

# PLATES AND PLUMES

*A Celebration of the Contributions of W. Jason Morgan  
to the Ongoing Revolution in Earth Dynamics*

DEPARTMENT OF GEOSCIENCES

Princeton University

October 10—11, 2003

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For me, in addition to being a leading scientist in hotspot theory, he is a good friend, and he has inspired me as well as many others to continue working in the field of hotspots. — Roger Hekinian

# AGENDA

## **THURSDAY EVENING, OCTOBER 9:**

Registration and setup of posters

Buffet dinner in Guyot Great Hall (Department of Geosciences)

## **FRIDAY, OCTOBER 10:**

Morning Session (Chaired by Christine Powell) - McDonnell A02:

7:30 Continental breakfast - Brush Gallery, McDonnell Hall

8:25 Welcome by Department of Geosciences Chair, F. Anthony Dahlen

8:30 Welcome address by Shirley M. Tilghman, President of Princeton University

8:45 – 9:30 Jason Phipps Morgan, GEOMAR, Kiel, Germany

“A retrospective on the scientific contributions of W. Jason Morgan”

9:30 – 10:15 Xavier Le Pichon, Géologie, École Normal Supérieure, Paris, France

“Asymmetry in elastic properties and the evolution of large faults”

10:15 – 11:00 Claude J. Allègre, Institut de Physique du Globe, Paris, France

“The chemical composition of the Earth”

11:00 – 12:00 Coffee and posters - Guyot Great Hall

12:00 – 1:00 Buffet lunch - Fine Hall Lawn

Afternoon Session (Chaired by John Chen) - McDonnell Hall A02:

1:00 – 1:45 Kurt Feigl, Toulouse, France

“Trade-offs between tropospheric artifacts and deformation signals in microwave geodetic measurements, or how W. Jason Morgan helped youngsters in the GPS and SAR business avoid another ‘Palmdale Soufflé’”

1:45 – 2:30 Thomas S. James, Geological Survey Canada, Sidney, BC, Canada

“Space geodesy, absolute gravimetry, and crustal deformation”

2:30 – 3:15 Henry J. Dick, Woods Hole Oceanographic Institution, Woods Hole, MA

“Ultra-slow spreading: a new class of ocean ridge”

3:15 – 4:00 Coffee break - Brush Gallery, McDonnell Hall

4:00 – 4:45 Donald W. Forsyth, Brown University, Providence, RI

“Intraplate volcanic ridges, seamount chains and the early evolution of the Pacific lithosphere”

4:45 – 7:30 Posters and informal discussions - Guyot Great Hall

7:30 Buffet Dinner (Master of Ceremonies: Lincoln Hollister) - Fine Hall Lawn

## **SATURDAY, OCTOBER 11:**

**Morning Session (Chaired by Richard Hey) - McDonnell Hall A02:**

7:30 Continental breakfast - Brush Gallery, McDonnell Hall

8:30 – 9:15 Richard M. Allen, University of Wisconsin, Madison, WI

“Mantle structure and flow beneath the Iceland hotspot”

9:15 – 10:00 Dan P. McKenzie, Bullard Laboratories, Cambridge, UK

“The thermal and chemical structure of plumes”

10:00 – 10:45 Albrecht W. Hofmann, Max-Planck Institut für Chemie, Mainz, Germany

“Anatomy of the Hawaiian plume”

10:45 – 11:15 Coffee break - Brush Gallery, McDonnell Hall

11:15 – 12:00 Paul R. Renne, Berkeley Geochronology Center, Berkeley, CA

“Mantle plumes, flood basalts, and mass extinctions”

12:00 – 1:00 Buffet lunch - Fine Hall Lawn

**Afternoon Session (Chaired by Anne Trehu) - McDonnell A02:**

1:00 – 1:45 Christopher L. Andronicos, University of Texas, El Paso, TX

“A North American arc perspective on the making of continents”

1:45 – 2:30 Christopher Beaumont, Dalhousie University, Halifax, Nova Scotia, Canada

“Crustal channel flows: an explanation for Himalayan-Tibetan tectonics?”

2:30 – 3:15 Paul E. Tapponnier, Institut de Physique du Globe, Paris, France

“Continental collision: hidden plate tectonics”

3:15 – 6:30 Coffee and posters - Guyot Great Hall

7:30 Reception and banquet (Master of Ceremonies: Gregory van der Vink) - Genomics Center Atrium

Despite Jason's global fame, most people in Princeton did not know about him. During the 1970s, more people in town knew the Morgan dachshund “Sneakers” than knew Jason. — Ken Deffeyes

# BIOGRAPHY OF W. JASON MORGAN



*Photo by Karin Sigloch*

## Passages About W. Jason Morgan from "Annals of the Former World,"

*by John McPhee (Farrar, Straus & Giroux, 1998)*

Morgan can fairly be described as an office geologist who spends his working year indoors, and he is a figure of first importance in the history of the science. In 1968, at the age of thirty-two, he published one of the last of the primal papers that, taken together, constituted the plate-tectonics revolution. Morgan had been trained as a physicist, and his Ph.D. thesis was an application of celestial mechanics in a search for fluctuations in the gravitational constant. Only as a post-doctoral fellow was he drawn into geology, and assigned to deal with data on gravity anomalies in the Puerto Rico Trench. Fortunately, he was assigned as well an office that he shared for two years with Fred Vine, the young English geologist who, with his Cambridge colleague Drummond Matthews, had discovered the bilateral symmetry of the spreading ocean floor. This insight was fundamental to the revolutionary theory then developing, and sharing that office with Fred Vine drew Morgan into the subject — as he puts it — “with a bang.” A paper written by H.W. Menard caused him to begin musing on his own about great faults and fracture zones, and how they might relate to theorems on the geometry of spheres. No one had any idea how the world’s great faults — like, say, the San Andreas and the Queen Charlotte faults — might relate to one another in a system, let alone how the

system might figure in a much larger story. Morgan looked up the work of field geologists to learn the orientations of great faults, and found remarkable consistencies across thousands of miles. He tested them — and ocean rises and trenches as well — against the laws of geometry for the motions of rigid segments of a sphere. At the 1967 meeting of the American Geophysical Union, he was scheduled to deliver a paper on the Puerto Rico Trench. When the day came, he got up and said he was not going to deal with that topic. Instead, reading the paper he called “Rises, Trenches, Great Faults, and Crustal Blocks,” he revealed to the geological profession the existence of plate tectonics. What he was saying was compressed in his title. He was saying that the plates are rigid — that they do not internally deform — and he was identifying rises, trenches, and great faults as the three kinds of plate boundaries. Subsequently, he worked out plate motions: the variations of direction and speed that have resulted in exceptional scenery. It was about a decade later when Morgan’s Princeton colleague Ken Deffeyes asked him what he could possibly do as an encore, and Morgan — who is shy and speaks softly in accents that faintly echo his youth in Savannah, Georgia — answered with a shrug and a smile, “I don’t know. Prove it wrong, I guess.”

Instead, he developed an interest in hot spots and the thermal plumes that are thought to connect their obscure roots in the mantle with their surface manifestations — a theory that would harvest many of the questions raised or bypassed by plate-tectonics, and similarly collect in one story numerous disparate phenomena.

In 1937, an oceanographic vessel called Great Meteor, using a newly invented depth finder, discovered under the North Atlantic a massif that stood seventeen thousand feet above the neighboring abyssal plains. It was fifteen hundred miles west of Casablanca. No one in those days could begin to guess at the origins of such a thing. They could only describe it, and name it Great Meteor Seamount. Today, Jason Morgan, with other hotspot theorists, is not only prepared to suggest its general origin but to indicate what part of the world has lain above it at any point in time across two hundred million years. Roughly that long ago, they place Great Meteor under the district of Keewatin, in the Northwest Territories of Canada, about halfway between Port Radium and Repulse Bay. That the present Great Meteor Seamount was created by a hot spot seems evident from

the size and configuration of its base, which is about eight hundred kilometres wide and closely matches the domal base of Hawaii and numerous other hot spots. If a submarine swell is of that size, there is not much else it can be. That it was once, theoretically, somewhere between Port Radium and Repulse Bay is a matter of tracing and dating small circles on the sphere traversed by moving plates.

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When Great Meteor arrived at the edge of the Canadian Shield, under the present site of Montreal, it presumably made the Monteregian hills, for one of which the city is named. The Monteregian hills are volcanic, but their potassium-argon age disagrees by twenty million years with the date when, by all other calculations, Montreal was over the hot spot — an exception that probes the theory. Morgan attributes the inconsistency to “random things you can’t explain” and mentions the possibility of faulty dating. He also says, quite equably, “If the Monteregian hills really don’t fit the model, you have to come up with another model.”

The hotspot hypothesis was put forward in the early nineteen-sixties by J. Tuzo Wilson, of the University of Toronto, as a consequence of a stopover in Hawaii and one look at the islands. The situation seemed obvious. James Hutton, on whose eighteenth-century “Theory of the Earth” the science of geology has been built, understood in a general way that great heat from deep sources

stirs the actions of the earth (“There has been exerted an extreme degree of heat below the strata formed at the bottom of the sea”), but no one to this day knows exactly how it works. Heat rising from hot spots apparently lubricates the asthenosphere — the layer on which the plates slide. According to theory, the plates would stop moving if the hot spots were not there. Why the hot spots are there in the first place is a question that seeks its own Hutton. For the moment, all Jason Morgan can offer is another shrug and smile. “I don’t know,” he says. “It must have something to do with the way heat gets out of the lower mantle.”

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An event of the brevity and magnitude of a great basalt flood is an obvious shock to the surface world. “We don’t know what flood basalts do to the atmosphere,” Morgan remarked one day in 1985, showing me a chronology he had been making of the great flood basalts that not only filled every valley “like water” and killed every creature in areas as large as a million square kilometres but also may have spread around the world lethal effects through the sky. Morgan’s time chart of flood basalts matched almost exactly the cycles of death that are currently prominent in the dialogue of mass-extinction theorists, including the flood basalts of the Deccan Plateau, which are contemporaneous with the death of the dinosaurs — the event that is known as the Cretaceous Extinction.

Many years ago, as a very young scientist, around 1971, I attended my first AGU meeting in Washington D.C. I was struck by two things: the proximity of the location to the zoo, which was only a short walk away, and an absolutely absurd talk by a speaker, who literally was dragged off the stage by the moderator as he went long past his allotted time. To put it politely, I thought his concept of deep mantle plumes distinctly odd to say the least — as did many in the audience. As the years went by, I discovered that this very scientist was not only an amiable fellow, endowed with a good nature and a natural charm, but quite capable of pulling rabbits out of hats as the geologic occasion demanded. The rabbits were always intriguing, and, as rabbits will be, prolific, spawning many children. It was not long before I found myself pursuing one of his rabbits. Committing myself to the same foolhardy notion that deep mantle plumes might exist, I spent about 1200 hours staring down a microscope counting roughly a half million points on thin sections of mantle peridotites from ocean ridges to determine their composition. I can testify that these rocks are the most miserably altered bits of grunge ever pulled from the seafloor. Thank God: there actually proved to be a correlation with the composition of these rocks and proximity to his postulated mantle plumes — otherwise I think I might have strangled him. Over the years I have encountered Jason many times, and have found that despite his many “wild” ideas, that he is a kind and gentle man who brings enthusiasm and good will to all he does. Fortunately for me, he has always been quite tolerant, even encouraging, of obstreperous young scientists. As for many others, my career has greatly benefited by my interactions with Jason, and I would like to say: “Thank you Jason for greatly enriching the lives of our community and pioneering its science.” — Henry J. Dick

## PUBLISHED PAPERS

- W. J. Morgan, J. O. Stoner and R. H. Dicke, Periodicity of earthquakes and the invariance of the gravitational constant, *J. Geophys. Res.*, 66, 3831-3843, 1961.
- W. J. Morgan, Gravity anomalies and convection currents, 1, a sphere and cylinder sinking beneath the surface of a viscous fluid, *J. Geophys. Res.*, 70, 6175-6187, 1965.
- W. J. Morgan, Gravity anomalies and convection currents, 2, the Puerto Rico trench and the mid-Atlantic rise, *J. Geophys. Res.*, 70, 6189-6204, 1965.
- W. J. Morgan, Reply, *J. Geophys. Res.*, 71, 3607-3608, 1966.
- W. J. Morgan, Rises, trenches, great faults and crustal blocks, *J. Geophys. Res.*, 73, 1959-1982, 1968.
- W. J. Morgan, P. R. Vogt and D. F. Falls, Magnetic anomalies and sea floor spreading on the Chile rise, *Nature*, 222, 137-142, 1969.
- D. P. McKenzie and W. J. Morgan, Evolution of triple junctions, *Nature*, 224, 125-133, 1969.
- W. G. Melson and scientific staff, Preliminary results of a geophysical study of portions of the Juan de Fuca ridge and Blanco fracture zone, *ESSA Technical Memorandum C&GSTM 6*, (Dept. of Commerce, Rockville, MD, December 1969) 33 pp.
- W. J. Morgan, Convection plumes in the lower mantle, *Nature*, 230, 42-43, 1971.
- W. J. Morgan, and T. P. Loomis, Correlation coefficients and sea-floor spreading: an automated analysis of magnetic profiles, *Marine Geophys. Res.*, 1, 248-260, 1971.
- W. J. Morgan, Deep mantle convection plumes and plate motions, *Bull. Am. Assoc. Petroleum Geol.*, 56, 203-213, 1972.
- W. J. Morgan, Plate motions and deep mantle convection, *Geol. Soc. Am. Memoir*, 132, (Harry H. Hess volume, ed. by R. Shagam), 7-22, 1973.
- T. P. Loomis and W. J. Morgan, Sea-floor spreading rate changes in the South Atlantic, *Marine Geophys. Res.*, 2, 3-9, 1973.
- W. J. Morgan, Heatflow and vertical movements of the crust, p. 23-43 in *Petroleum and Global Tectonics*, ed. by A. G. Fischer and S. Judson, (Princeton University Press, Princeton, 1975).
- D. E. Jackson, I. Koizumi, and scientific staff, leg 55, Drilling confirms hotspot origins, *Geotimes*, 23, 23-26, Feb. 1978.
- W. J. Morgan, Rodriguez, Darwin, Amsterdam, ..., a second type of hotspot island, *J. Geophys. Res.*, 83, 5355-5360, 1978.
- R. Hey, F. K. Duennebieer and W. J. Morgan, Propagating rifts on mid-ocean ridges, *J. Geophys. Res.*, 85, 3647-3658, 1980.
- S. T. Crough, W. J. Morgan, and R. B. Hargraves, Kimberlites: their relation to mantle hotspots, *Earth Planet. Sci. Lett.*, 50, 260-274, 1980.
- Shipboard Scientific Party, Explanatory notes for DSDP Leg 55 site chapters, Site 430: Ojin seamount, Site 431: Yomei seamount, Site 432: Nintoko seamount, and Site 433: Suiko seamount, p. 33-282 in E. D. Jackson, I. Koizumi, et al., *Initial Reports of the Deep Sea Drilling Project, vol. 55*, (U. S. Government Printing Office, Washington, 1980).



Jason was one of the recipients of the Vetlesen Prize, awarded in January 2000, along with Walter Pittman (left) and Lynn Sykes. Photo courtesy of The Smilodon.

- M. Kono, Y. Hamano and **W. J. Morgan**, Physical properties of basalts from DSDP Leg 55, p. 715-721 in E. D. Jackson, I. Koizumi, et al., *Initial Reports of the Deep Sea Drilling Project, vol. 55*, (U. S. Government Printing Office, Washington, 1980).
- W. J. Morgan**, Hotspot tracks and the opening of the Atlantic and Indian Oceans, p. 443-487 in *The Sea, vol. 7, The Oceanic Lithosphere*, ed. by C. Emiliani, (John Wiley & Sons, New York, 1981).
- W. J. Morgan**, Hotspot tracks and the early rifting of the Atlantic, Lunar and Planetary Institute Contribution No. 457, 1-4, 1981.
- W. J. Morgan**, Hotspot tracks and the early rifting of the Atlantic, *Tectonophysics*, 94, 123-139, 1983.
- G. A. Thompson and **W. J. Morgan**, Introduction and tribute to S. Thomas Crough 1947-1982, *J. Geophys. Res.*, 89, 9867-9872, 1984.
- G. E. Vink, **W. J. Morgan**, and W.-L. Zhao, Preferential rifting of continents: a source of displaced terranes, *J. Geophys. Res.*, 89, 10072-10076, 1984.
- W.-L. Zhao and **W. J. Morgan**, Uplift of Tibetan plateau, *Tectonics*, 4, 359-369, 1985.
- G. E. Vink, **W. J. Morgan**, and P. R. Vogt, The earth's hotspots, *Sci. Amer.*, 252/4, 50-57, 1985.
- G. Foulger, R. Bilham, **W. J. Morgan**, and P. Einarsson, The Iceland GPS geodetic field campaign 1986, *EOS Trans. Am. Geophys. Union*, 68, 1809,1817-1818, 1987.
- W.-L. Zhao and **W. J. Morgan**, Injection of Indian crust into Tibetan lower crust; a two-dimensional finite element study, *Tectonics*, 6, 489-504, 1987.
- W. J. Morgan**, Flood basalts and mass extinctions, p.126 in Global Catastrophes in Earth History; an interdisciplinary conference on impacts, volcanism, and mass mortality, *Lunar and Planetary Institute Contribution 673*, P.126, 1988.
- T. S. James, L. S. Hollister, and **W. J. Morgan**, Thermal modeling of the Chugach metamorphic complex, *J. Geophys. Res.*, 94, 4411-4423, 1989.
- T. S. James and **W. J. Morgan**, Horizontal motions due to post-glacial rebound, *Geophys. Res. Lett.*, 17, 957-960, 1990.
- Y. Chen and **W. J. Morgan**, Rift valley / no rift valley transition at mid-ocean ridges, *J. Geophys. Res.*, 95, 17571-17581, 1990.
- Y. Chen and **W. J. Morgan**, Origin of mid-ocean ridge axis topography, *J. Geophys. Res.*, 95, 17583-17604, 1990.
- G. R. Foulger and 10 others, The Iceland 1986 GPS geodetic survey: tectonic goals and data processing results, *Bull. Géodésique*, 67, 148-172, 1993.
- J. Phipps Morgan, **W. J. Morgan**, and E. Price, Hotspot melting generates both hotspot volcanism and a hotspot swell?, *J. Geophys. Res.*, 100, 8045-8062, 1995.
- J. Phipps Morgan, **W. J. Morgan**, Y.-S. Zhang, and W. H. F. Smith, Observational hints for a plume-fed, suboceanic asthenosphere and its role in mantle convection, *J. Geophys. Res.*, 100, 12753-12767, 1995.
- P. Eriendsson and 11 others, Heiti Reiturinn, Nr. 1, Uppsetning mælanets sumarið 1996 (Hotspot Project, No. 1, Installation of the hotspot network, summer 1996), *Veðurstofa Íslands Greinargerð, VÍ-G96028-JA01*, 1-11, 1996.
- P. Eriendsson and 11 others, Heiti Reiturinn, Nr. 3, Mælingum lokið og fyrstu niðurstöður (Hotspot Project, No. 3, Measurement results and first interpretations), *Veðurstofa Íslands Greinargerð, VÍ-G98030-JA03*, 1-13, 1998.
- G. E. van der Vink and 14 others, Why the United States is becoming more vulnerable to natural disasters, *EOS Trans. Am. Geophys. Union*, 79, 533,537, 1998. Also re-printed in *Earth in Space*, 11(6), 6-9, 1999.
- J. Phipps Morgan and **W. J. Morgan**, Two-stage melting and the geochemical evolution of the mantle: a recipe for mantle plum-pudding, *Earth Planet. Sci. Lett.*, 170, 215-239, 1999.
- E. R. Flueh and shipboard party, FS SONNE Cruise Report SO142 HULA: Interdisciplinary investigations on the timing of the Hawaii-Emperor bend and the origin of lithosphere anomalies along the Musician Seamount Chain, Midway-Honolulu, May 30 - June 28, 1999, *GEOMAR Report 90*, (Forschungszentrum für Marine Geowissenschaften der Christian-Albrechts-Universität zu Kiel, 1999) 224 pp.
- R. M. Allen, G. Nolet, **W. J. Morgan**, K. Vogfjord, B. H. Bergsson, P. Eriendsson, G. R. Foulger, S. Jacobsdottir, B. R. Julian, M. J. Pritchard, S. Ragnarsson, and R. Sefansson, The thin hot plume beneath Iceland, *Geophys. J. Internat.*, 137, 1, 51-63, 1999.

- G. R. Foulger, M. J. Pritchard, B. R. Julian, J. R. Evans, R. M. Allen, G. Nolet, **W. J. Morgan**, B. H. Bergsson, P. Erlendsson, S. Jakobsdottir, S. Ragnarsson, R. Stefansson, and K. Vogfjord, The seismic anomaly beneath Iceland extends down to the mantle transition zone and no deeper, *Geophys. J. Internat.*, 142, 3, F1-F5, 2000.
- Bonini, W. E., L. S. Hollister, and **W. J. Morgan**, Memorial to Sheldon Judson, *Geological Society of America Memorials*, v. 31, 51-54, 2000.
- K. I. Konstantinou, G. Nolet, **W. J. Morgan**, R. M. Allen, and M. J. Pritchard, Seismic phenomena associated with the 1996 Vatnajokull eruption, central Iceland, *J. Volcan. Geotherm Res.*, 102, 169-187, 2000.
- A. A. P. Koppers, J. Phipps Morgan, **W. J. Morgan**, and H. Staudigel, Testing the fixed hotspot hypothesis using  $^{40}\text{Ar}/^{39}\text{Ar}$  age progressions along seamount trails, *Earth Planet. Sci. Lett.*, 185, 237-252, 2001.
- G. R. Foulger, M. J. Pritchard, B. R. Julian, J.R. Evans, R.M. Allen, G. Nolet, **W. J. Morgan**, B.H. Bergsson, P. Erlendsson, S. Jakobsdottir, S. Ragnarsson, R. Stefansson, and K. Vogfjord, Seismic tomography shows that upwelling beneath Iceland is confined to the upper mantle, *Geophys. J. Int.* 146, 504-530, 2001.
- Z. Du, G.R. Foulger, B. R. Julian, R. M. Allen, G. Nolet, **W. J. Morgan**, B. H. Bergsson, P. Erlendsson, S. Jakobsdottir, S. Ragnarsson, R. Stefansson, and K. Vogfjörd, Crustal structure beneath western and eastern Iceland from surface waves and receiver functions, *Geophys. J. Int.*, 149, 349-363, 2002.
- R. M. Allen, G. Nolet, **W. J. Morgan**, K. Vögjford, M. Nettles, G. Ekstrom, B. H. Bergsson, P. Erlendsson, G. R. Foulger, S. Jakobsdottir, B. R. Julian, M. Pritchard, S. Ragnarsson, and R. Stefansson, Plume driven plumbing and crustal formation in Iceland, *J. Geophys. Res.*, 107(B8), doi:10.1029/2001JB000584, (19 pages) 2002.
- R. M. Allen, G. Nolet, **W. J. Morgan**, K. Vögjford, B. H. Bergsson, P. Erlendsson, G. R. Foulger, S. Jakobsdottir, B. R. Julian, M. Pritchard, S. Ragnarsson, and R. Stefansson, Imaging the mantle beneath Iceland using integrated seismological techniques, *J. Geophys. Res.*, 107(B12), doi: 10.1029/2001JB000595, (16 pages) 2002.
- Y. Shen, S. C. Solomon, I. Th. Bjarnason, G. Nolet, **W. J. Morgan**, R. M. Allen, K. Vogfjord, S. Jakobsdottir, R. Stefansson, B. R. Julian, and G. R. Foulger, Seismic evidence for a tilted mantle plume and north-south mantle flow beneath Iceland, *Earth Planet. Sci. Lett.*, 197, 261-272, 2002.
- H. Kopp, C. Kopp, J. Phipps Morgan, E. R. Flueh, W. Weinrebe, and **W. J. Morgan**, Fossil hotspot-ridge interaction in the Musicians Seamount Province: Geophysical investigations of hotspot volcanism at volcanic elongated ridges, *J. Geophys. Res.*, 108(B3), 2160, doi:10.1029/2002JB002015, (20 pages) 2003.



*Jason with family, friends and colleagues in Brittany, spring 1983. Cary Morgan is seated at the far left.*

My first year at Princeton, Jason was on sabbatical, so I did not meet him until my second year. I was quite intimidated by Jason during his absence as I knew he would be added to my committee when he returned. I was really worried because I had never had a formal class in tectonics, and I am not a geophysicist. When Jason returned in my second year I was quite relieved to find out that he was nothing like what I thought he was. First of all, he was just as interested in rocks as in calculations, and he proved to be the most approachable faculty member that I interacted with while in graduate school.

Looking back now at my time in Princeton, I realize how enriched my experience was by Jason. Jason would drop by at least once a week and have coffee with me, and we would talk about everything from geology to Steely Dan. I was quite surprised when Jason told me that my apartment at Butler had been his home when he was first at Princeton. I thought to myself, I have big shoes to fill. I will never make it. The day I took my Comprehensive Exam, Jason stopped by my house to congratulate me on passing. It was great. We talked about the cherry tree in the back yard and how much things had changed and stayed the same over the years. That afternoon I realized for the first time that I really could complete my Ph.D. at Princeton. Thanks for stopping by Jason and expressing your confidence in me. — Chris Andronicos



*Jason in l'Herz, Pyrenees, May 1996. This is the type locale for lherzolite.*



*Jason installing seismic station "#5," Bru, Iceland July 1996.*



*Jason at Mammoth Lakes, CA, fall 1997.*

# ABSTRACTS

**JASON PHIPPS MORGAN**  
GEOMAR  
Kiel, Germany



## *A retrospective on the scientific contributions of W. Jason Morgan*

I will review some of the highlights of Jason Morgan's contributions to Earth Sciences. These include the demonstration of gravity anomalies induced by viscous mantle flow, plate tectonics, mantle plumes, continental rifting, oceanic and continental uplift and subsidence, links between plumes, flood basalts and mass extinctions, the role of lower crustal flow in the uplift of Tibet, the

origin of axial relief at mid-ocean ridges, the effects of horizontal deformation in post-glacial rebound, the origin of hotspot swells, and the geochemical evolution of Earth's mantle. Almost every one of these contributions introduced a new idea or approach to the community.



Even after Michele and Jason had grown up to near-adult size, the Morgan family drove on cross-country trips in their Volkswagen bug. How they, and their luggage, fit in that orange bug is an unsolved mystery. — Ken Deffeyes

*Jason Phipps Morgan (left) and Jason in San Diego, August 1991.*

“Young Jason” is now Jason Morgan DeLossa; Michele's 9-year-old son. Jason Phipps Morgan has moved up to “middle-aged Jason.” — Ken Deffeyes

## XAVIER LE PICHON

Géologie, École Normal Supérieure  
Paris, France



### *Asymmetry in elastic properties and the evolution of large faults*

The nature of faults is to juxtapose rock bodies of different elastic properties. This is especially true of large-scale strike-slip faults. This juxtaposition of material of highly different elastic properties affects the distribution of elastic deformation and influences the rupture process. [Weertman, 1980], [Andrews and Ben-Zion, 1997] and others showed that if the fault is a material discontinuity interface, the rupture tends to occur as a narrow pulse that propagates in a wrinklelike mode within the low rigidity material. As a result, once an elastic contrast is created across the fault, it tends to localize the rupture along it and to stabilize the fault geometry. Contrasts in seismic velocity across a fault do not usually exceed 1.35 [Ben-Zion and Andrews, 1998]. Because the elastic parameter varies approximately as the seismic velocity to the third power (see for example [Andrews and Ben-Zion, 1997]), the maximum elastic parameter ratio expected is about 2.5 ( $1.35^3$ ). However, other effects such as the difference in altitude on both sides of the fault, for example along a continental margin, may accentuate the average contrast.

The asymmetry in elastic properties at a scale of 10-20 km can be tested by measuring the elastic deformation during both the interseismic phase and the coseismic phase. [Reid, 1910] observed at the beginning of the last century an asymmetry in the coseismic motion of the 1906 San Francisco earthquake and stated that “this is probably in part due to the fact that the rocks on the western side are more rigid than those on the eastern side.” [Prescott and Yu, 1986] noted an asymmetry in interseismic strain across the northern San Andreas Fault near Point Reyes and [Lisowski et al., 1991] pointed out that lateral inhomogeneity could explain this asymmetry.

They computed simple models assuming a ratio of 5 in the elastic parameter. They demonstrated further that the effect of a low-rigidity fault is to concentrate deformation within it. [Li and Rice, 1987] proposed that “the upper mantle to the SW of the San Andreas there could be too cool to deform readily and hence could move as an effectively rigid zone.” The best example we know of measured asymmetry in interseismic elastic deformation is along the northern Sumatra fault [Genrich et al., 2000] where the ratio is up to 10. Yet, curiously, most of the interpretations of elastic deformation along large-scale faults have assumed symmetry of the elastic properties. We show below several cases where this assumption is not correct and where the asymmetry is probably responsible for the long-term geometric stability of the fault.

The Main Marmara fault, which is part of the northern branch of the North Anatolian Fault, closely follows the northern margin of the Sea of Marmara. Along the margin, there is a vertical offset of the basement of several kilometers and the crust in the trough is highly sheared and faulted. We should thus expect asymmetry of elastic deformation there. New GPS data demonstrate the existence of this asymmetric elastic loading [Le Pichon et al., 2003]. The elastic loading is 10 times less to the north of the fault than to the south. Further west, the western North Anatolian Fault in the Aegean Sea follows one side of deep preexisting troughs that should lead to the same type of asymmetric loading. Both in these troughs and within the Sea of Marmara, the built-in asymmetry appears to act as traps for the fault. The same process may exist along other large faults such as the Dead Sea Fault. Concerning the San Andreas Fault, we noted above that asymmetry of elastic loading had also

been observed there. We examine existing geodetic data for the possibility of asymmetry there both in the present interseismic loading and the 1906 coseismic motion. We show that some limited asymmetry exists to the north of the fault near Cape Mendocino, in agreement with the seismically measured distribution of elastic properties, but that there is no significant asymmetry at the level of Point Reyes.

Finally, another important consequence of the asymmetry in elastic properties concerns the way in which decollements of subduction zones tend to bifurcate into several splay faults. A spectacular example is provided by the recent Chi-Chi earthquake in Taiwan that occurred on a splay fault branching upward of the decollement near the front of the prism [Cattin *et al.*, in press]. As noted by [Ben Zion and Andrews, 1998], “the theory of dynamic rupture in a homogeneous elastic solid predicts branching and bifurcation of the rupture front. This

general expectation is confirmed in laboratory experiments and is also compatible with the disordered geometrical appearance characterizing immature low slip fault systems.” These authors argue that large offset faults are stabilized by their built-in asymmetry. Decollements in subduction zones generally coincide with a material discontinuity. However, in the simplest models of accretionary wedges, this discontinuity should decrease and finally disappear as they shallow seaward. We suggest that the disappearance of the material discontinuity might be the cause of the seaward branching of the subduction faults which has important implications concerning the nature and location of large subduction earthquakes.

**Co-Authors:**

Corné Kreemer, Nicolas Chamot-Rooke, Alan Levander and Pierre Henry

The talk that Jason Morgan gave on April 19, 1967, at the AGU in Washington marked a turning point in my scientific career. As I have written elsewhere, Jason has a special gift for disorienting his listeners and this gift was especially well displayed on that occasion. Apparently nobody, including myself, understood the importance of what he discussed then. But Jason had the good idea of distributing an extended outline of his presentation that I received shortly afterward. And, as soon as I read it, I realized the importance of what he developed in it and dropped everything else I was doing to work on the implications. This led to the development of my six-plates model during what was certainly the most exciting research time of my whole life. From this time on, I have always been quite careful not to dismiss offhand suggestions made by Jason, even when they did not make sense to me. This happened again several years later in a seminar he gave at Lamont where he presented his hotspots model. He started his talk by the following extraordinary statement that he refused to justify: “Let us assume that there are plumes rising from the core-mantle boundary to the surface of the Earth.” I have often wondered what mental processes have been at work in the brain of Jason to lead to such developments. But Jason has given very little information on the mental processes that lead to these discoveries. Is it induction or pure intuition, the source of which remains hidden in his long stunning silences? It would be nice to hear somewhat more about it during this Morganfest. — Xavier LePichon



*Jason and Lincoln Hollister in Death Valley, GEO 416 field trip, March 2002. Photo by Ben Phillips.*

## CLAUDE J. ALLÈGRE

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### *The chemical composition of the Earth*

Since the Earth has a radius of 6,400 km and the deepest drill core reaches a depth of 15 km, the determination of the chemical composition of the Earth is a formidable exercise. It can be done by combining three types of information: (1) Geophysical information which provides the seismic velocities and densities. (2) The analysis of surface and sub surface samples including volcanic rocks which originate from several 100 kms through a complex process. (3) Material from meteorites which are the witnesses of early solid materials in the Solar System.

The classical approach is to use geophysical and sub surface sample analysis to compare the Earth with a certain class of meteorites. The most likely candidates and the most popular until recently were the carbonaceous chondrites CI (Ringwood, Wänke). Unfortunately, these meteorites do not fit the abundance of volatile elements which are strongly depleted in the Earth.

In a recent study, we have shown that the Earth is similar to carbonaceous chondrites but does not fit a

single type:

- It has high contents of the refractory elements Uranium and Thorium, similar to the CI chondrites.
- It has contents of the moderately refractory elements Mg, Si, and Hf, similar to the CM chondrites.
- It lies below the trend of CV carbonaceous chondrites.

Based on the geochemical constraints we calculate an abundance-volatility index curve. A model of planet formation is developed to explain those observations:

- All carbonaceous chondrites accreted within a short interval of time in the following order CI, CM, CO, CV; this is shown by  $Mn^{53}$ - $Cr^{53}$  chronologies.
- Planet Earth is made on a 100 My time scale. It is an integral part of the Nebulae Condensation History.

In the fall of 1968, our beginning geology course had Hess, Vine, and Morgan as visiting speakers on three consecutive Fridays. We have no record of Copernicus, Galileo, and Newton showing up for freshman physics. — Ken Deffeyes

## KURT FEIGL

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*Trade-offs between tropospheric artifacts and deformation signals in microwave geodetic measurements, or how W. Jason Morgan helped youngsters in the GPS and SAR business avoid another “Palmdale Soufflé”*

Geodetic measurements of crustal deformation provide boundary conditions for many tectonic problems. Since all modern surveying techniques measure the travel time of electromagnetic waves propagating through the atmosphere to determine the distance between two points, their accuracy depends on our ability to account for variations in the refractive index. For satellite instruments such as GPS, it is usually water vapor in the troposphere absorbing microwave radiation that proves the most meddlesome. The simplest first-order model assumes a single layer with a refractive index slightly greater than unity. Since the thickness of this layer depends on the altitude of the benchmark, summits can appear foreshortened relative to valleys. If neglected, this effect can erroneously augment the topographic measurement with a field mimicking the relief. Over time, if the refractive index changes between successive measurements, the same effect can produce an artifact that

resembles deformation. In this way, one might mistake a cloud cap over a volcano for magmatic activity within it, the same sort of systematic error that led to faulty interpretations of leveling surveys over Palmdale, California, in the 1970's. W. Jason Morgan's early insight was to recognize the importance of second-order tropospheric effects. Horizontal gradients of the refractive index in the troposphere can perturb estimates of relative position. For example, Morgan and Debiche calculated horizontal shifts as large as 2 cm by simulating GPS signals propagating laterally through the “President's Day Cyclone” of 18-19 February 1979 [Debiche Ph.D. thesis, Princeton, 1992]. Thanks in part to this insight, solid earth geophysicists have been able to avoid interpreting tropospheric artifact as tectonic signal. Morgan's idea has now come full circle as meteorologists use geodetic measurements to probe the atmosphere. What was noise for one community has become signal for another.

In my 4<sup>th</sup> year of undergraduate study, I visited various graduate schools. Jason came to Newark airport to meet me and show me around when I visited Princeton. That gesture, as much as the reputation of the Geosciences department, convinced me to go to Princeton for graduate studies. I have always been glad I made the choice to come to Princeton – my initial impressions of a soft-spoken and considerate person were borne out many times. I remember with fondness Jason's wife Cary, who welcomed me to their home on many occasions.

During my stay at Princeton I gained an increasing regard for Jason's scientific insight, in which a few words or a phrase would go to the heart of a problem and convince me to think about it in a different way. Jason's style was to give suggestions, and when I ignored the suggestions it was usually to my later dismay.

Although my research was focused on computer modeling, Jason's diverse interests meant that I did not completely escape field work. We spent parts of two summers in Iceland making GPS observations. Jason's enthusiasm was unflagging, whether it be trying out unpronounceable Icelandic phrases, lunching on dried fish, discussing rifting and volcanism, or overcoming faulty alarm clocks, horizontally-driven rain, and impenetrable fog. He was assisted in these endeavours by his unbreakable stainless steel thermos, of which he was very proud.

I am sure that although Jason is retiring he will continue to be active, dispensing sound advice to those who request it. My best wishes for the future. — Tom James

## THOMAS S. JAMES

Geological Survey of Canada  
Pacific Geoscience Centre  
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### *Space geodesy, absolute gravimetry, and crustal deformation*

Space geodesy, especially GPS, is presently defining a revolution in the Earth sciences in terms of the precision with which crustal deformation can be observed. Jason Morgan foresaw that development in the mid-1980's when he suggested I work on the three-dimensional crustal deformation due to postglacial rebound. Here I touch on three recent activities related to postglacial rebound and/or space geodesy and absolute gravimetry in which I am involved with many colleagues\*.

1. An important advantage of space geodetic and absolute gravity observations is that they give measurements of crustal deformation in locations where traditional observations related to postglacial rebound, such as relative sea-level observations, are lacking. For example, a transect of absolute gravity sites running south from Churchill, on Hudson Bay, to Iowa City, shows a consistent pattern of secular surface gravity trends. Surface gravity is strongly decreasing at Churchill at a rate in agreement with a tide gauge trend and late Holocene relative sea-level observations. The secular rates decrease in magnitude systematically to the south, indicating decreasing amounts of postglacial uplift. The gravity rates have implications for former ice sheet thickness.

2. Space geodesy is especially valuable in Antarctica. Most of the coastline is ice-locked, and the sparse relative sea-level observations have uncertain radiocarbon reservoir effects. Continuous GPS measurements from the Antarctic perimeter are now sufficient to define Antarctic plate motion, and episodic measurements from the interior give indications of postglacial uplift and horizon-

tal motions. A region in Victoria Land that has had repeated GPS occupations appears to show horizontal rates larger than predicted by postglacial rebound models, suggesting a tectonic component to the deformation.

3. On the west coast of Canada, along the northern Cascadia Margin, continuous GPS measurements have resolved episodic transient slip events. These were first thought to be "aseismic" but have recently been found to be accompanied by unique low-frequency tremors. This newly discovered dynamic plate behaviour has been named Episodic Tremor and Slip (ETS). It occurs remarkably regularly about every 14.5 +/- 2 months. ETS activity occurs downdip from the locked portion of the subduction plate interface, that portion which is thought to rupture every 200 to 700 years causing an M>8 earthquake. ETS activity relieves stress on or above the deeper (25 to 45 km) plate interface but in so doing, adds stress to the locked zone in discrete steps. This suggests the potential for time-dependant hazard assessment in the future.

#### **\*Co-Authors:**

Tony Lambert, Nicholas Courtier, and Stephane Mazzotti, Geological Survey of Canada (mid-continent absolute gravity and GPS); Carol Raymond and Erik Ivins, Jet Propulsion Laboratory, California Institute of Technology (Antarctic GPS); Terry Wilson and Michael Willis, Ohio State University (Antarctic GPS); Herb Dragert, Kelin Wang, and Garry Rogers, Geological Survey of Canada (Cascadia episodic tremor and slip (ETS))

## HENRY J. DICK

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### *Ultra-slow spreading: a new class of ocean ridge*

Investigations of the SW Indian (SWIR) and Arctic Ridges reveal a new ultra-slow class of ocean ridge. Lacking transform faults, with intermittent volcanism and the mantle emplaced continuously to the seafloor over large regions, these ridges represent the true slow end-member for seafloor spreading. The differences between ultra-slow and slow spreading ridges are as great or greater than those between slow and fast spreading ridges. They form at full spreading rates  $\sim 12$  mm/yr and consist of linked magmatic and amagmatic accretionary ridge segments rather than the linked transforms and magmatic segments characteristic of faster spreading ridges.

Amagmatic ridge segments are a new class of plate boundary structure, equal in hierarchy to transform faults, and magmatic ridge segments. They assume any orientation from orthogonal to acute angles to the spreading direction, replacing both transforms and magmatic accretionary ridge segments along the plate boundary. Amagmatic accretionary segments extend ridges in both the direction of plate motion and perpendicular to it. They coexist with magmatic ridge segments for millions of years, forming stable plate boundaries, or may displace or be displaced by transforms and magmatic ridge segments as spreading rate, mantle thermal structure, and ridge geometry change. The fundamental unit of accretion at amagmatic ridge segments appears to be

mantle blocks emplaced tectonically along an axis that follows the zone of lithospheric necking at the lithosphere-asthenosphere boundary, with only a thin or missing volcanic crust forming over large regions.

There is an abrupt discontinuity in crustal structure and magmatism at an effective spreading rate for mantle upwelling of 12 mm/yr (the spreading rate corrected for ridge obliquity). Below this rate, ultraslow spreading ridges no longer exhibit a continuous volcanic carapace. Magmatism is more sensitive to mantle thermal structure and composition than to spreading rate, with some of the largest non-hotspot volcanoes on the global ridge system forming in otherwise amagmatic regions.

The SW Indian Ridge, with a spreading rate  $\sim 14$ -16 mm/yr, is actually transitional between slow and ultra-slow spreading, exhibiting ultra-slow and slow spreading morphologies over long stretches depending on ridge geometry, mantle thermal structure and composition. This behavior is similar to that found at intermediate rate ridges like the Central Indian Ridge, which exhibit discontinuous slow and fast spreading characteristics over large regions at constant spreading rate.

#### **Co-Authors:**

Jian Lin and Hans Schouten, WHOI

For decades, diamonds have been found in the glacial till in the northern USA and southern Canada. Somewhere, upstream along the glacial striations, there had to be a source of diamonds but the potential track was 1000 kilometers long. Where that trail crossed one of Jason's hotspot tracks focused the exploration. X marked the spot where the diamonds were buried. — Ken Deffeyes

## DONALD W. FORSYTH

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### *Intraplate volcanic ridges, seamount chains and the early evolution of the Pacific lithosphere*

The southern East Pacific Rise spreading center is asymmetric. The seafloor subsides much more rapidly with increasing age on the Nazca plate side to the east than on the Pacific plate to the west. The recent MELT and GLIMPSE experiments have revealed other fundamental asymmetries in physical properties that accompany the anomalous subsidence and point to the possibility that flow in the asthenosphere of hot, enriched mantle from the Pacific superswell is responsible for the asymmetry.

The shear wave velocity structure is symmetric in the crust, but, in the mantle, asymmetry begins at the axis immediately beneath the Moho and increases with increasing depth. On the west side, there is a gap in the high velocity lithospheric lid, which begins to grow slowly about 20 km from the axis. On the east side, velocities increase rapidly with increasing distance from the axis down to depths of about 60-70 km. Shear wave splitting shows that the structure is anisotropic on both sides, with the fast splitting axis oriented perpendicular to the ridge and parallel to plate motion, but the splitting delays are nearly twice as large on the Pacific plate as on the Nazca side. Rayleigh waves in young seafloor on the Pacific plate travel about 3.5% faster perpendicular to the ridge than parallel to it. To explain the splitting delays with this degree of anisotropy requires an anisotropic layer about 200 km thick. The anisotropy reaches a minimum near the axis, perhaps indicating a region of near vertical upwelling.

To the west of the East Pacific Rise (EPR), there is a

much greater abundance of volcanic ridges and small seamount chains. In the MELT and GLIMPSE experiments, we deployed arrays of ocean-bottom seismometers for periods of 6 months and 1 year, respectively, to record teleseismic earthquakes and probe the mantle beneath. The study area includes the Rano Rahi seamount field, connecting to the Puka-Puka ridge; the Hotu-Matua volcanic complex, characterized by recent, off-axis lava flows scattered along a line from 200 to 400 km from the EPR; and the Sojourn and Brown ridges, which parallel the Garrett Fracture zone. S-wave velocities in the shallow mantle are anomalously low beneath the eastern end of the Sojourn/Brown ridge, indicating a relatively broad zone of high temperatures and the presence of melt beneath the only part of this ridge complex that has young lava flows. At asthenospheric depths, the dominant velocity anomalies trend perpendicular to the EPR, with particularly low velocities beneath the Rano Rahi seamount field.

One possible interpretation of all these observations is that the East Pacific Rise is fed by rapid asthenospheric flow from the west, perhaps from the Pacific superswell region. The mantle feeding the ridge is variably enriched and undergoes small degrees of partial melting as it approaches the spreading center and rises beneath the thinning Pacific lithosphere, creating the seamount chains. Return flow to the EPR may be channeled or concentrated in fingers of higher temperature, more water-rich, lower viscosity mantle.

## RICHARD M. ALLEN

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### *Mantle structure and flow beneath the Iceland hotspot*

In the three decades since Morgan's seminal papers proposing deep-seated mantle plumes as the stationary source of mantle melting anomalies responsible for chains of volcanic islands, geoscientists have tested and retested this hypothesis against others in numerous locations around the world. While the existence of mantle plumes remains a controversial topic, the model persists as the most favored explanation for hotspots.

In our continuing efforts to better constrain the mechanisms responsible for hotspot manifestation, regional seismic experiments provide a detailed picture of the structure and flow characteristics of the mantle. We present the results of studies of the isotropic and anisotropic structure of the mantle beneath the Iceland hotspot using the regional HOTSPOT dataset. Tomographic imaging of the isotropic structure shows a cylindrical low-velocity anomaly extending from ~400 km up toward the surface. The low-velocity, presumably buoyant, material spreads out laterally beneath the lithosphere, forming a horizontal low velocity anomaly

beneath all of Iceland. While the maximum depth of resolution (around 400 km depth) prevents imaging of the upwelling source depth, the observations above 400 km depth are consistent with the presence of a mantle plume.

Azimuthal anisotropy beneath Iceland can be constrained using splitting observations of SKS arrivals. In eastern Iceland fast polarization directions are oriented NNW and rotate to NW in central Iceland. In both regions splitting times are large, greater than 1 second, indicating a mantle rather than crustal source. In northwestern Iceland splitting times are significantly reduced (averaging 0.5 seconds) and are more variable in direction. This distribution of fast-axis orientations provides no indication of radial flow away from a mantle upwelling. Instead, it can be explained by mid-ocean ridge dynamics: the shear of lithospheric plates on the asthenosphere either side of the mid-Atlantic ridge. Thus, azimuthal anisotropy apparently provides no indication of mantle upwelling.

When I received the invitation to participate in this celebration of Jason's career I was simply delighted. Jason was one of my advisors during the five-and-a-half years I spent in Princeton and they were fantastic years. One of the times that immediately comes to mind is a seminar Jason gave on the development of plate tectonic theory and the plume hypothesis. It was not just his personal contribution to these theories that made this seminar stand out, but also his insight into the scientific method and what is necessary first to convince others, and perhaps later prove, a new theory. Another favorite recollection comes from oral exams I took with Jason as a member of my committee. Jason would usually sit toward the rear, behind the other examiners, and gently nod or frown as my answers veered in different directions. Other times spent were in the field, either for education or research, in Iceland, France and Puerto Rico — good times Captain Morgan! I add my thanks to those of many others for all of Jason's efforts as a scientist and educator, and I look forward to future times well spent — Richard Allen.

## DAN P. MCKENZIE

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### *The thermal and chemical structure of plumes*

More than 30 years ago Jason (Morgan 1971) wrote one of his most intellectually daring papers on convective plumes from the lower mantle. The main purpose of the paper was to account for the age progression of volcanism along ridges like the Hawaiian Ridge. Tuzo Wilson had earlier proposed that these were generated by melting in the interior of convection cells, whose rising limbs were beneath ridges. In a very influential paper Jason proposed instead that such features were instead underlain by the hot rising plumes of convection cells, and that these were stationary with respect to each other. The first part of this proposal was generally accepted, partly because Tuzo's sketch of his suggestion made no fluid dynamical sense. By 1971 we understood that the Rayleigh number of the mantle was at least  $10^6$ . Convection at such large Rayleigh numbers transports heat through the interior of the layer in rising and sinking plumes. But the circulation is strongly time dependent. Even though Jason's suggestion was an obvious solution to the problem of the Hawaiian Ridge, which I also had noticed seemed to be approximately stationary with respect to North America, I could not understand how Jason's suggestion could be correct, and how one could use a time-dependent convective pattern to define a reference frame.

We now have a good understanding of the dynamics of plumes on Earth, and also, perhaps more surprisingly, on Venus, where they have a much more dominant effect on gravity and topography than they do on Earth.

How they generate large volumes of melt is also understood, at least in outline. As expected from the fluid dynamical experiments carried out in the laboratory, the convective pattern is time dependent, with new plumes suddenly arising by boundary layer instabilities. It is even possible to show that the venusian plumes are also time dependent.

The most important remaining puzzle is the association of plumes with isotopic variations. Every possible geochemical reservoir has been suggested as the source of these variations at one time or another. Detailed analysis of three of the best existing data sets, from Iceland, Kilauea and Pitcairn, suggests that the material responsible comes from ancient subducted oceanic islands, which were themselves produced by plumes in oceans that have long since vanished. Jason and Jason Phipps Morgan carried out a detailed study of the geochemical consequences of the subduction of ocean islands, which they argued could produce the geochemical anomalies. The new analysis confirms their proposal.

#### References:

- Morgan W.J. 1971 Convection plumes in the lower mantle. *Nature* **230** 42-43.
- Phipps Morgan J. and Morgan W.J. (1999) Two-stage melting and the geochemical evolution of the mantle: a recipe for a plum-pudding *Earth. Earth Planet. Sci. Lett.* **170** 215-239.



### *Anatomy of the Hawaiian plume*

Tholeiitic magmas from the Hawaiian plume display a bewildering range of chemical and isotopic heterogeneities, with spatial scales ranging from micrometers to tens of kilometers. Extensive sampling from several volcanoes moving across the plume and from the chemostratigraphy of one volcano (Mauna Kea) is beginning to enable us to untangle the underlying plume anatomy. Many of the chemical characteristics and all of the (radiogenic) isotope variations are derived from source heterogeneities. The smallest spatial scale is manifested by extreme chemical and isotopic differences between melt inclusions hosted by single olivine crystals and separated by only tens of micrometers (Sobolev et al., 2000). This requires injections of small batches of chemically and isotopically diverse magmas into crustal magma chambers, where the olivine crystals grow and incorporate heterogeneous melt inclusions before these melts are homogenized in the chamber and erupted at the surface. These observations indicate source heterogeneity of extreme amplitude and unknown, but probably small, spatial scale. Larger scales of source heterogeneity are evident from the Pb isotope stratigraphy of the 3000m drill core of the Hawaiian Scientific Drilling Project (HSDP-2). In addition to rapid oscillations of isotopic composition along specific mixing lines (in  $^{206}\text{Pb}/^{204}\text{Pb}$  -  $^{207}\text{Pb}/^{204}\text{Pb}$  -  $^{208}\text{Pb}/^{204}\text{Pb}$  space), there are longer-wavelength changes, which can be related to the movement of the Pacific plate across the Hawaiian plume. Thus, 500-ka-old Mauna Kea lavas appear to tap the same source composition as do present-day Kilauea lavas. This is consistent with the relative motions of plume and lithosphere. The frequency of the isotopic oscillations decreases from the older to the younger lavas in the drill hole. This may reflect the movement of the volcano from the locus above the highest shear within the plume

conduit to the margin of the conduit with decreasing shear. The (spatially) largest scale variations are revealed by high-precision Pb isotope data (Abouchami et al. 2000; Eisele et al., 2002) and by certain trace element ratios (Sr/REE) in lavas from the two parallel lines of volcanoes, the “Loa trend” and “Kea trend.” The high Sr/REE ratios, unradiogenic Pb isotopes, and high  $^{208}\text{Pb}/^{206}\text{Pb}$  ratios of the Loa trend are best explained by a source enriched in recycled oceanic gabbro, whereas the more “normal” compositions found in Kea trend volcanoes contain a recycled basaltic component. These observations are not consistent with models of a concentrically zoned plume. Rather, they can be explained by a plume that is fed by larger-scale heterogeneities at its base. Such large-scale heterogeneities might be generated, for example, by subduction of a magmatically differentiated oceanic plateau. The plume stem compresses these heterogeneities horizontally and draws them out vertically, possibly over hundreds of kilometers, causing extreme thinning and creating a spaghetti-like assemblage similar to the numerical model of Farnetani et al. (2002).

#### References:

- Abouchami, W., Galer, S.J.G. Hofmann, A.W. (2000) High precision lead isotope systematics of lavas from the Hawaiian Scientific Drilling Project. *Chem. Geol.* **169**, 187-209.
- Eisele, J., Abouchami, W., Galer, S.J.G. Hofmann, A.W. (2003) The 320 kyr Pb isotope evolution of Mauna Kea lavas recorded in the HSDP-2 drill core. *Geochem. Geophys. Geosystems* **4**, doi: 10.1029/2002GC000339
- Farnetani, C.G., Legras, B. and Tackley, P.J. (2002). *Earth Planet. Sci. Lett.* **196**, 1-15.
- Sobolev, A.V., Hofmann, A.W. and Nikogosian, I.K. (2000). *Nature* **404**, 986-990.

## PAUL R. RENNE

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### *Mantle plumes, flood basalts, and mass extinctions*

More than thirty years ago, Morgan hypothesized that plumes originating in the lower mantle are responsible for such phenomena as hotspots and flood basalts. Subsequent research has generally supported the notion that much intraplate magmatism is indeed the product of deep-rooted plumes. One of the intriguing revelations of the past decade or so has been that the initial phases of plume-related magmatism on Earth's surface, manifest in flood basalt eruptions, are of immense spatial proportions. Chiefly through progress in geochronology, it has become possible to delineate vast provinces of flood basalts that were emplaced in remarkably brief episodes

of order one million years' duration. Along with recognition of the brevity of these events came the realization that they appear to be highly correlated in time with major extinctions observed in the fossil record, as Morgan suggested might prove to be the case. Qualitatively, the most probable link between flood basalts and mass extinctions is catastrophic atmospheric loading by climate-modifying volcanogenic gases such as carbon dioxide and sulfates. However, quantitative evaluation of the mass transfer of such gases to the atmosphere by flood basalts remains elusive, and requires further attention.

When I was a postdoc at Princeton in the late 1980's, Jason spurred my interest in dating flood basalt provinces. I remember distinctly his suspicion that the large range of K-Ar ages might be spurious — this was borne out resoundingly when I and others began to tackle the problem in earnest. Unfortunately I wasn't wise enough to jump on it right away, and it was only several years after leaving Princeton that I stumbled back into the problem. — Paul Renne

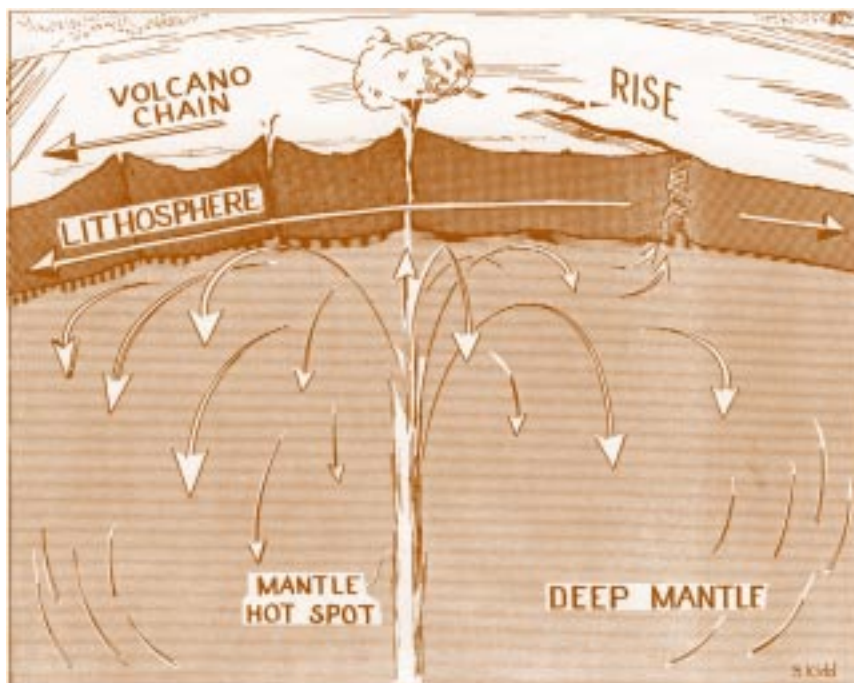


Figure in 1985 Princeton Alumni Weekly article on plumes by artist S. Kidd.

## CHRISTOPHER L. ANDRONICOS

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### *A North American arc perspective on the making of continents*

The theory of plate tectonics, as proposed by W. Jason Morgan, gave us a model by which we can understand the displacements of lithospheric plates and the kinematic relationships between sea floor spreading, subduction zones, and transform plate boundaries. However, a fundamental problem is how plate tectonics results in continental crust with chemistry distinct from that of oceanic crust. This difference is reflected in several phenomena including the bimodal distribution of elevation between the oceans and continents and the persistence of continents through long periods of geologic time. Despite the importance of this petrologic difference, we still do not have a complete understanding of how the chemical bimodality is produced. The following synthesis attempts to relate plate tectonics to the differentiation of continents.

Several distinct models have been suggested for the production of continental crust. One of the most popular is that crustal formation occurs above mantle plumes which generate large volumes of basaltic melts in short time periods. A second popular model is that island arcs are accreted and sutured together at convergent plate margins, forming the continents. However, both island arcs and hotspots are characterized by the production of melts with *basaltic* bulk compositions. If island arc or hotspot models are to be accepted, then a second distillation stage must occur in order to produce crust with an andesitic bulk composition.

Continental magmatic arcs are likely to provide the key to understanding this distillation process. Recent work on continental arcs in the North American Cordillera has shown that these arcs are underlain by huge batholiths, with thicknesses as great as 30 km. Studies of the metamorphic carapace of these arcs indicates crustal

thicknesses in excess of 50 km during batholith formation. Experimental studies and geochemical modeling of arc magmas imply that such thick arcs should be underlain by ultramafic garnet pyroxenite restites produced by extraction of the batholiths. The integrated composition of the batholith and its residues results in a crustal column with a basaltic bulk composition. The fate of these residues is critical to understanding the formation of the continents. These residues have seismic properties that are indistinguishable from typical mantle lithologies, however, their density is higher than typical mantle rocks. This leaves two possible end member fates for these residues. The first is that the residues reside hidden below the seismic Moho. The second is that these residues founder into the mantle (delaminate) due to their high density. If the first process is dominant, then our understanding of the composition of continental lithosphere needs to be reevaluated. If the second process occurs, then the formation of continents results from a complex two-stage recycling process.

Recent geological studies, deep crustal seismic profiling, gravity modeling, and xenoliths erupted in young volcanic rocks suggests the following evolution for thick Cordilleran margin arcs in North America. First, batholiths are constructed with deep-seated ultramafic residues forming their roots. Termination of arc magmatism results either from plate reorganization or continental collision. Delamination of ultramafic residues follows within  $10^7$  years. The arc subsequently undergoes deep erosion and ultimate cratonization. If proven to be generally correct then this two-stage distillation of continents is a result of plate tectonics at convergent plate margins.

## CHRISTOPHER BEAUMONT

Dalhousie University  
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### *Crustal channel flows: an explanation for Himalayan-Tibetan tectonics?*

Recent interpretations of Himalayan-Tibetan tectonics have proposed that gravitationally driven channel flows of partially molten, migmatitic, and therefore low viscosity middle crust can explain both the growth of the Tibetan plateau as the channel tunnels outward, and the ductile extrusion of the Greater Himalayan sequence (GHS). The latter may be an erosionally exhumed example of a relict channel, or it may have been tectonically modified during exhumation and remain active today. Although by no means universally accepted, this topical view of Himalayan-Tibetan tectonics is clearly rooted in work by Wu-Ling Zhao and Jason Morgan who more than fifteen years ago proposed that the crust beneath the Tibetan plateau may act as a weak viscous fluid and that injection of strong Indian crust into this zone acts as a piston, the ‘ZM-plunger’, to jack up the Tibetan plateau hydraulically.

Results from a numerical model that includes a self-generating mid-crustal channel flow are certainly compatible with many first-order features of the Himalayan-Tibetan system. In this model radioactive self-heating and rheological melt-weakening of thickened orogenic crust lead to the development of a hot, low-viscosity mid-crustal channel and a broad plateau. The channel tunnels its way outward at the flank of the plateau by consuming crust as it melt weakens. Under these circumstances the ZM-plunger is assimilated and converted to weak fluid faster than it converges...not much of a piston.

However, the model channel may be exhumed to the surface by aggressive erosion focussed on the windward margin of the plateau. Channel material corresponding to the GHS is then extruded and juxtaposed with cooler, newly accreted material corresponding to the Lesser

Himalayan sequence (LHS). The model channel is bounded by coeval thrust-sense and normal-sense ductile shear zones, equivalent to the Main Central Thrust (MCT) zone and South Tibetan Detachment (STD) system, respectively. The model results are consistent with a range of metamorphic and geochronological data as will be demonstrated.

Moreover, one style of continued deformation is for convergent strong Indian crust to underthrust the exhumed channel and act as a ZM-plunger. The numerical model results suggest that this process occurred during the Miocene and, therefore, that the piston, if it exists, is a recent feature of Himalayan tectonics. Model results also suggest that the plunger, here interpreted to be the footwall of the Main Himalayan Thrust (MHT), acts to destabilize the overlying Tibetan crust, which extends, thereby allowing the channel material to upwell to form domes. These domes resemble the Kangmar and other north Himalayan gneiss domes suggesting that at least some of these young gneiss domes were triggered by underthrusting.

Zhao and Morgan may also have been correct in pointing to the Adirondacks as, “a piece of the ‘Tibet’ of the Grenville(ian) orogeny.” It now appears possible that Grenvillian channel material is also exposed in the Central Gneiss Belt of Ontario.

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## PAUL E. TAPPONNIER

Institut de Physique du Globe  
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### *Continental collision: hidden plate tectonics*

Ever since the advent of Plate Tectonics, continental tectonics have been puzzling. The widespread deformation of the crust in regions of continental collision has been taken to suggest that the continental lithosphere should be regarded as a viscous fluid. Viscous models of continental deformation, however, fail to account for the existence of the 1000-km-long strike-slip faults and shear zones that are observed in all large collision zones, whether in the Middle East or in central Asia.

Incoming evidence from seismic tomography experiments in and around Tibet, and the kinematic picture deduced from long term, Quaternary slip-rate measurements suggests that the thickening crust in Asia hides motions of lithospheric mantle blocks or plates that are quantitatively similar to those commonly seen along convergent plate margins. In particular, both the lithospheric mantle of India, and of Asian blocks beneath and along the edges of Tibet appears to have subducted hundreds of kilometers, down to or even across the

transition zone.

This implies that the upper crust thickened while the mantle, decoupled beneath flat or gently-dipping decollements in the weak lower crust, did not, and that the continental lithospheric mantle retained enough strength even in the heart of the collision zone to behave “platelike.” The deep deformation probably became localized on reactivated lithospheric cuts corresponding to ancient sutures. The long strike slip faults are simply accounted for by slip partitioning, with oblique subduction of mantle slabs being consequently coupled with extrusion. Continental Tectonics thus appears to be little more than “hidden Plate Tectonics.” It is only the difficulty of maintaining steady-state motions for more than 10-20 million years, and the ease with which large shear zones localize and propagate along weak interfaces that makes it peculiar and more complex at the crustal level.



Jason has an uncanny way of disappearing within Guyot. His office door is open, his jacket is there, he isn't in the library: an unresolved mystery. — Ken Deffeyes

*Jason atop Drumadoon Sill in Arran, Scotland, March 1995.*



*Jason installing seismic station “#21” in Fagurholsymri, Iceland, July 2, 1996.*



*Jason at “Nouveau Menhir de Kerhallet” in May 1996.*

Cratonic basins, like the Illinois and Michigan basins, were an enduring puzzle. Jason pointed out that the dividers between basins, like the Kankakee arch, were probably old hotspot tracks. The basins were just the leftover spaces in between. — Ken Deffeyes

When I first arrived in Woods Hole the summer of 1969, I knew nothing of geophysics or the recent revolution in plate tectonics. My advisor handed me a copy of “Rises, Trenches, Great Faults and Crustal Blocks” and said, “Read this.” That paper of Jason’s served as my inspiration and directly guided my first research efforts on transform faults and plate motions. This pattern of inspiration, guidance and influence by Jason Morgan has continued throughout my career, studying the thermal evolution of the oceanic lithosphere, hotspots in the Indian Ocean, formation of rift valleys at slow spreading ridges, and so on.

Shortly after that first summer in Woods Hole, Jason gave a talk at MIT on some of his ideas about hotspots and mantle plumes. I remember being very unimpressed with the presentation, with hand-drawn overheads and what seemed to be ideas evolving even during the talk, but oh, what exciting ideas they were! I was amazed when the papers later began to come out in print how clear and convincing they were. This example of sharing your ideas as they evolve seems to me to be the essence of Jason’s approach to science and part of what makes his contribution to geophysics so important. Following a somewhat incoherent talk that I once gave about gravity anomalies on the Mid-Atlantic Ridge, Jason suggested a better way to approach modeling mantle flow beneath mid-ocean ridges that led to the three-dimensional thermal model that was at the heart of my papers with my students on gravity bulls-eyes on mid-ocean ridges. Of course, another major contribution of Jason’s to science, his son Jason Phipps Morgan, also helped enormously on that set of papers in developing the finite-difference code for the temperature calculations. More recently, the conceptual model of a plume-fed, suboceanic lithosphere developed by the two Jasons in collaboration with others served as the foundation for our interpretation of the MELT Experiment. So, although I have never collaborated directly with Jason on a project, his influence has been constantly present throughout my scientific career. — Donald W. Forsyth

# POSTERS PRESENTED

**THORA ARNADOTTIR, NORDIC VOLCANOLOGICAL INSTITUTE:**

“Continuous GPS Observations in Iceland”

**JANET BARAN, LAMONT-DOHERTY EARTH OBSERVATORY:**

“Relationship Between Axial Magma Chambers, Layer 2a, and Axial Morphology Along the Southeast Indian Ridge”

**ASHISH BASU, UNIVERSITY OF ROCHESTER:**

“On Flood Basalt Volcanisms at the K-T and P-T Boundaries”

**MARK BEHN, CARNEGIE INSTITUTION OF WASHINGTON:**

“Evidence for Mantle Flow Associated with the African Superswell”

**LAWRENCE CATHLES, CORNELL UNIVERSITY:**

“Glacial Rebound Constraints on Mantle Viscosity and their Implications for Plumes and Mantle Convection”

**YONGSHUN JOHN CHEN, PEKING UNIVERSITY:**

“Tomographic Study of North China Continental Lithosphere”

**ROBERT DETRICK, WOODS HOLE OCEANOGRAPHIC INSTITUTE:**

“Plume-Ridge Interactions at the Galapagos Spreading Center”

**ADAM DZIEWONSKI, HARVARD UNIVERSITY:**

“Seismic Tomography and Scale of the Mantle Convection”

**JOHN R. EVANS, U.S. GEOLOGICAL SURVEY:**

“Holistic modeling of the Santa Clara Valley, California, based on inadequate, inhomogeneous, incompatible data”

**MARK FEIGENSON, RUTGERS UNIVERSITY:**

“Insights on the Structure of the Hawaiian Plume as Inferred from REE Inverse Modeling of HSDP2 Basalts”

**JEAN FRANCHETEAU, INSTITUT UNIVERSITAIRE EUROPÉEN DE LA MER:**

“Olinde Rodrigues and the composition of finite rotations”

**NICHOLAS HARMON, BROWN UNIVERSITY:**

“Non Hot Spot Intraplate Melting on the Pacific Plate: The GLIMPSE Experiment’s Gravity Perspective”

**RICHARD HEY, UNIVERSITY OF HAWAII:**

“Propagating Rift and Microplate Tectonics”

**BENJAMIN HOLTZMAN, UNIVERSITY OF MINNESOTA:**

“Deformation, Melt Migration, and the Dynamics of the Asthenosphere”

**DONNA JURDY, NORTHWESTERN UNIVERSITY:**

“Coronae, Hotspots on Venus?”

**CHARLES A. LANGSTON, ANDREW A. NYBLADE, THOMAS J. OWENS, CERI, UNIVERSITY OF MEMPHIS:**

“Continental breakup in East Africa: results from Tanzania”

**RAFFAELLA MONTELLI, GUUST NOLET, F. A. DAHLEN, PRINCETON UNIVERSITY; G. MASTERS, IGPP UNIVERSITY OF CALIFORNIA, SAN DIEGO; R. E. ENGDahl, UNIVERSITY OF COLORADO AT BOULDER; S-H. HUNG, NATIONAL TAIWAN UNIVERSITY:**

“Joint Short- and Long-Period P Traveltimes Tomography Reveals a Variety of Plumes in the Mantle”

**MLADEN NEDIMOVIC, LAMONT-DOHERTY EARTH OBSERVATORY:**

“Reflection Signature of Seismic and Aseismic Slip on Subduction Thrusts”

**MARTA PEREZ-GUSSINYE, UNIVERSITY OF OXFORD:**

“On the recovery of effective elastic thickness using spectral methods: examples from synthetic data and from the Fennoscandian Shield.”

**MALCOLM S PRINGLE, SCOTTISH UNIVERSITIES ENVIRONMENTAL RESEARCH CENTRE:**

(1) Rapid formation of the North Atlantic Tertiary Volcanic Province: No evidence for a pulsing plume [Lynne M Chambers and Malcolm S Pringle]

(2) Ar/Ar whole rock results from ODP Leg 192: Constraints on the age and duration of Ontong Java Plateau volcanism [Lynne M Chambers and Malcolm S Pringle]

(3) Secondary Hotspots in the South Pacific as a Result of Mantle Plumelets and Lithospheric Extension? [Antony A P Koppers, Hubert Staudigel, Jan R Wijbrans, Malcolm S Pringle]

**REX PILGER, LANDMARK GRAPHICS CORPORATION:**

“Hot spots, Lineations, and Paleostresses: Mesoplate Manifestations”

**CHRISTINE POWELL, UNIVERSITY OF MEMPHIS:**

“Velocity structure in failed arms and continental intraplate seismic zones”

**BARBARA ROMANOWICZ, UNIVERSITY OF CALIFORNIA AT BERKELEY:**

“Combining Attenuation and Elastic Tomography to Track Superplumes Through the Earth’s Mantle”

**TRACY RUSHMER, UNIVERSITY OF VERMONT:**

“Core Formation Under Dynamic Conditions: Results from Deformation Experiments on Ordinary Chondrite”

**TOM SIMKIN, SMITHSONIAN INSTITUTION, NATIONAL MUSEUM OF NATURAL HISTORY:**

“DRAFT 3rd edition of ‘This Dynamic Planet’, a world map of volcanoes, earthquakes, impact craters, and plate tectonics”

**FREDERIK SIMONS, PRINCETON UNIVERSITY:**

“Mantle Flow, Plate Motion Reference Frames, and Seismic Anisotropy”

**ANN TREHU, OREGON STATE UNIVERSITY:**

“Gas Hydrates in Marine Sediments: Results from 2 Months at Sea on ODP Leg 204”

**GREGORY VAN DER VINK, EARTHSCOPE:**

“Why we are Becoming More Vulnerable to Natural Hazards: Teaching Geo 499 with W. Jason Morgan”

**KRISTOFFER WALKER, SCRIPPS INSTITUTE OF OCEANOGRAPHY:**

“Probing for Plumes with Shear-wave Splitting”

**DAVID YUEN, UNIVERSITY OF MINNESOTA:**

“‘Cold Plumes’ Rising from Slabs by Rayleigh-Taylor Mechanism and Their Magmatic Consequences”

By the third week of a Freshman Seminar, Jason would know all the students by name. By the end of the semester, he had an amazing knowledge of each student's intellectual and social background. After any misadventure, it was Jason who diagnosed the history. — Ken Deffeyes

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**Contributions to support this event came from:**

The National Science Foundation, Program in Ocean Sciences, Marine Geology and Geophysics

The National Science Foundation, Program in Earth Sciences, Geophysics

The National Science Foundation, Program in Earth Sciences, Continental Dynamics

Unocal Corporation

ExxonMobil Foundation

**Special thanks** for making this event happen go to John Fahey, Stephanie Resko, Sheryl Rickwell, Debbie Smith, and Laurie Wanat of the Princeton University Department of Geosciences and to Scott Sibio and Sylvia Swain of the Geosciences Library.

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Back Cover Photo courtesy of Jason Morgan, showing Jason in Iceland

