehole provides about 60 MW of thermal power of which about 30 MW are utilizable. This power is sufficient to heat a settlement of 7,500 people. Cold ground water is heated to just above 80°C and piped to Reykjavík (25 km) where it is used for central heating. The diameter of the pipe is 90 cm. The construction of the Nejavellir Power Plant began in early 1987 and was opened by 1990 using four holes generating 100 MW with production capability of 560 l/s. At present, the capacity is 1100 l/s of hot water and 90 MW of electricity. The Nesjavellir thermal field is projected to sustain hot water production of 400 MW for at least the next 30 years.

Thingvellir

Thingvellir is at the western margin of the major fissure swarm associated with the Hengill system. This part of the fissure swarm is a large graben structure, about 6 km in length and 80 m deep, and results from extensional tectonics and postglacial subsidence. It is bounded by very recent normal faults and open fissures. To the northeast of Thingvellir is the large basaltic shield volcano Skjaldbreidur, which erupted about 10,000 years ago and produced ~ 17 km^3 of lavas. The lava also flowed over Thingvellir and to the south, over land that since has subsided to form the lake. Major subsidence and crustal extension continued subsequently, forming the spectacular Almannagja (lit. “Commonwealth fissure”) fissure and normal faults. Further subsidence occurred at Almannagja in 1789, and Thingvallavatn then subsided about 2.5 m, when the lake advanced onto fields and farmland.

The most recent volcanic event in the Thingvallavatn area occurred ~ 2,000 years ago, when a fissure eruption in the Nesjavellir region formed the Nesjahraun basaltic lava flow, which advanced into the lake. At the same time a volcanic eruption broke out in the center of the lake, producing the tuff cone of Sandey, rising from about 100 m depth, and reaching 74 m above lake level.

In the Thingvellir area, the fissures occur within a basaltic lava flow of about 9,000 years old, derived from a fissure eruption in Tindfjallaheidi to the north-east. In 1938 the total extension or dilation of the 6.16 km wide graben, post-dating the lava flow cover was 75 m, or 1.25%, with almost all of the extension near the margins of the graben and no extension in the center. This amounts to an average rate of extension of 0.83 cm/yr and is broadly comparable to recent GPS measured rates of extension. This is consistent with the expectation that the NUVEL full 1.9 cm/year extension rate at Iceland is shared between the Western and Eastern Volcanic Zones in south Iceland.

The Almannagja fissure can be traced over a distance of 7.7 km, and its maximum width is 64 m. Most of the larger fissures are really normal fault features, with near vertical walls. The maximum vertical displacement in Almannagja is 40 m. The Almannagja and other fissures may be related to the intrusion of dikes at depth in the crust. Nevertheless, many fissures are reactivated and long-lived, and also exhibit vertical displacements.

Geysir

The Great Geysir of Iceland is the source of the English word “geyser”, meaning an erupting hot spring. Geysers occur where groundwater flows through rocks with exceptionally high thermal gradients and relatively low permeability, resulting from the self-sealing of rock formations due to the deposition of silica or other chemical precipitates from hot hydrothermal solutions. The vertical water column of water in the geyser is heated to near its boiling temperature. Because of the effect of water pressure, the boiling temperature increases with depth. At 5 m it is about 112˚C, and at 10 m depth it is about 121˚C. Any perturbation that leads to decrease of pressure of the hot water column will bring about superheating and boiling at depth. If water is ejected at the surface, deeper waters exceed boiling point, flash to steam, and bring about an eruption.

The Great Geysir ejects a jet of steam and water to height of 60 to 70 m, and the eruptions last about 10 minutes. The eruptions are preceded by rumbling sounds at depth, due to the collapse of large steam bubbles in the water column, and this is accompanied by rise and fall of the water level in the large bowl over the vent. After a few seconds the jets of steam and water begin, rapidly reaching a climax that lasts a few minutes. Then the eruption ceases suddenly, and the water level is deep within the pipe because of the large amount which has been expelled. After a few seconds a new and very powerful jet emerges, which lasts about five minutes. The vertical pipe of Geysir is about 20 m long.

The hydrothermal waters of the Geysir region carry large quantities of dissolved silica, which are preciptitated as siliceous sinter around the hot springs when the waters emerge at the surface. The deposition is the result of decreased solubility of silica in the waters due to cooling at or near the surface. In the Geysir region the sinter may be 1 - 2 m thick.

In the early part of this century the eruptions of Geysir became infrequent, and essentially ceased by 1916. This was attributed to the fact that the surface area of the bowl had become very large, resulting in rapid cooling of the water at the surface, and raising the water level. New eruptions were induced by cutting a notch in the edge of the Geysir bowl, and lowering the water level. Another method to induce an eruption is to place large quantities of soap in the water. This has the effect of decreasing the surface tension and facilitates superheating of the water, leading to eruption. Most of the steam eruptions in the Geysir area today occur from the geyser Strokkur, which is an old borehole. The eruptive behaviour of the geysers at this field are very sensitive to large earthquakes in the South Iceland Seismic Zone.

Gullfoss

The waterfall Gullfoss (lit. “Golden waterfall”) is fed by the river Hvita (lit. “White river”) which arises from under the Langjokull glacier and reaches the sea after travelling 133 km. The canyon below Gullfoss extends for ~ 2.5 km and reaches a depth of 70 metres. It may have been formed in torrential floods caused by so-called jökulhlaups (glacial outbursts) near the end of the last ice age. During a jökulhlaup the amount of water running seaward during a single 24-hour period can equal a normal flow of up to five years, but the erosive force of such sudden deluges is many times greater.

Gullfoss is actually two separate waterfalls, the upper one has a drop of 11 metres and the lower one 21 metres. The rock of the river bed was formed during an interglacial period. Water flows over the falls at an average rate of 109 m^3/s. The heaviest floods have recorded a flow of 2,000 m^3/s. During the summer the flow is 130 m^3/s, but during the winter the waterfall is largely frozen. The gorge below the waterfall cuts into a succession of interglacial lava flows intercalated by fluvial sediments.

Proposal for dams and hydro-electric power plants on the Hvita river have been proposed, which could produce ~ 2,500 GW hrs of electricity annually and double Iceland's production. However, Gullfoss is considered a national treasure, and it is extremely unlikely that such a thing will ever be done.

Gullfoss

Bibliography

Evans, J.R., G.R. Foulger, B.R. Julian, and A.D. Miller, Crustal shear-wave splitting from local earthquakes in the Hengill triple junction, southwest Iceland, Geophys. Res. Lett., 23, 455-458, 1996.

Feigl, K.L., J. Gasperi, F. Sigmundsson, and A. Rigo, Crustal deformation near Hengill volcano, Iceland 1993-1998: Coupling between magmatic activity and faulting inferred from elastic modeling of satellite radar interferograms, J. geophys. Res., 105, 25655-25670, 2000.

Foulger, G.R., Hengill triple junction, SW Iceland; 1. Tectonic structure and the spatial and temporal distribution of local earthquakes, J. geophys. Res., 93, 13493-13506, 1988a.

Foulger, G.R., Hengill triple junction, SW Iceland; 2. Anomalous earthquake focal mechanisms and implications for process within the geothermal reservoir and at accretionary plate boundaries, J. geophys. Res., 93, 13,507-13,523, 1988b.

Foulger, G.R., The Hengill geothermal area, Iceland: Variation of temperature gradients deduced from the maximum depth of seismogenesis, J. Volc. Geotherm. Res., 65, 119-133, 1995.

Foulger, G.R., and B.R. Julian, Non-double-couple earthquakes at the Hengill-Grensdalur volcanic complex, Iceland: Are they artifacts of crustal heterogeneity?, Bull. seismol. Soc. Am., 83, 38-52, 1993.

Foulger, G.R., A.D. Miller, B.R. Julian, and J.R. Evans, Three-dimensional Vp and Vp/Vs structure of the Hengill triple junction and geothermal area, Iceland, and the repeatability of tomographic inversion, Geophys. Res. Lett., 22, 1309-1312, 1995a.

Foulger, G.R., and D.R. Toomey, Structure and evolution of the Hengill-Grensdalur volcanic complex, Iceland; Geology, geophysics, and seismic tomography, J. geophys. Res., 94, 17,511-17,522, 1989.

Julian, B.R., A.D. Miller, and G.R. Foulger, Non-double-couple earthquake mechanisms at the Hengill-Grensdalur volcanic complex, southwest Iceland, Geophys. Res. Lett., 24, 743-746, 1997.

Marty, B., E. Gunnlaugsson, A. Jambon, N. Oskarsson, M. Ozima, F. Pineau, and P. Torssander, Gas Geochemistry of Geothermal Fluids, the Hengill Area, Southwest Rift-Zone of Iceland, Chem. Geol., 91, 207-225, 1991.

Miller, A.D., Seismic structure and earthquake focal mechanisms of the Hengill volcanic complex, SW Iceland, Ph. D. thesis, University of Durham, Durham, U. K., 1996.

Miller, A.D., B.R. Julian, and G.R. Foulger, Three-dimensional seismic structure and moment tensors of non-double-couple earthquakes at the Hengill-Grensdalur volcanic complex, Iceland, Geophys. J. Int., 133, 309-325, 1998.

Saemundsson, K., Hengill, geological map (bedrock), Orkustofunun, Hitaveita Reykjavikur, Landmaelingar Islands, 1995.

Sigmundsson, F., P. Einarsson, S.T. Rognvaldsson, G.R. Foulger, K.R. Hodgkinson, and G. Thorbergsson, The 1994-1995 seismicity and deformation at the Hengill triple junction, Iceland: Triggering of earthquakes by minor magma injection in a zone of horizontal shear stress, J. geophys. Res., 102, 15151-15161, 1997.

Toomey, D.R., and G.R. Foulger, Tomographic inversion of local earthquake data from the Hengill-Grensdalur central volcano complex, Iceland, J. geophys. Res., 94, 17497-17510, 1989.

Tronnes, R.G., Basaltic Melt Evolution of the Hengill Volcanic System, Sw Iceland, and Evidence for Clinopyroxene Assimilation in Primitive Tholeiitic Magmas, J. geophys. Res., 95, 15893-15910, 1990.

Holden, J.C. & P.R. Vogt,
EOS Trans. AGU, **56**,
573-580, 1977.

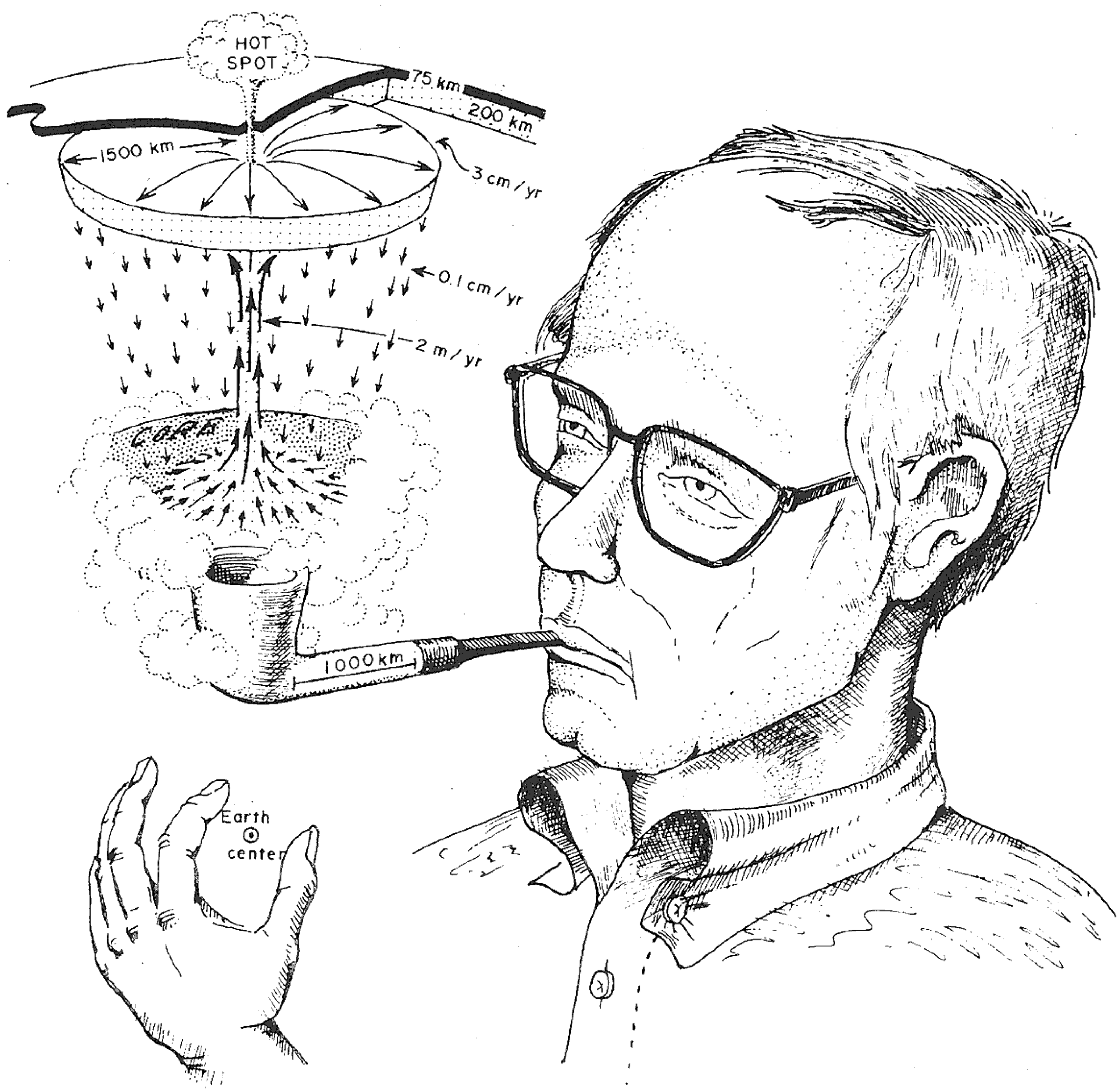


Fig. 1. Conception of the mantle plume theory, adapted liberally from W. J. Morgan (unpuffed data, 1977).

Graphic Solutions to Problems of Plumacy

John C. Holden and Peter R. Vogt

Preface

The mantle plume is just the youngest member of a big and colorful family of geological fads and fashions: diluvialisms and catastrophisms, earths expanding and contracting, global tectonics new and old. Some of these fads have become bandwagons rolling from theory to fact. Others are intellectual white elephants gathering library dust. We do not know yet how the mantle plume will fare; certainly it has not quite attracted the bandwagon that the new global tectonics did.

Since plumes are better hidden from observation than plates, it may take years to prove or disprove their existence. This is just as well—one cannot write a research proposal to prove that the earth is round or that the continents drift.

In this paper we hope to cut through the hullaballoo surrounding mantle plumes by offering a graphic commentary on the 'hot' topic. Any resemblance between persons or deities depicted here and those living or dead may or may not be coincidental. If kings and statesmen fall to the cartoonist's pen, why not scientists, their students, instruments, and Mother Earth herself?

Introduction

It was *Wilson* [1963] who first suggested that hot spots were fixed in the upper mantle and created aseismic ridges as crustal plates moved over them. This idea was expanded to include a mechanism that would also

Order of authors is alphabetical.

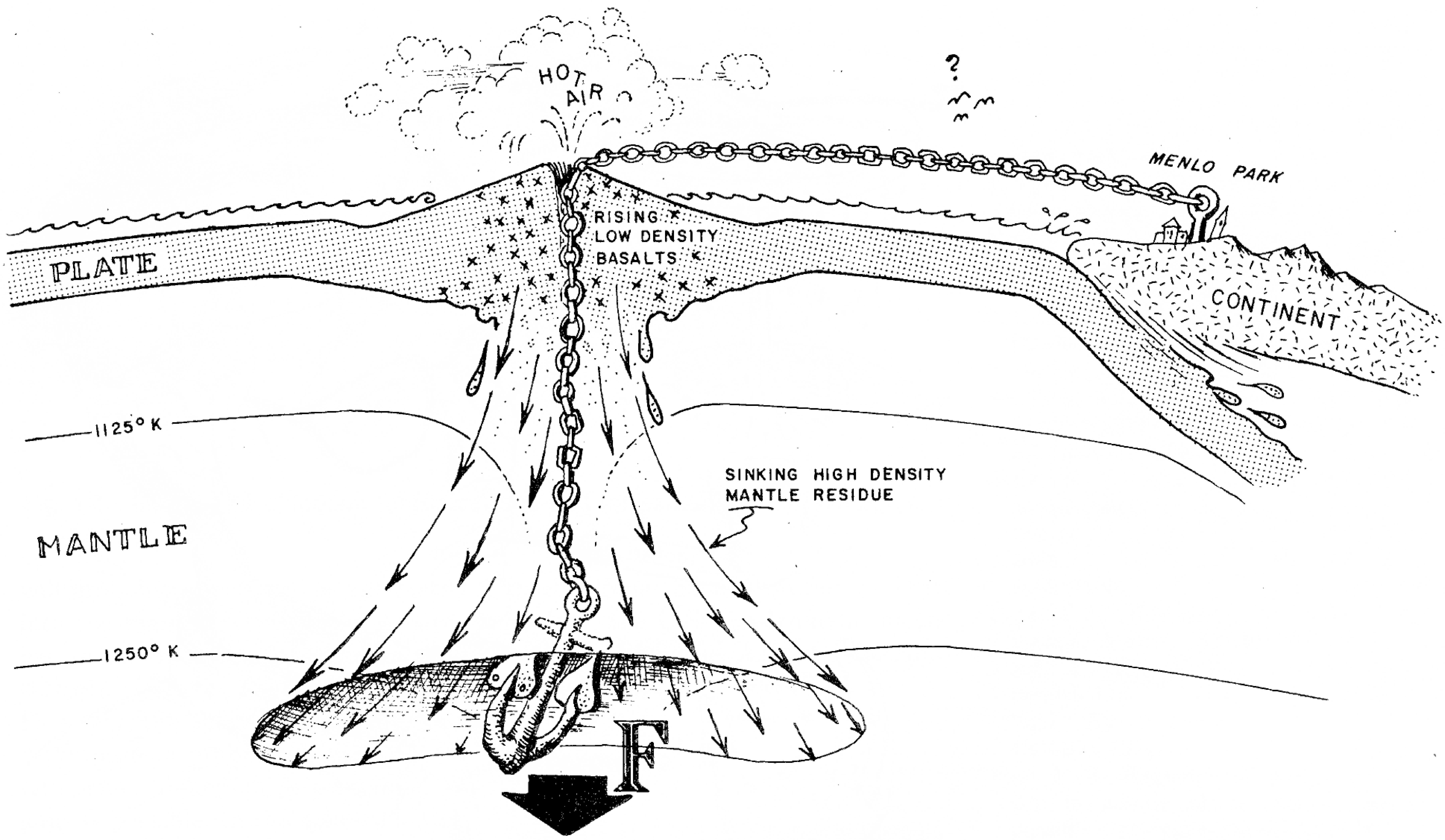


Fig. 2. Gravitational anchor theory, showing the origin of Hawaii [*Shaw and Jackson*, 1973]. According to this hypothesis, even the motion of California can be explained (although the motions of Californians remain as mysterious as ever).

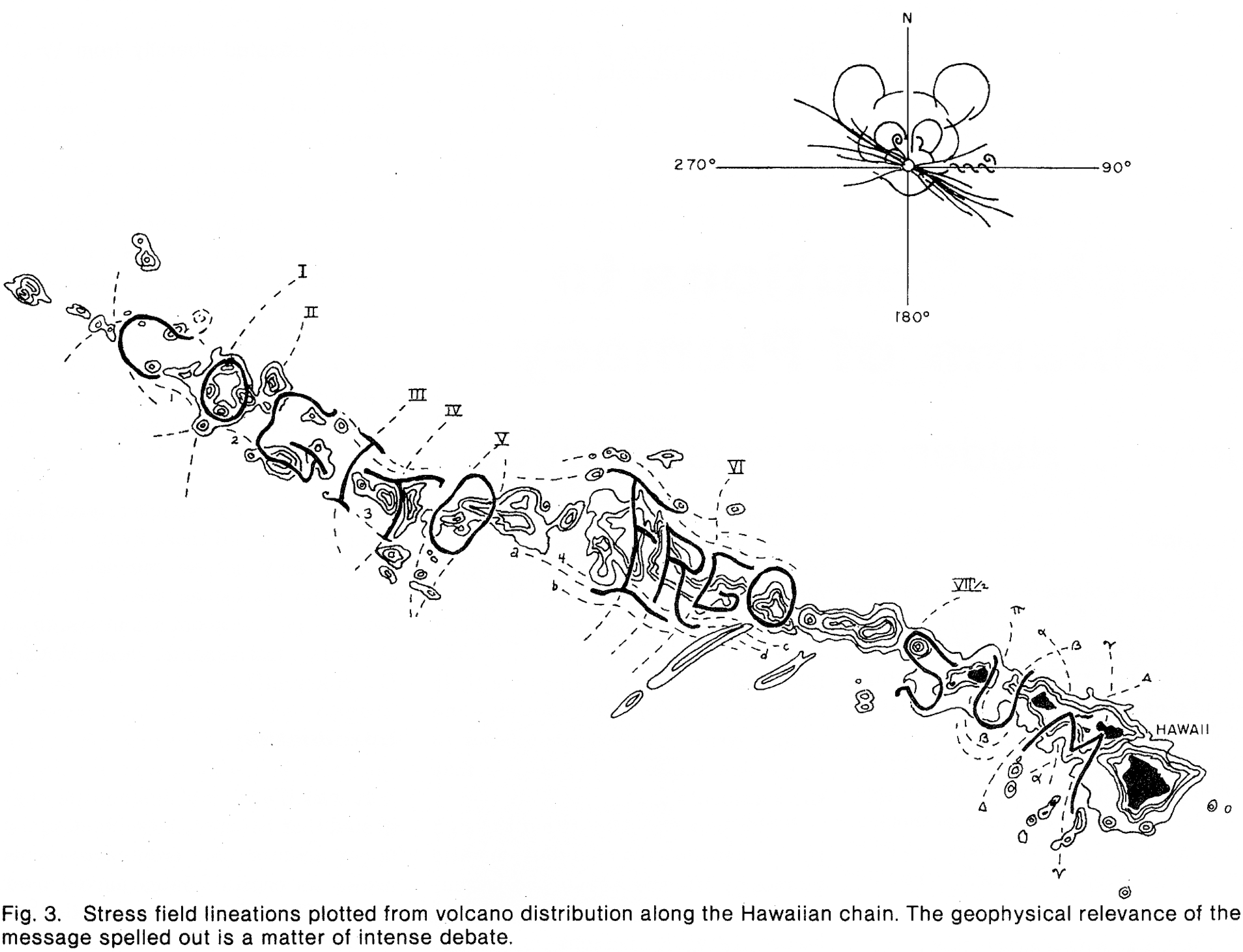


Fig. 3. Stress field lineations plotted from volcano distribution along the Hawaiian chain. The geophysical relevance of the message spelled out is a matter of intense debate.

account not only for hot spots but also for the causal forces of plate tectonics and continental drift. In short, it was proposed that ascending convection plumes exist in the deep mantle below active hot spot volcanism [*Morgan*, 1971, 1972]. Geometrically, these features are toroidal cells with narrow (200–300 km wide) vertical axes through which hot material is transferred from the lower to the higher regions in the mantle.

An entire science has developed around the study of plumes, albeit perhaps no more scientific than social, spiritual, or political science. If the concept is valid, then most first-order features of the earth's surface may be attributed directly or indirectly to plumes. We term this discipline 'plumacy,' its practioners 'plumatics' (also 'plume freaks'). Recognizing the parallels between religious and geological faiths, we also propose the term 'aplumatics' for those who do not believe that mantle plumes exist; we carry over the term 'agnostic' to apply to all those fainthearted earth scientists who refuse to debate the issue on grounds that the existence or nonexistence of mantle plumes cannot be proved since the terms are not defined. This position is untenable, since the definition and etymology of the word plume has been published in the geological literature [*Anderson*, 1975]. Because he is a little-known author (just one of the numerous Andersons in earth science) publishing in an obscure journal, it is worthwhile to reproduce his definition here.

> *Tozer* [1973] has objected to the use of the word 'plume' because of prior usage and connotations. However, the various definitions of 'plume' and its antecedents in French, Latin, and German seem to provide enough flexibility to describe the phenomenon, its implications, and its raison d'être on the one hand and its inventors, supporters, and detractors on the other: *Plume* (English, from French and Latin, pluma) — a feather, a long handsome feature, a token of honor or prowess; a prize, to pride or congratulate; to preen. *Plombe* (Germanic) — a plug. *Plombe* (Old English from West Germanic) — something especially desirable, as a good position. panache (French) — trail, stripe, swagger; fumée (French) — smoke, fumes, steam; fumer (verb) — to fume, to dung, to manure; plumitif (familiar) — scribbler, pen-pusher.

We leave the definition of hot spots (also called melting spots and melting

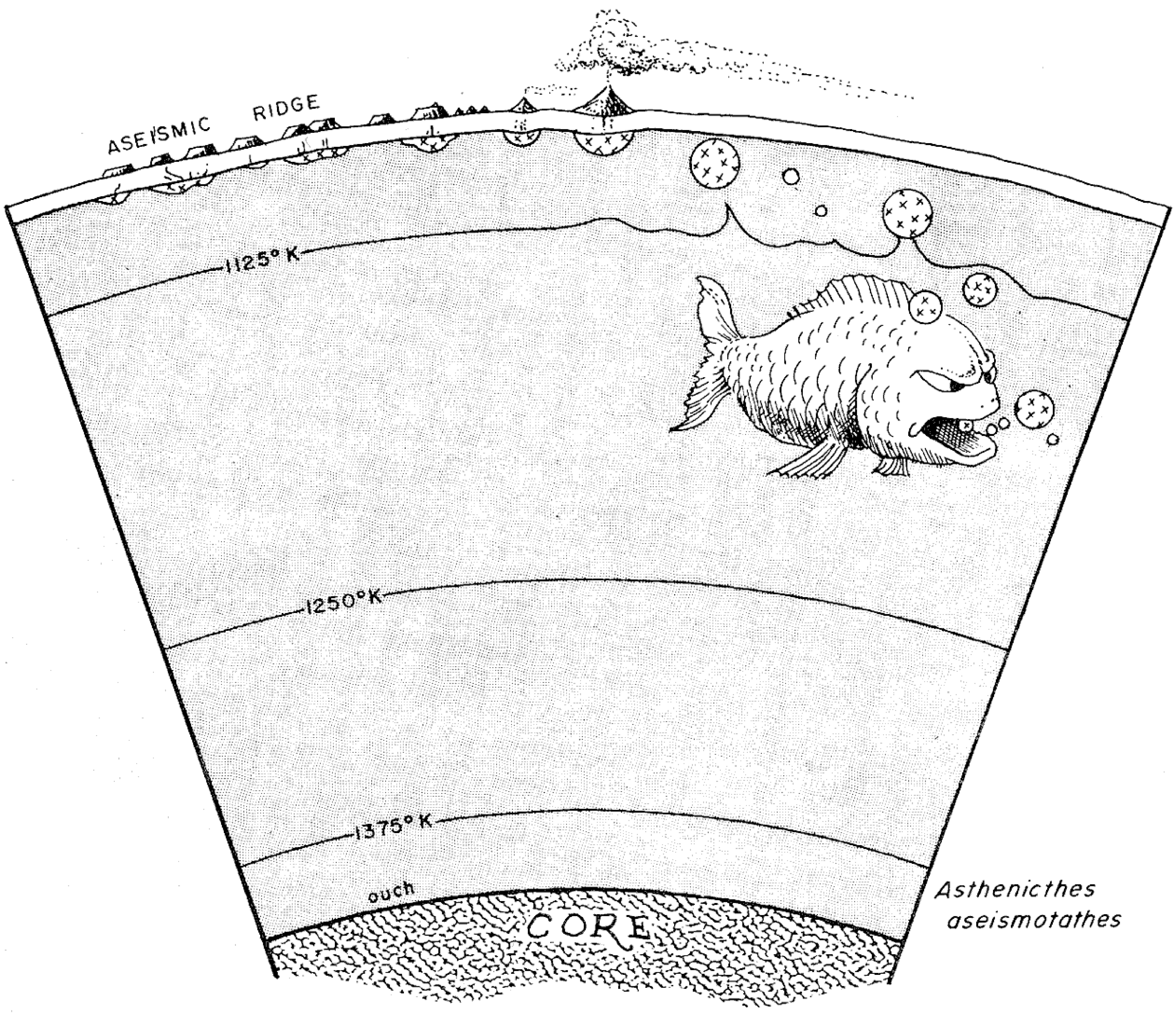


Fig. 4. Alternative to the mantle plume theory (based on an ancient Japanese legend).

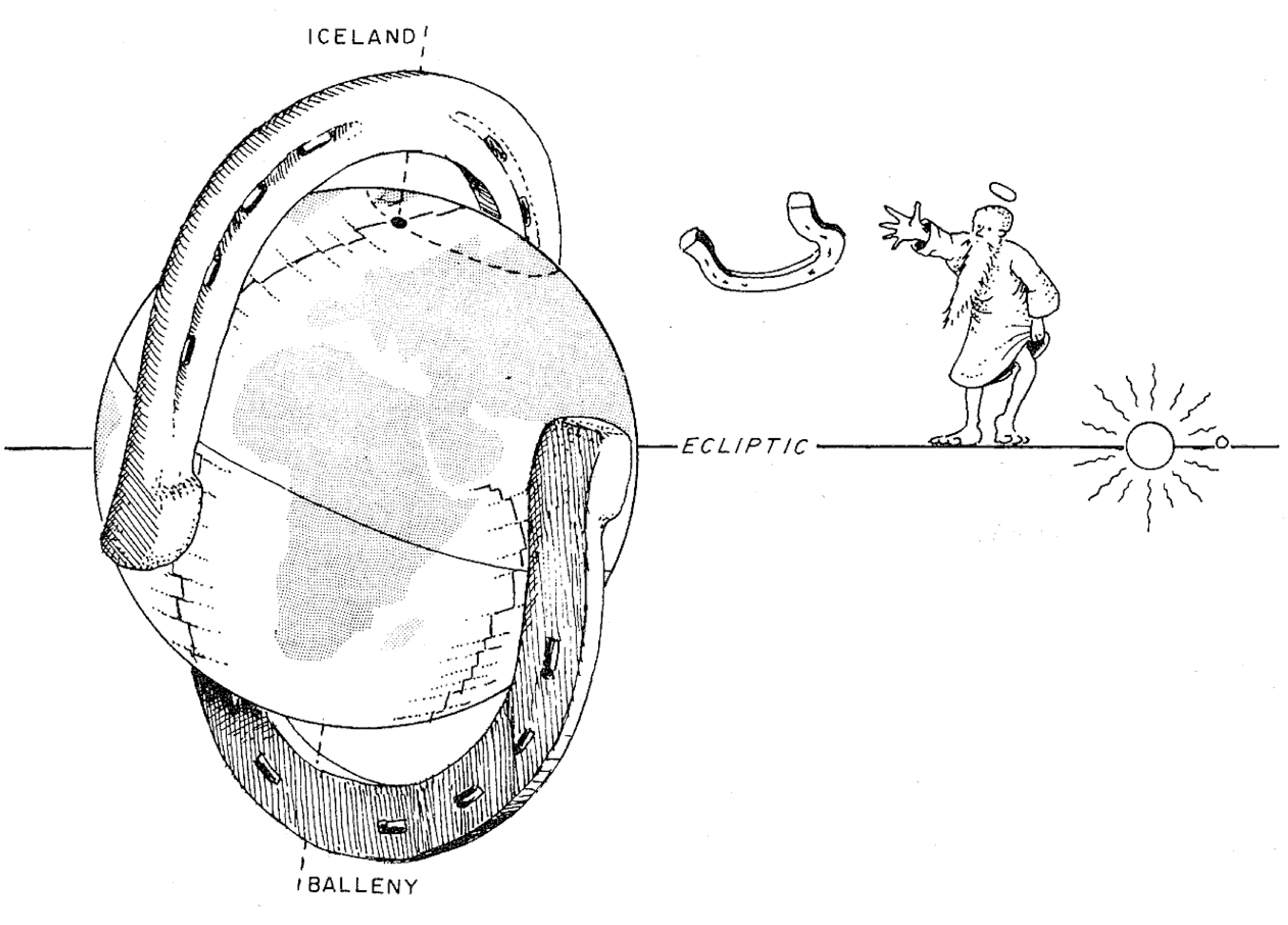


Fig. 5. Schematic of a theory for the origin of midoceanic rifts, hot spots, the solar system, creation, and God.

anomalies) as an exercise for the reader.

Plumes, Antiplumes, and Other Explanations for Hot Spots

Plumes are often invoked to explain the source of the force causing sea floor spreading and plate motion. Unfortunately, no airtight case has been made for the cause of the plumes themselves, and the original problem of where it all begins is not solved but merely pushed deeper into the earth's interior. Therefore we must in all fairness discuss not only mantle plumes but alternate theories put forth to explain hot spots.

One wonders what was being smoked when the plume concept was formed (Figure 1). It is a well-known dictum in geopolitics that for popular acceptance the terms one chooses are equally as important as the ideas themselves. Therefore when the plume concept was under construction, the stem of the plume was cleverly dubbed a pipe, which immediately brings to mind kimberlite pipes of mantle origin. . . Bingo, a winner! After all, it is much more propitious for material to move 'up the pipes' than to go 'down the tubes.' However, to suggest that the term pipe was picked only for its public relations value is not entirely fair. After all, when geophysicists conceptualize, they habitually use the stems of their pipes as a scale for relative proportions. So it is only logical that the stem of a plume should be called a pipe; Q.E.D.

A few years after the plume idea was out, *Shaw and Jackson* [1973] proposed a slight modification of it in their gravitational anchor theory (Figure 2). According to this scheme, dense crustal residues are sinking beneath Pacific hot spots at the eastern ends of the Hawaiian, Tuamoto, and Austral chains as low-density basaltic magmas are distilled out and up to form the spot on the hot spot. The geometry of this specialized convection cell is that of an upside-down plume, or antiplume as it were. Shaw and Jackson are absolutely correct in assuming that these anchors do not drive the plates but rather act as pinning points. We presume that the chain (not the volcanic chain) attached to the anchor (and nowhere discussed by the original authors) extends out of the orifice of the volcano. Where it goes after that is uncertain; perhaps it

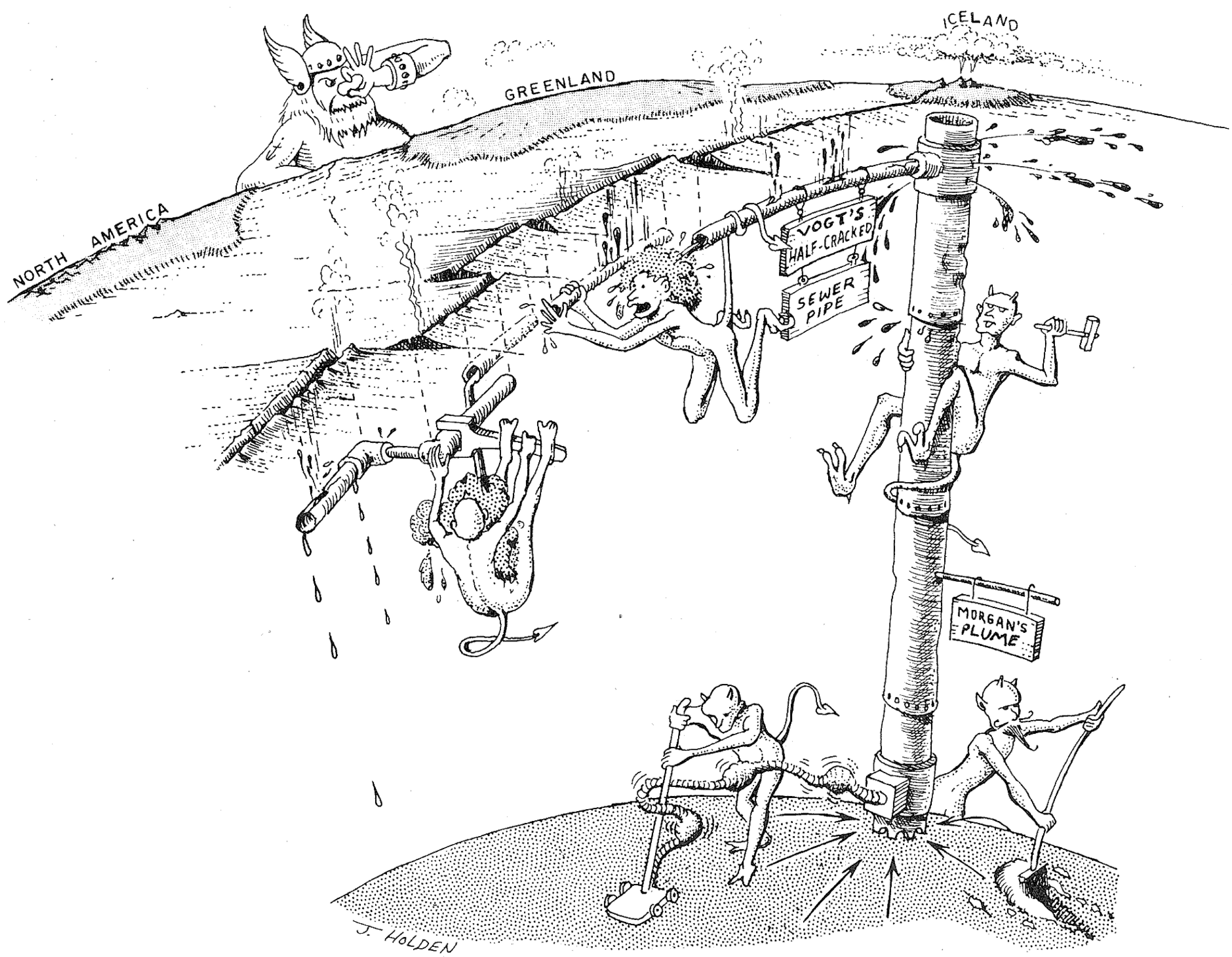


Fig. 6. Mantle plume materials transported by faulty plumbing system from the lower regions to the midoceanic ridge. (Devils not to scale.)

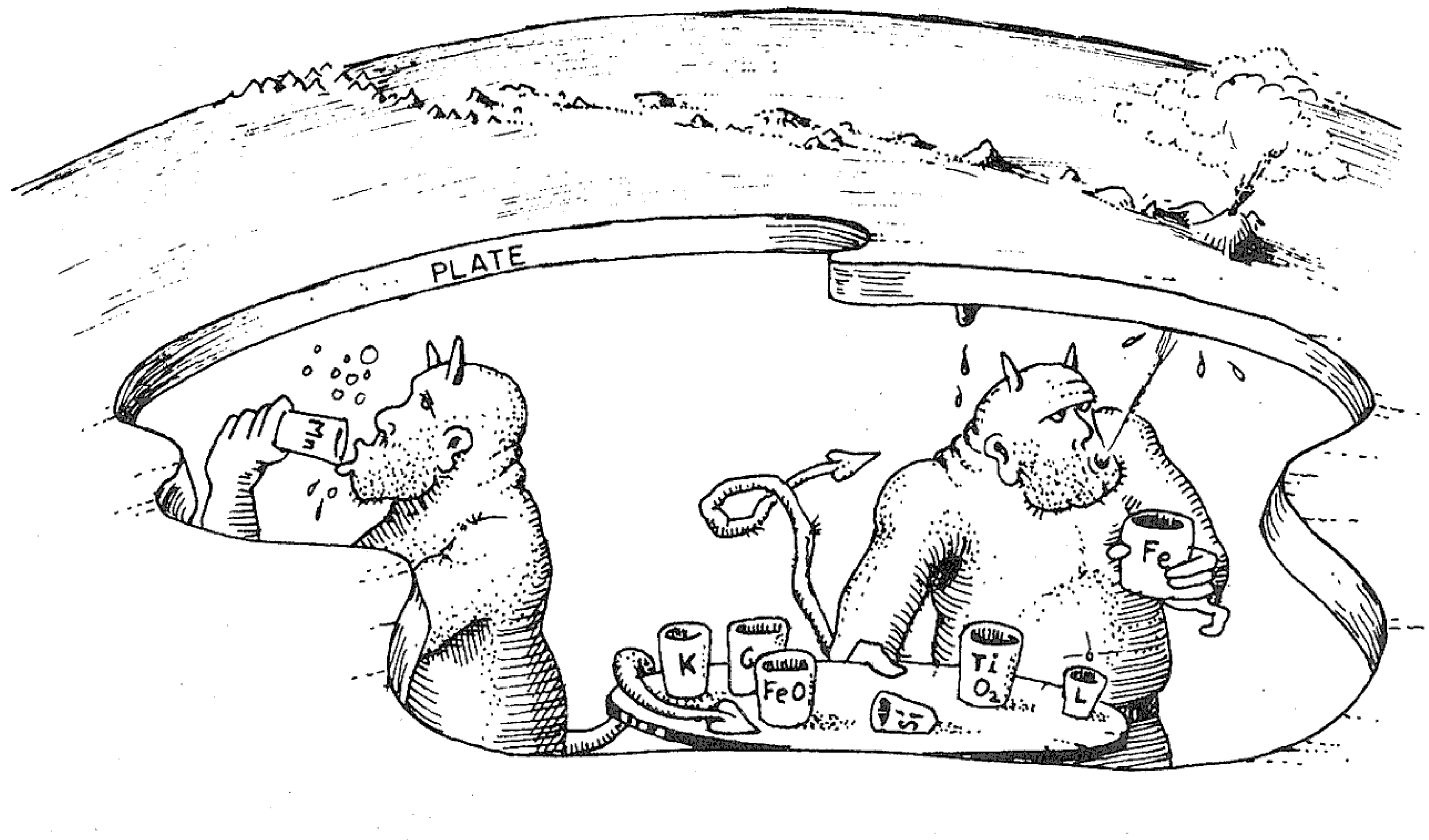


Fig. 7. Strange chemistry of ocean island tholeiites, hawaiites, balonites, and similar hot spot generated rocks, attributed to the culinary habits of X. Vulcan et al. (regurgitated material, in preparation, 1977).

is attached to the nearest continent, and if it does not drive the oceanic plate, it pulls the continent over it. Because this theory accounts for the large shield volcanoes at Hawaii and elsewhere, gravitational anchors are associated with an abundance of tephra-laden hot air that often tends to obfuscate a clear understanding of these features.

On occasions when the clouds do clear somewhat, some authors can identify stress fields in the Hawaiian chain (not the anchor chain) indicating the stress of the anchor [*Jackson and Shaw*, 1975]. They define two stress fields, a Polynesian and a Hawaiian field. We see that a third pattern and a reassessment of all three fields yields a remarkable phenomenon (Figure 3). Carefully plotting the three lineation sets actually spells out this fact, and in Latin, no less. We misinterpret these data to read, 'We think, therefore they exist.' The mouse diagram showing trend bearings about an imaginary center marks the overall trend of the Hawaiian chain (the volcanic chain, not the anchor chain).

Plumes, antiplumes, and propagating fractures are certainly not the only possible explanations for features such as the Hawaiian chain. Ancient legend has it that the island of Japan is situated atop a giant carp and that every time the beast shifts position Mount Fuji erupts. As most legends have some basis in fact, we propose that this creature also finds its home throughout the viscous asthenosphere (Figure 4). Could it be that as it swims, at a rate of only a few centimeters per year within the mantle, it leaves behind a buoyant trail of tholeiitic bubbles which rise ponderously to create aseismic ridges? We name this fish *Asthenicthes aseismotathes*, or the asthenospheric fish that makes aseismic ridges. No doubt there are some who would question our taxonomy and would want to call the species a form of crappie. Readers may find something fishy about this theory, but then there is at least something fishy about the other theories as well.

How plumes are oriented, orifice up or orifice down, awaits future adjudication. On the other hand, we can make some definite statements about the distributions of plumes. There are, for example, two plumes on the Arctic and Antarctic circles, namely, Iceland and Balleny Islands, respectively. If Balleny Islands are, in fact, a plume, as *Morgan* [1972] predicted, it is nearly perfectly antipodal to the Iceland plume [*Holden*, 1976*a*]. If these two hot spots are taken as midpoints of the two world rift systems, the rifts have an interesting relationship to each other, as shown in Figure 5. One supposes that this proves the athletic excellence of the Creator, for the game is certainly horseshoes, and He has scored two perfect ringers. It would seem that this particular game has been going on for at least 200 m.y. if the rift margins of Antarctica are any indication. This continent has been located at the south pole since Pangaea broke apart, and its rift margins are all close to the Antarctic Circle [*Holden*, 1976*b*]. Unfortunately, this only accounts for two plumes; we leave it up to the reader to devise explanations for the distribution of the remaining 120.

How Many Plumes?

Mantle plumes are in the midst of a population explosion that threatens to engulf the earth in a volcanic catastrophe [*Vogt*, 1972]. The facts speak eloquently for themselves—no need to consult the Club of Rome. In 1971 there were 20 plumes [*Morgan*, 1971, 1972]; in a mere half decade the population has risen to no less than 122 [*Burke and Wilson*, 1976]. Our extrapolations from these data show that there will be 1,000,000 hot spots by the year 2000. We hope someone proves that hot spots do not exist, before it is too late.

Cracked Sewer Pipes

If mantle material rises below Iceland, it must somehow spread out from the top (head) of the plume. Presumably, the flow occurs primarily in the asthenosphere below the plate. *Vogt* [1971, 1974] and *Schilling* [1973, 1975] have suggested that this flow is concentrated in the bidirectional pipe formed below the spreading axis as a result of extensive partial melting and lowered viscosity there (Figure 6). This slightly tilted 'cracked sewer pipe' flushes away the material rising in the stem of the vertical pipe.

The sewer pipe is cracked (or, more exactly, half-cracked like its author) in the sense that tholeiitic magmas must rise vertically to feed the constantly accreting oceanic crust. To further complicate matters, transform faults offsetting the spreading axis also offset the subaxial conduit, thus creating transform dams [*Vogt and Johnson*, 1975]. Despite all this faulty plumbing the conduit can do it, beHolden though it is to numerous mantle demons (Figure 6). Fluctuations in plume discharge down the cracked sewer pipes are thought to

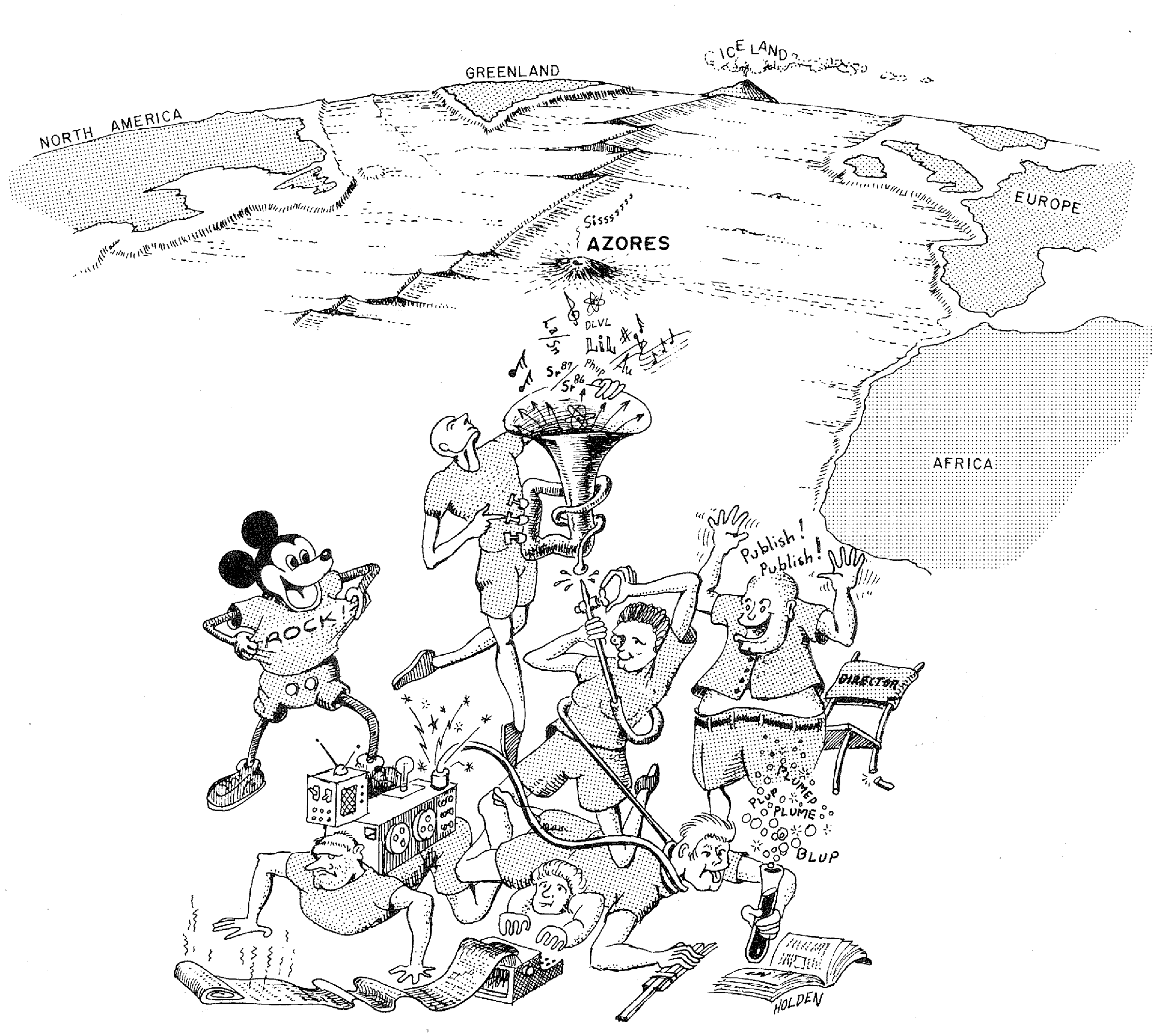


Fig. 8. Geochemical research on mantle plumes, as conducted at a modern university. The significance of the Azores, Iceland, and Mickey Mouse in this scheme is still under discussion.

leave V-shaped ridges imprinted on the ocean crust [*Vogt*, 1971]. Vogt is currently searching bathymetric charts to see whether there is a good spot for a P on it.

The extreme case of a fluctuating plume is the mantle blob [*Schilling*, 1975], a concept possibly suggested to Schilling by the behavior of a lava lamp. We expect future hot spot authors to embellish this already descriptive terminology with, for example, mantle drops and dabs and drips, mantle splats and burps and belches and spurts and. . .

Before leaving the intriguing though semiscatological subject of tectonic toiletimetry we offer an interesting historical note. The famous early geophysicist Jules Verne had his team descend the vertical pipe beneath Iceland in their Journey to the Center of the Earth and ascend through a volcano in the Mediterranean. This path no doubt accounts for the great difficulties they encountered, since mantle material rises at Iceland and sinks in the Mediterranean subduction zone. They were fighting against strong currents all the way. (Soon after this ordeal, Verne spent 80 days in a balloon floating around the world to recuperate.)

Plume Chemistry

It now seems that the final answers concerning the earth's largest features will be found by those dedicated research teams studying the rarest elements and smallest subdivisions of matter.

Hot spot basalts have long been known to differ from ocean floor basalts. Even beginning Geology 1 students could take some Icelandic basalts for granite, since some of them are. Sunken continental crust was once thought to exist at depth but has since dissolved into mantle. More recently [*Schilling*, 1973, 1975], systematic variations in some isotope ratios and LIL (large ionic lithophile) elements along the midocean ridge away from hot spots have suggested unique PHMP (primary hot mantle plume) chemistry distinct from the DLVL (depleted low-velocity layer). Although the various PHMP's differ among themselves in LIL's, such as

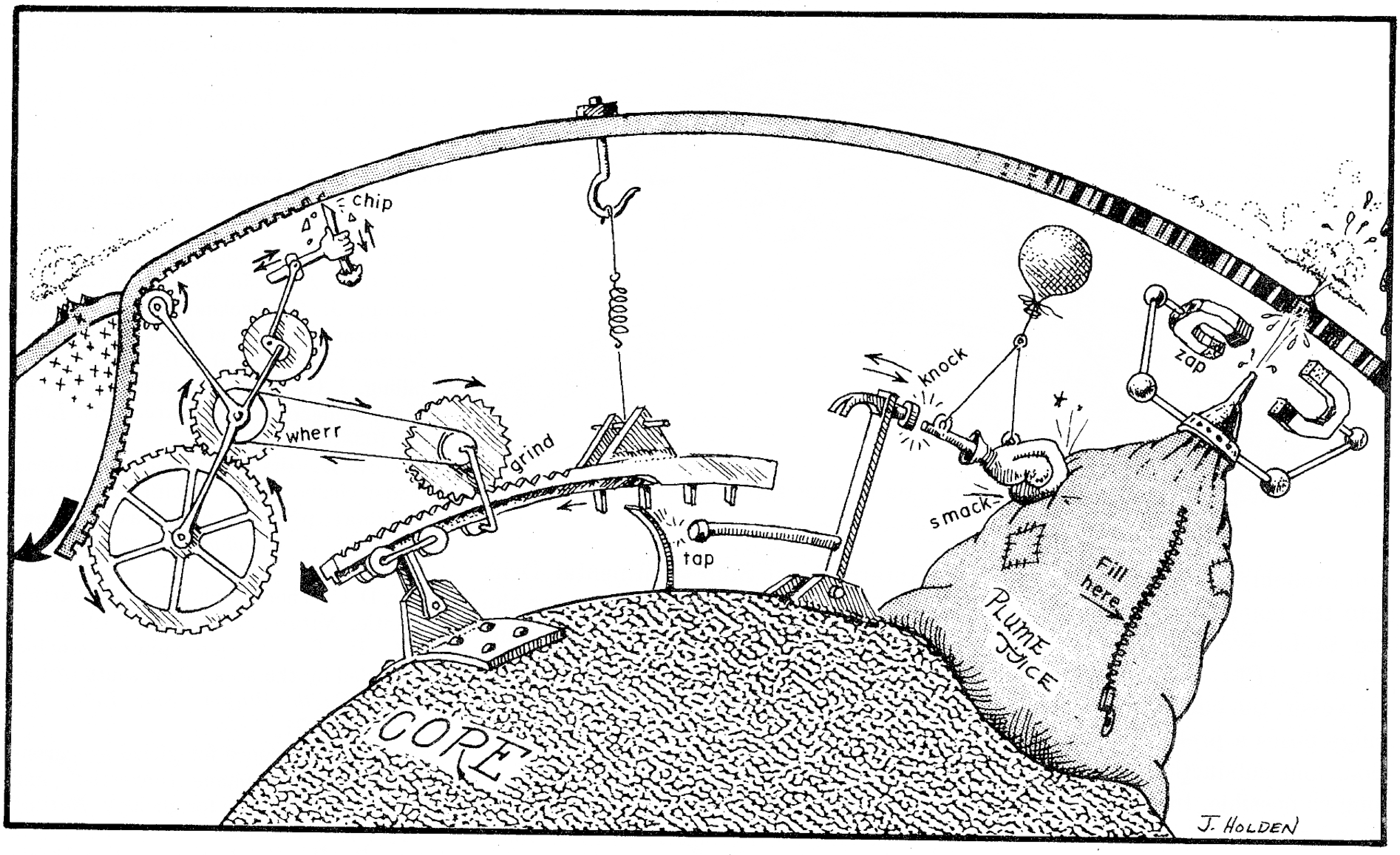


Fig. 9. Diagram hypothesizing the correlation between discharge of island arc and hot spot volcanoes. Mantle viscosity is assumed to be zero as a first approximation (with apologies to S. K. Runcorn).

La, K, P, and Ti, the DLVL always has fewer LIL's than the PHMP.

We see that hot spot basalts are really a GAS (geochemical alphameric soup) that seems diabolically difficult to understand, probably because it is the work of the UMD's (upper mantle demons; see Figure 7). The decoding of this GAS clearly requires elaborate technologies, such as mass spectrometers, neutron activators, eutecticized equilibrating quasi-partial melting fractionators, and multi-phased polyglazing computers. To operate this fancy gadgetry and produce significant results, a LAGS (large army of graduate students) is also required (Figure 8).

To make chemistry of ocean crust more accessible to the simpleminded (and penniless) layman, *Vogt and Johnson* [1973] have invented 'magnetic telechemistry.' In this modern version of water-witching, all that is needed is a $2,000,000 aircraft or a $15,000,000 research ship outfitted with a magnetometer. Iron-rich basalts associated with mantle plumes can be charted once the measurements are corrected for sunken submarines and schools of magnetic fish. The concentrations of other elements (gold!?) can be predicted accurately, at least to within a few orders of magnitude, over at least 0.1% of the ocean floors.

Global Synchronism

For many years now, dashed correlation lines have connected short, fat magnetic anomalies with tall, skinny magnetic anomalies and even with featureless magnetic plains. But such correlation is simply a correlary of the Geologic Correlation Axiom. According to this rule, any variable can be made to correlate with any other variable once the vertical and horizontal scales are suitably adjusted, the eyeball suitably trained, and the correlation lines suitably slanted to the author's prejudices.

Vogt [1972] has applied this axiom to show that hot spot volcanoes, magnetic reversals, dinosaur populations, the stock market, and the annual number of Norman Watkins papers all follow the same global rhythm. Although further proofs of global synchronism are really unnecessary, *Kennett and Thunell* [1975] have shown that volcanic activity along the world's island arcs has indeed fluctuated in sympathy with the hot spot discharge curve inferred by *Vogt* [1972]. But why should this be so? Why should volcanoes in the Marianas or the Caribbean 'know' what the Hawaiian volcanoes are doing? One answer is that mantle plumes speed up plate motions and thereby increase subduction rates and related volcanic activity. However, since many scientists still do not accept mantle plumes, we offer a yet more plausible mechanism in Figure 9. (To the reader who might question who would fill the plume juice bag, we would answer, 'Nitpicker!')

Logjam Tectonics

Having dwelt too long on the generation of aseismic ridges, we close by considering their destruction. Basalts deposited on continental crust will tend to be eroded off, along with some of the underlying intrusives. Aseismic ridges formed on ocean crust

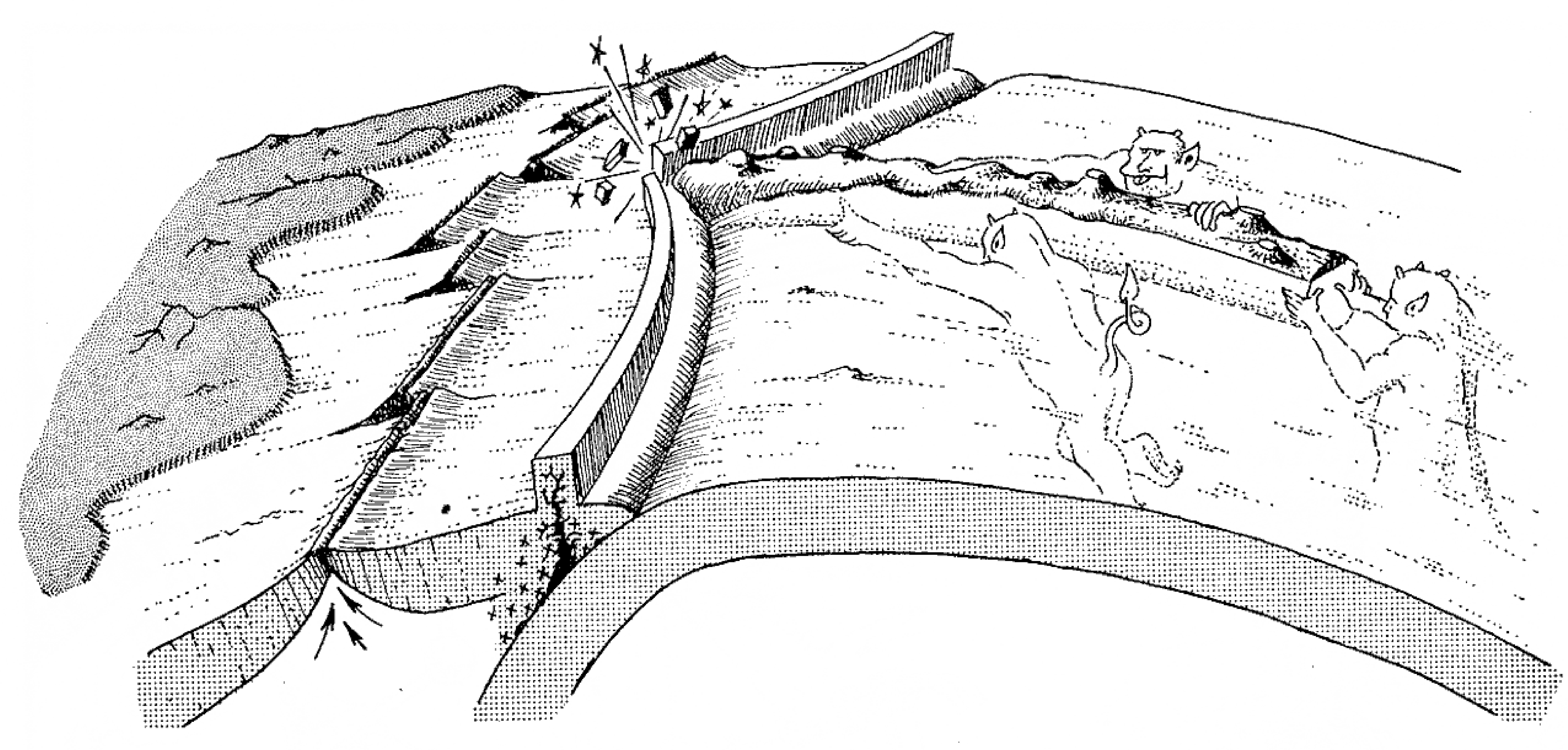


Fig. 10. Illustration of logjam tectonics (see text for explanation of symbols).

will probably eventually be subducted into the mantle (The Gospel According to Le Pichon, Francheteau, and Bonnin (*Plate Tectonics*): 7-3). However, the bulky, buoyant aseismic ridge poses a problem to plate digestion, and subduction is postponed as long as possible. In the meantime, the island arc and trench migrate toward the downgoing plate as a result of back-arc spreading. This migration is slowed or stopped where the ridge is being subducted, and (Eureka!) a cusp is formed [*Vogt*, 1973]. Isn't that cleaver? Figure 10 shows the battering ramifications of the pushy process postponing plate plunging.

The only other theory for island arc formation besides logjam tectonics is Ping-Pong ball tectonics. This theory holds that the earth is a giant Ping-Pong ball, its surface dented inward in numerous places to produce island arcs [*Frank*, 1968]. Frankly, we find any theory that likens the earth to a wet, dirty, dented Ping-Pong ball too ludicrous to debate.

Acknowledgments

The authors completed this paper while on sabbatical at the Plumatic Asylum, Lower Slobbovian Institute of Advanced Geoquackery. P.R.V. wishes to thank the anonymous reviewers for censoring the original manuscript and AGU copy editor Joan Welsh for humor above and beyond the call of duty. He also thanks the lampooned individuals and institutions not to press libel charges. This paper does not necessarily reflect the views of the Plumatic Asylum, the Institute of Geotectonic Redundancies, the International Stop Continental Drift Society, the U.S. Government, or the authors. Plumatic Asylum contribution 0000001.

References

Anderson, D., Chemical plumes in the mantle, *Bull. Geol. Soc. Amer.*, *86*, 1593–1600, 1975.

Burke, K. C., and J. T. Wilson, Hot spots on the earth's surface, *Sci. Amer.*, *235*, 46–57, 1976.

Frank, F. C., Curvature of island arcs, *Nature*, *220*, 363, 1968.

Holden, J. C., Present and past symmetry of rifts (abstract), *Eos Trans. AGU*, *57*, 89, 1976*a*.

Holden, J. C., Permian-Triassic continental configurations and the origin of the Gulf of Mexico: Comment, *Geology*, *4*, 324-325, 1976*b*.

Jackson, E. D., and H. R. Shaw, Stress fields in central portions of the Pacific plate: Delineated in time by linear volcanic chains, *J. Geophys. Res.*, *80*, 1861-1874, 1975.

Kennett, J. P., and R. C. Thunell, Global increase in Quaternary explosive volcanism, *Science*, *187*, 497-503, 1975.

Le Pichon, X., J. Francheteau, and J. Bonnin, *Plate Tectonics*, 300 pp., Elsevier, New York, 1973.

Morgan, W. J., Convection plumes in the lower mantle, *Nature*, *230*, 42–43, 1971.

Morgan, W. J., Deep mantle convection plumes and plate motions, *Amer. Ass. Petrol. Geol. Bull.*, *56*, 202-213, 1972.

Schilling, J. G., Iceland mantle plume: Geochemical study of Reykjanes Ridge, *Nature*, *242*, 565–571, 1973.

Schilling, J. G., Azores mantle blob: Rare-earth evidence, *Earth Planet. Sci. Lett.*, *25*, 103–115, 1975.

Shaw, H. R., and E. D. Jackson, Linear island chains in the Pacific: Results of thermal plumes or gravitational anchors?, *J. Geophys. Res.*, *78*, 8634–8652, 1973.

Tozer, D. C., Thermal plumes in the earth's mantle, *Nature*, *244*, 398–400, 1973.

Vogt, P. R., Asthenosphere motion recorded by the ocean floor south of Iceland, *Earth Planet. Sci. Lett.*, *13*, 153–160, 1971.

Vogt, P. R., Evidence for global synchronism in mantle plume convection, and possible significance for geology, *Nature*, *240*, 338–342, 1972.

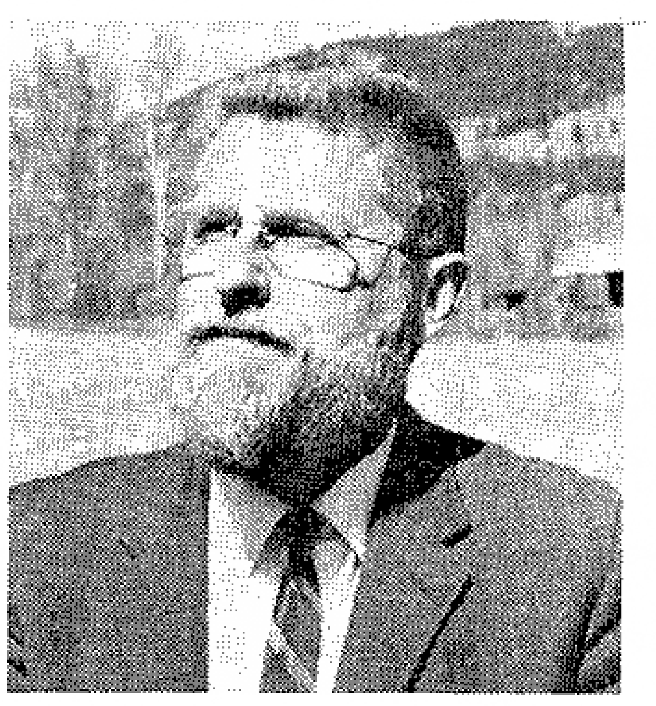
Vogt, P. R., Subduction and aseismic ridges, *Nature*, *241*, 189–191, 1973.

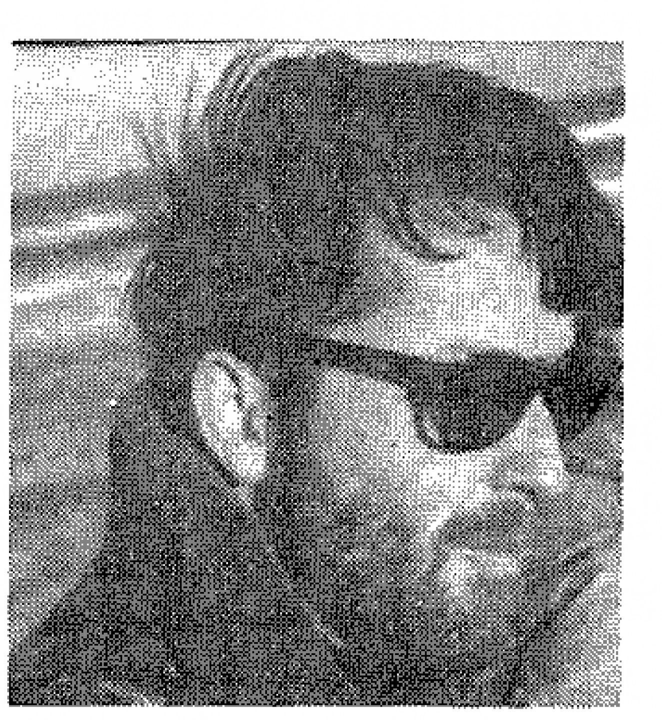
Vogt, P. R., The Iceland phenomenon: Imprints of a hot spot on the ocean crust, and implications for flow below the plates, in *Geodynamics of Iceland and the North Atlantic Area*, edited by L. Kristjansson, pp. 105–126, D. Reidel, Hingham, Mass., 1974.

Vogt, P. R., and G. H. Johnson, Magnetic telechemistry of oceanic crust?, *Nature*, *245*, 373–375, 1973.

Vogt, P. R., and G. H. Johnson, Transform faults and longitudinal flow below the midoceanic ridge, *J. Geophys. Res.*, *80*, 1399–1428, 1975.

Wilson, J. T., Continental drift, *Sci. Amer.*, *208*, 86–100, 1963.





John C. Holden received his training at San Diego State University (geology) and the University of California at Berkeley (paleontology) and has served over the past 16 years as a marine geologist and geophysicist intermittently for the U.S. Coast and Geodetic Survey, ESSA, and NOAA. He has also been employed in private industry as an exploration geologist and paleontologist and is now a consultant and scientific illustrator. To lighten his work load, he is Director of the Mazama Institute of Geotectonic Redundancies and President of the International Stop Continental Drift Society (ISCDS).

Peter Vogt holds all the usual academic credentials, including a valid Birth Certificate and a Third Degree, from recognized, well-meaning academic, mental, and corrective institutions. When not engaged in lively battles with the reviewers of his scientific manuscripts, he works at correlating various kinds of anomalies at the Naval Research Laboratory, Washington, D. C. Vogt is a Fellow of the Geological Society of America and a member of the ISCDS.

Words of wisdom

"It is a standing vice of geophysics not to argue against unpalatable facts and arguments but simply to ignore them and carry on as if they did not exist."

Prof. Peter Fellgett, FRS, Astronomy & Geophysics, 2003

"Of experiments intended to illustrate a preconceived truth and convince people of its validity: a most venomous thing in the making of sciences; for whoever has fixed on his cause, before he has Experimented, can hardly avoid fitting his Experiment to his cause, rather than the cause to the truth of the Experiment itself."

Thomas Spratt, "History of the Royal Society", 1667

"The traditional method of confronting the student not with the problem but with the finished solution means depriving him of all excitement, to shut off the creative impulse, to reduce the adventure of mankind to a dusty heap of theorems."

Arthur Koestler

"I cannot give any scientist of any age better advice than this: the intensity of the conviction that a hypothesis is true has no bearing on whether it is true or not. The importance of the strength of our conviction is only to provide a proportionally strong incentive to find out if the hypothesis will stand up to critical examination."

Sir Peter Medawar, "Advice to a Young Scientist", 1979

"It is all too easy to derive endless strings of interesting-looking but untrue or irrelevant formulae instead of checking the validity of the initial premises."

John Ziman, "Reliable Knowledge", 1978, p. 14

"...highly speculative, or boldly generalized theories are easily formulated, and take hold of the imagination of scientist and layman alike. Such theories may acquire widespread authority, not because they are well founded and reliable but because they have no competition from other less consensual sources of knowledge or insight. Whether or not it is eventually validated by overwhelmingly convincing evidence the 'scientific picture' presented by this sort of theory is inevitably schematic and oversimplified. The danger is that its limitations will not be adequately recognized, and that it will be extrapolated recklessly into an all-embracing dogma."

John Ziman, "Reliable Knowledge", 1978, pp. 91-92

"The voluminous literature on hypothetical plumes is notable for its ingenuity in the near-total absence of constraints."

Warren Hamilton, Precamb. Res., 1998

"When anybody contradicted Einstein he thought it over, and if he was found wrong he was delighted, because he felt that he had escaped from an error, and that now he knew better than before."

Otto Robert Frisch, on Einstein

"It was a reaction from the old idea of protoplasm, a name which was a mere repository of ignorance."

J.B.S. Haldane, "Perspectives in Biochemistry", 1938

"What is known for certain is dull. I rarely plan my research; it plans me."

Max Perutz

"It takes many years of training to ignore the obvious."

The Economist on "Theories of Economic Growth"

"Whether true or false, others must judge; for the firmest conviction of the truth of a doctrine by its author, seems, alas, not to be the slightest guarantee of truth."

Charles Darwin, letter to Lyell, 25th June, 1858

"In fact, no opinion should be held with fervour. No-one holds with fervour that 7 x 8 = 56, because it is known that this is the case. Fervour is necessary only in commending an opinion which is doubtful or demonstrably false."

Voltaire, quoted by Bertrand Russell

"Great God, how can we possibly be always right and the others always wrong?"

Montesquieu, Cahiers

"We see that many assumptions used in previous hypotheses can be discarded as unnecessary. ...there is no need to locate the source of plumes in the lower mantle."

Richter & Parsons, 1975

"Finding the world would not accommodate to his theory, he wisely determined to accommodate the theory to the world."

Washington Irving

"Every dogma must have its day."

H.G.Wells

"Convictions are more dangerous enemies of truth than lies."

Nietzsche

"As soon as I hear 'everybody knows' I start asking 'does everybody know this, and how do they know it?'"

Dave Jackson, from J. Fischman, "Falling into the gap", Discover, 58-63, October, 1992

"There is something fascinating about science. One gets such wholesale returns of conjecture out of such trifling investment of fact."

Mark Twain, "Life on the Mississippi", 1883

"Words, as is well known, are the foes of reality."

Joseph Conrad, "Under Western Eyes", 1911

List of Abstracts

Citing these abstracts: The approved citation style for these abstracts is illustrated by this example:

Anderson, D.L., Plate Tectonics: The General Theory, abstract in The Hotspot Handbook, Proceedings of Penrose Conference Plume IV: Beyond the Plume Hypothesis, Hveragerdi, Iceland, August 2003.

Don L. Anderson, California Institute of Technology, USA
What is a plume?
Plate Tectonics: The General Theory

Ayalew Dereje, Addis Ababa University, Ethiopia
Evidence for intermediate composition in bimodal basalt-rhyolite large igneous province

Ken Bailey, Univ. Bristol, UK
Tristan volcano complex: oceanic end-point of a major African lineament

Tiffany Barry, Cardiff University, UK
Cenozoic intraplate volcanism in Mongolia; if not a mantle plume then what?

Erin Beutel, College of Charleston, USA
Lithospheric stress state responsible for hotspots at ridge-transform intersections?

Axel Bjornsson, University of Akureyri, Iceland
In search for an Iceland plume: Long period magnetotellurics

Enrico Bonatti, Istituto di Geologia Marina-CNR, Italy
Is the Mid-Atlantic Ridge becoming hotter with time?

Francoise Chalot-Prat, Nancy University, France
Volcanism synchronous with mantle exhumation at the axial zone of a fossil slow spreading ocean: evidences from the Chenaillet ophiolite (Franco-Italian Alps)

Richard Chamberlin, New Mexico Bureau of Geology & Mineral Resources, USA
Oligocene calderas, mafic lavas and radiating mafic dikes of the Socorro-Magdalena magmatic system, Rio Grande Rift, New Mexico: surface expression of a miniplume?

Robert Christiansen, U.S. Geological Survey, USA
Structural control and plate-tectonic origin of the Yellowstone melting anomaly

Corrado Cigolini, University of Torino, Italy
The search for a primitive magma at Mount Vesuvius: possible role of a MORB-derived picrite in the genesis of Vesuvian magmas

Marc Davies, Open University, UK
The Origin of High-Ti Picrites from the Ethiopian Flood Basalt Province

Don DePaolo, University of California at Berkeley, USA
Geochemical structure of the Hawaiian plume: Results from the Hawaii Scientific Drilling Project

Henry Dick, Woods Hole Oceanographic Institute, USA
How much heterogeneity in the mantle MORB source?

Carlo Doglioni, Università La Sapienza, Italy
On the westward drift of the lithosphere

Adam Dziewonski, Harvard University
Global seismic tomography:What we really can say and what we make up

Wolf Elston, University of New Mexico, USA
The Proterozoic Bushveld complex, South Africa: Plume, astrobleme or both?

Zuzana Fekiacova, Universität Mainz, Germany
Tertiary Eifel volcanism – intraplate mantle plume or extension-related activity?

Carol Finn, U.S. Geological Survey, USA
Definition of a Cenozoic alkaline magmatic province in the southwest Pacific without rift or plume origin

Godfrey Fitton, University of Edinburgh, UK
A plume origin for the Ontong Java plateau?

Martin Flower, University of Illinois, USA
Collision-induced mantle flow during Tethyan closure: a link between magmatism, lithosphere 'escape', and arc-trench rollback?

Gillian R. Foulger, University of Durham, UK
An alternative model for Iceland & the North Atlantic Igneous Province
On the apparent eastward migration of the spreading ridge in Iceland
The Emperor and Hawaiian volcanic chains

Fred Frey, MIT, USA
The Kerguelen Plume: What We Have Learned From ~120 Myr of Volcanism

Geist Dennis, University of Idaho
Perturbations to the Galapagos hotspot due to interactions with the Galapagos spreading center

Steven Golden, Johann Wolfgang Goethe-Universität, Germany
In search for an Iceland plume: Long period magnetotellurics

David Green, Australian National University, Australia
Primary magmas at mid-ocean ridges, 'hot-spots'and other intraplate settings: constraints on mantle potential temperatures

Gudmundur Gudfinsson, Carnegie Institution of Washington, USA
Contrasting origins of the most magnesian glasses from Iceland and Hawaii

Giuseppe Guzzetta, Università di Napoli "Federico II", Italy
Global departure from equilibrium in a self-gravitating system and global tectonics
Convection in a self-gravitating system

Warren Hamilton, Colorado School of Mines, USA
An alternative Venus – plume-free planet preserves pre-3.9 Ga accretionary surface

Karen Harpp, Colgate University, USA
Alternative mechanisms for volcanic activity in hotspot-ridge systems: The northern Galapagos province

Anne M. Hofmeister, Washington University, Missouri, USA
Evidence for layered mantle convection: implications for lower mantle plumes

Lirim Hoxha, Albanian Geological Survey, Albania
A schematic comparison between Albanian ophiolites with idealized ophiolite sequence, Penrose conference

Gregory Huffman, Laurentian University, Canada
Variations in the trace-element systematics of the mafic rocks from Archean Belleterre-Angliers Greenstone Belt, SE Superior Province, Canada: A product of contamination, source variation, or both?

Phillip D. Ihinger, Univ. Wisconsin, USA
Plume magmatism and mantle convection: Revising the standard model

Sveinn P. Jakobsson, Icelandic Institute of Natural History, Iceland
Volcanic systems and segmentation of the plate boundary in SW-Iceland

Kevin Johnson, Bishop Museum and University of Hawaii
Temporal variation of Hawaiian plume composition: Evidence from Hana ridge (submarine Haleakala volcano), Hawaii

Bruce R. Julian, U.S. Geological Survey, USA
What can seismology say about hot spots?

Donna Jurdy, Northwestern University, USA
Upwellings on Venus: Evidence from coronae and craters

Scott King, Purdue University, USA
Edge driven convection and Iceland

Vlad Manea, Universidad Nacional Autonoma de Mexico, Mexico
Mantle wedge flow and thermal models for the central Mexican subduction zone

Jose Mangas, Universidad de las Palmas de Gran Canaria, Spain
Magmatic processes in the oceanic lithosphere: characterization of the ultramafic and mafic materials from the Holocene volcanic centers of Bandama and La Caldera de Pinos de Gáldar (Gran Canaria, Canary Islands)

Greg McHone, University of Connecticut, USA
Volcanic features of the central Atlantic ocean: Tectonic and magmatic models

Jean-Paul Montagner, Institut de Physique du Globe, France
Plume-lithosphere interactions: Cases of Afar (Africa), and Pacific hotspots

Raffaella Montelli, Princeton University, USA
Finite frequency tomography reveals a variety of plumes in the mantle

James H. Natland, University of Miami, USA
What really happened in the Pacific?
What's going on at Iceland?

Yaoling Niu, University of Houston, USA
"Plume-ridge interactions" as a consequence of ridge suction

Amos Nur, Stanford University, USA
What's driving what?

John O'Connor, Christian-Albrechts University, Germany
Distinguishing local from deep sources using high-resolution age-mapping of oceanic-hotspot volcanism?

Mike O'Hara, Cardiff University, UK
Mantle plumes: fertile? fecund? phantasmagorical? or simply fantastic? PIMMs anyone?

Angelo Peccerillo, University of Perugia, Italy
Geochemical and isotopic variability of plio-quaternary magmatism in italy : plume vs. shallow mantle processes

Brian Pope, Saint Louis University, USA
Is hot spot magmatism, like Hawaii, coming from shallow mantle

Dean Presnall, University of Texas & Carnegie Institution of Washington, USA
Petrological Constraints on Potential Temperature

Hannah L. Redmond, Purdue University, USA
Tharsis Rise, Mars: Is there room for a plume?

Will Sager, Texas A&M University, USA
Tectonic evolution of Shatsky Rise: A plateau formed by a plume head or not?

Kamal Sharma, Government Postgraduate College, India
Malani Magmatism of Northwestern Indian Shield: Implications of Mantle Plume?

Hetu C. Sheth, Indian Institute of Technology, India
The Deccan beyond the plume hypothesis

Olgeir Sigmarsson, Universite Blaise Pascal, France & University of Iceland
Geographical variations of mantle source fertility beneath Iceland

John Sinton, University of Hawaii, USA
Chemical Variations and Melting Systematics along the Western Galápagos Spreading Center, 90.5° - 98°W

Yvonne Smit, Université Blaise Pascal, France
Dynamics of the Iceland plume: Recycling the Iapetus ocean?

Alan Smith, CIE-UNAM, Mexico
The Fate of Subducted Oceanic Crust and the Sources of Intraplate Volcanism
The Regular Distribution of Intraplate Volcanism in the Pacific Basin

Suzanne Smrekar, Jet Propulsion Laboratory, USA
Venus as a mantle plume laboratory

Carol Stein, University of Illinois, USA
Spots yes, hot barely or not

Moti Stein, Geological Survey of Israel, Israel
The size and fate of the Pan-African plume mantle

Seth Stein, Northwestern University
Spots yes, hot barely or not

Ellen R. Stofan, Proxemy Research, USA
Morphology and distribution of hotspots on Venus

Reidar G. Trønnes, Nordic Volcanological Institute, Iceland
Mantle source composition, melting regime and mantle flow in the NE Atlantic

Peter R. Vogt, Naval Research Laboratory, USA
Sea-floor basement morphology: Distinguishing hotspot effects from plate tectonic effects - Examples from Iceland and the Azores

Richard Walker, University of Maryland College Park, USA
Isotopic detection of possible core-mantle interactions in plume sources: Rules of engagement

Phil Wannamaker, Univ. Utah/EGI, USA
Upper mantle physical state and lower crustal igneous input: A test of current models with data from the U.S. Great Basin

Dayanthie Weeraratne, Brown University
An alternative model for the origin of non-hotspot intraplate volcanism in the Pacific

Marge Wilson, University of Leeds, UK
Sea-floor spreading and deformation processes in the South Atlantic Ocean: An evaluation of the role of mantle hotspots
The geodynamic setting of Tertiary-Quaternary intra-plate magmatism in Europe: The role of asthenospheric diapirs or mantle "hot fingers"

Jerry Winterer, Scripps Institution of Oceanography, USA
Seamount chains result from episodic changes in in-plate stress that open cracks through the lithosphere and permit magma ascent : they do not require plumes

Donald Wright, Memorial University of Newfoundland, Canada
Geology, structure, and source of the Kikkertavak anorthosite, northern Labrador, Canada

Gezahegn Yirgu, Addis Ababa University, Ethiopia
Lithospheric control on silicic magma generation associated with the Ethiopian flood basalt province