

Deep Mantle Plumes and Geoscience Vision

George A. Thompson, GSA President, 1997



Joy and amazement at the beauty and grandeur of this World of which Man can just form a faint notion
—Albert Einstein

INTRODUCTION

Humans, perhaps alone in the animal world, have a basic spiritual hunger to soar beyond the mundane. This has led to superstition and magic, but more importantly to a serious awe and reverence for the nighttime sky and a hunger for understanding Nature in all its variety. This spiritual hunger was a theme of Eldridge Moores in his address to you a year ago, and I carry on the theme. Einstein may have been a geologist at heart. Geoscience, along with astronomy, provides a far more fantastic reality than magic, of our tiny place in the immense span of time and space—in the case of geoscience we enjoy a full range from the spiritual to useful applications. We geoscientists are lucky to be able to enjoy that vision and also to find oil, manage groundwater, mitigate landslides, and predict volcanic eruptions. Most important, we need to learn, and to help our fellow humans learn, to interact with Earth without degrading it irretrievably, to live sustainably beyond our individual tiny niche in space and time.

I am pleased to report that your Society is doing an excellent job of reaching out, in education and in public policy, through two programs that are largely self-

sustaining. A glance through the program of this meeting [the 1997 GSA Annual Meeting] will demonstrate that a large fraction of the program is devoted to GSA's efforts to educate at all levels.

Now, what does all this have to do with deep mantle plumes?

GEOSCIENCE CONCEPTS

Great unifying concepts or models, sometimes called paradigms to make them more mysterious, not only cut through the barriers of specialization and jargon among ourselves but also allow us to communicate the beauty and challenge of science to nonscientists, a goal advocated by Richard Feynman: *"The world looks so different after learning science. For example, trees are made of air, primarily. When they are burned, they go back to air, and in the flaming heat is released the flaming heat of the sun which was bound in to convert the air into tree. [A]nd in the ash is the small remnant of the part which did not come from air, that came from the solid earth, instead. These are beautiful things, and the content of science is wonderfully full of them. They are very inspiring, and they can be used to inspire others."* [Quoted in *National Science Education Standards*, National Academy Press, 1996.]

Clearly, the theory of plate tectonics, now about 30 years old, tops the list of great unifying concepts in earth sciences. To illustrate its power for communication with the public: Anita and I, who are weekend tree farmers, discovered that a logger friend with an abbreviated high school education knows all about plate tectonics—mostly learned from public television and popular reading, but not far from the accurate scientific mark (Fig. 1). And besides the *fun* of plate tectonics, no exploration program can afford to ignore it!

A second great unifying concept is that of biological mass extinctions and the role of asteroid impacts. The resulting fits and starts of evolution are responsible for the rise of mammals like us. Despite erosion and subduction, impact structures are abundant on Earth. The Manicouagan impact crater on the Canadian shield, for example, (Fig. 2) is 70 km in diameter and is 210 m.y. old. Meteor Crater, Arizona (Fig. 3), is 1.2 km in diameter and has an age of only 25 ka. I show Meteor Crater in memory of Gene Shoemaker, who studied it so well. The implications of larger

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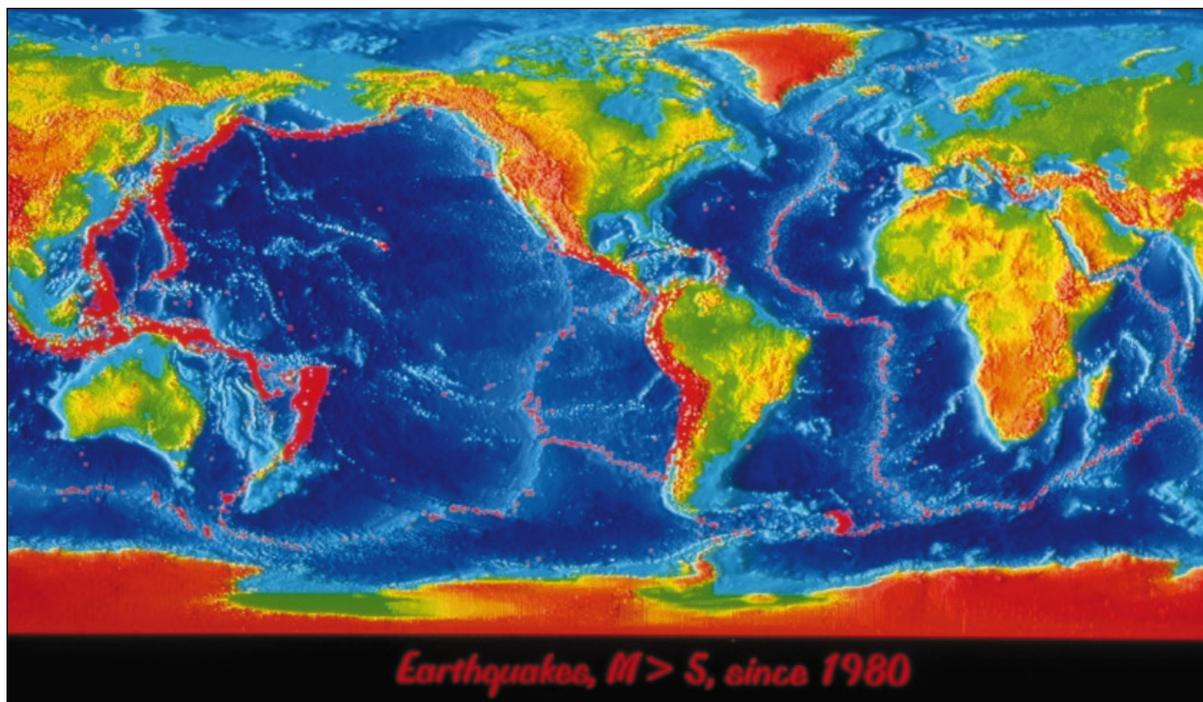


Figure 1. Tectonic plates on Earth. The Hawaiian seamount chain is near the upper left. From NASA.

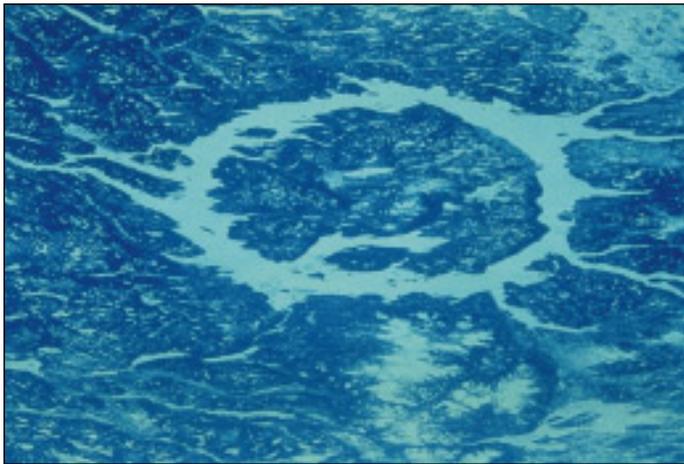


Figure 2. The Manicouagan impact crater on the Canadian shield, 70 km in diameter and 210 m.y. old. From NASA.



Figure 3. Meteor Crater, Arizona, 1.2 km in diameter and 25 ka. From NASA.

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impacts for life and for evolution are staggering. They include the confirmation of impact splashes from Mars onto Earth and intense speculative interest in the possibility of transfer of fossils or even of primitive life among the planets.

Third are the extremophiles, life forms that live in extremes of boiling water and in rocks at depths and temperatures that seem like pure fantasy. They are an abundant biomass, unsuspected until recently, and their implications for evolution, for chemical changes, and for applications are barely imagined.

Finally, my own current fascination with an important unifying concept is with deep mantle plumes. Tuzo Wilson (1993) did not live to deliver his talk on the neglect of deep mantle plumes, but he would be excited to learn of progress since 1993. I focus here on the geophysical and tectonic aspects, and outline without much qualification models that in some cases are quite speculative. By adopting

the simplest interpretation of present evidence—the criterion of Occam’s razor—I’ll be at the risk illustrated in a cartoon of Jack Oliver’s showing Occam accidentally cutting his own throat.

CONCEPT OF DEEP MANTLE PLUMES

Mantle plumes are the mothers of flood basalts and of the greatest dike swarms on Earth (e.g., Ernst and Buchan, 1997); they help to drive tectonic processes and to deposit ores. Their surface expression, long-lived *hotspots*, such as Hawaii, Iceland, and Yellowstone, form a comparatively stationary reference frame over which the tectonic plates perform their slow dance, making volcanic tracks such as the Hawaii-Emperor seamount chain, which tracks the differential movement between the hotspot and the Pacific plate (e.g., Tarduno and Cothrell, 1997).

Even at the world scale of Figure 1 one can make out this chain. About 40 hotspots are usually identified worldwide; a compilation for the western hemisphere is shown in Figure 4. Some of these are almost certainly secondary, produced by sublithospheric buoyant flow from major plume heads (e.g., Ebinger and Sleep, 1998). In contrast to plumes, ordinary convection expressed at ocean ridges cools the mantle, and, as pointed out to me about 30 years ago by Tanya Atwater, the ridges move about with respect to each other. This is easily seen in the ridges surrounding Africa (Fig. 1), where the

Figure 4. A compilation of hotspots in the western hemisphere; the Cape Verde hotspot is highlighted for this paper. From unpublished work by Stephen Gardoll (University of Western Australia) and Andrew Long (Stanford University).

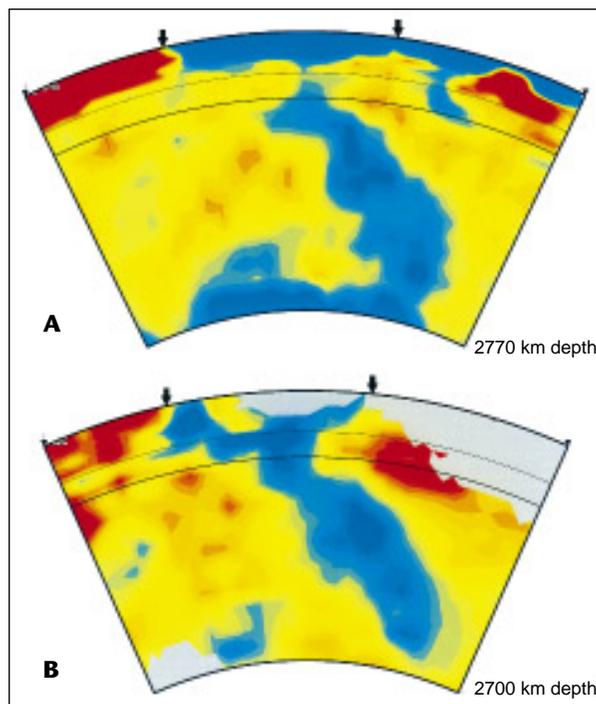
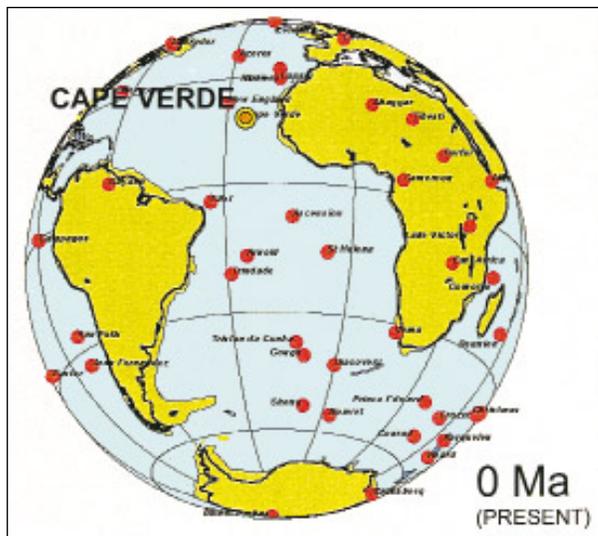
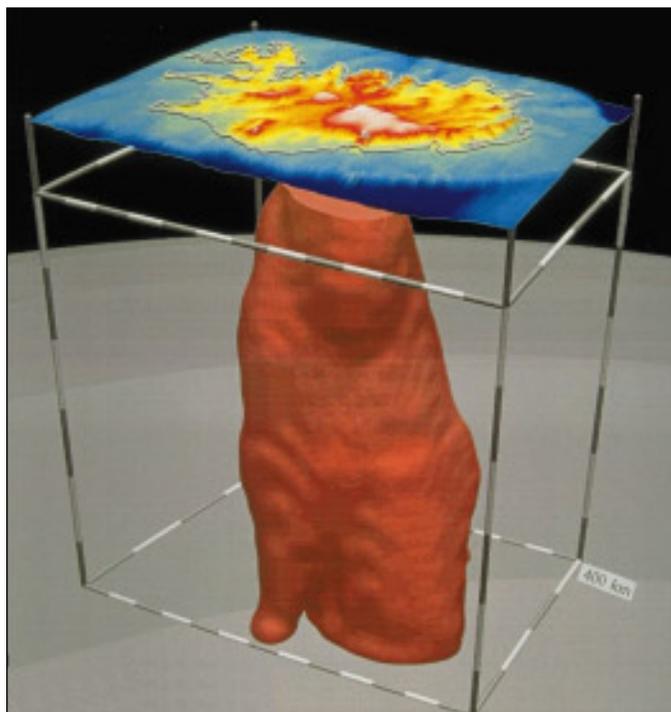


Figure 5. The Farallon subducted slab independently imaged by P and S waves (A and B, respectively) in a section across North America. Blue represents seismically slower and therefore cooler regions. The base of each section is near the thin D'' layer, transitional from the mantle to the liquid core. From Grand et al. (1997).

Figure 6. Earthquake tomographic image of the Iceland plume column to a depth of about 400 km. From C. Wolfe (Wolfe et al., 1997).



ridges must move apart because there is no subduction within the African plate. Deep mantle plumes, on the other hand, supply the cooling mechanism for Earth's liquid core.

Improved earthquake tomography shows that at least some subducted slabs plunge all the way to the core-mantle transition zone, the D'' layer of seismology (Fig. 5). The Central America and Japan subducted slabs are similar (van der Hilst et al., 1997) to the Farallon slab. Earthquake tomography also demonstrates a surprisingly low velocity and lateral

heterogeneity in the thin (200 km) core-mantle transition zone (e.g., Kuo and Wu, 1997; Wysession et al., 1992), an unstable situation that leads to buoyant rise of incipient plumes, which are too small to be clearly imaged at these depths.

Plumes in laboratory models (e.g., Whitehead and Luther, 1975) develop a rising viscous column topped by a voluminous head several times as large—imagine a mushy golf ball on a mushy tee. In nature, the rising column is perhaps as thin as 100 km in diameter, and the head is many times larger. When the head reaches the base of the lithosphere, a geologic drama begins. The column of the Iceland plume is shown to a depth of about 400 km in the earthquake tomographic image of Figure 6. The plume head (the golf ball) has already dispersed from the Iceland plume by buoyant flow into and along the rift, as computationally modeled by Sleep (1997).

The starting plume head, hundreds of degrees hotter than normal mantle, spreads laterally beneath the comparatively refractory lithosphere, incorporates

surrounding mantle, and buoyantly uplifts a region roughly 1000 km in diameter to produce a topographic bulge about 1 km high (Sleep, 1997, and references therein). Decompression melting in and around the plume head can produce immense volumes of magma rapidly, generating huge dike swarms and erupting as flood basalts, whose volumes are typically several million cubic kilometers. The plume tail (the tee under the golf ball) lives on as a rising convective column for tens to hundreds of millions of years and produces a track of volcanism such as the Hawaii-Emperor seamount chain if the overlying plate is moving relative to the plume. It is important to emphasize that the starting head and the presumed flood basalts that signaled the first emergence of the Hawaiian plume are long gone—probably subducted at the Aleutian trench. Hawaii and its hotspot track, as well as Yellowstone and Iceland, are solely manifestations of plume tails.

Mackenzie Dike Swarm and Intrusive Sheets

Giant, radiating dike swarms are key to recognizing ancient mantle plumes even where tell-tale flood basalts have been tectonically or erosionally removed (e.g., Ernst and Buchan, 1997). A striking example is the 1.265 Ga Mackenzie swarm of northern Canada (Fahrig and West, 1986) (Fig. 7) with an extent of about 2000 km! Dikes make their own fractures in the brittle crust, inflate to widths of tens of meters, and propagate, at about the rate a person can walk, for hundreds of kilometers.

In addition to dike swarms, which are usually mapped aeromagnetically, seismic reflection imaging has discovered extensive subhorizontal intrusive sheets in the mid-crust. Some are connected with the Mackenzie dikes (Mandler and Clowes, 1997). The Winagami reflection sequence, of an age bracketed between 1.89 and 1.76 Ma, has been found over an area of 120,000 km² in western Canada (Ross and Eaton, 1997). The intrusive sheets, typically about 10–300 m thick, usually cut

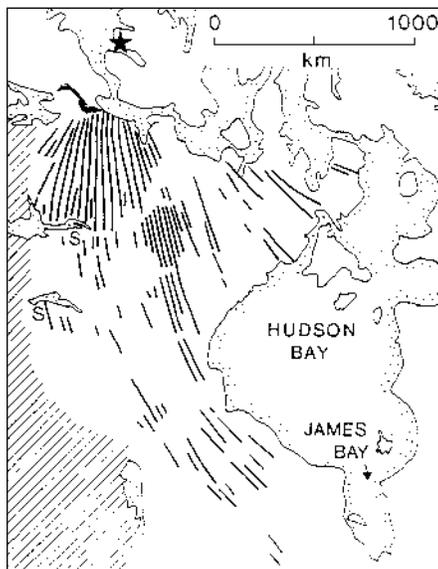


Figure 7. Simplified map of the Mackenzie giant radiating dike swarm (1.265 Ga) of northern Canada. S marks coeval sills; black area indicates coeval Coppermine volcanics. From Ernst et al. (1995).

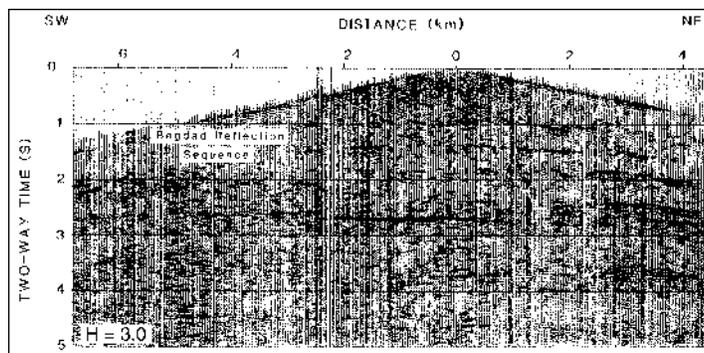


Figure 8. Subhorizontal intrusive sheets in the Precambrian crust of Arizona, imaged from a single large explosion (Goodwin et al., 1989).

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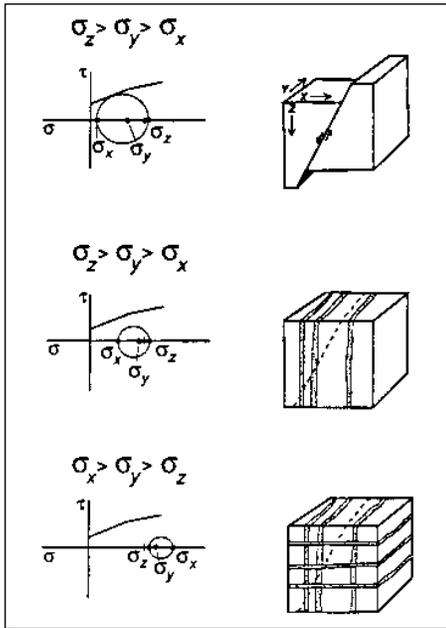


Figure 9. Progressive (from top to bottom) effect of dike injection on stress relations in an extending (normal faulting) environment. The Mohr diagrams show how dike inflation tends to increase the least horizontal stress, diminish the stress difference (shown by the diameter of the Mohr circle), suppress normal faulting, make the vertical stress least, and lead to injection of horizontal sheets. From Parsons and Thompson (1991).

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across rock fabric and reside at a range of mid-crustal depths. Similar subhorizontal intrusions are common the world over. Figure 8 shows a seismically imaged example from Arizona (Goodwin et al., 1989). The explanation for the process of subhorizontal sheet intrusion is intriguing (e.g., McCarthy and Thompson, 1988; Parsons and Thompson, 1991). As shown in Figure 9, dikes inject perpendicular to the least horizontal stress, as in artificial hydraulic fracturing, but unlike the hydrofrac process, magma chills against the fracture walls, inflates the dike, and in so doing increases the horizontal stress until the vertical stress becomes least. Melt then shoots off in horizontal sheets, again perpendicular to the least stress, lifting the crust above. Injection of a 5-m-thick dike is equivalent to a very large normal-fault earthquake in its effect on the elastic stress in the crust. Dike injection always tends to decrease the stress difference and therefore to suppress faulting and earthquakes.

Deep crustal reflection imaging now has the resolution to illuminate tectonic events and processes in three dimensions.

YELLOWSTONE MANTLE PLUME

The Yellowstone plume first emerged at the McDermitt caldera along the Oregon-Nevada border about 16–17 m.y. ago (Fig. 10), although it may have had ancestral expressions (Geist and Richards, 1993; Opplinger et al., 1997). From this center, dikes raced southward for hundreds of kilometers, forming the northern Nevada rift, and northward to feed the Columbia River flood basalts (Pierce and Morgan, 1992; Zoback and Thompson, 1978; Zoback et al., 1994). The Nevada aeromagnetic map (Fig. 11) shows the expression of the northern Nevada rift and subparallel or radiating rifts to the west. A map of exposed dikes in part of the rift is shown in Figure 12. A region perhaps 1000 km in diameter was buoyantly elevated perhaps 1 km by the starting plume head and has now tectonically extended and subsided. The effects of the plume in the northern Basin and Range province and eastern Sierra Nevada were dramatic and profound.

The extended crust is only half as thick as needed to support the elevation, and the excess buoyancy is in the upper mantle (Fig. 13). The relic of the Yellowstone plume head is a mass deficiency cal-

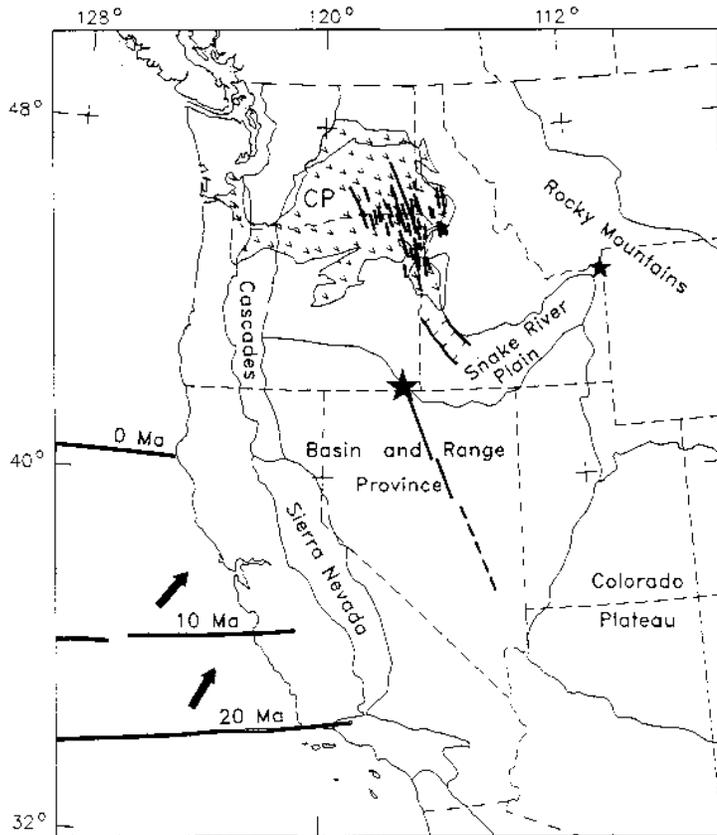


Figure 10. Emergence point of Yellowstone plume (large star), its track on the Snake River Plain, and its present position at Yellowstone (small star). The line extending south from the large star indicates dike swarms of the northern Nevada rift. To the north are shown the Columbia River flood basalts (CP) and their feeder dikes. Heavy lines at left indicate the position of the Mendocino fracture zone at three time intervals. From Zoback et al. (1994).

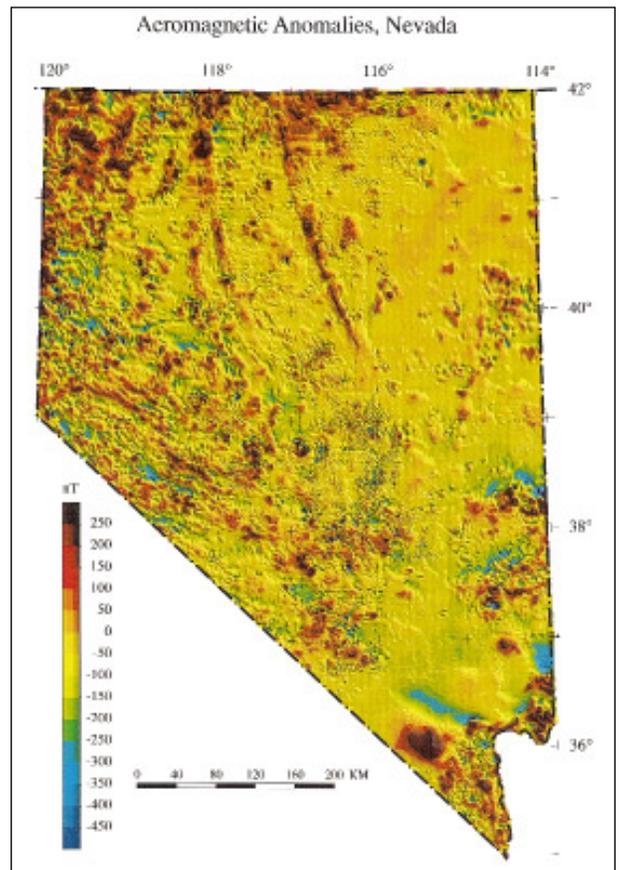


Figure 11. Aeromagnetic map of Nevada; the most prominent anomaly is associated with the dike swarms of the northern Nevada rift. Smaller subparallel anomalies west of the rift probably indicate concealed dikes radiating from the emergence point of the Yellowstone plume. From Blakely (1988).

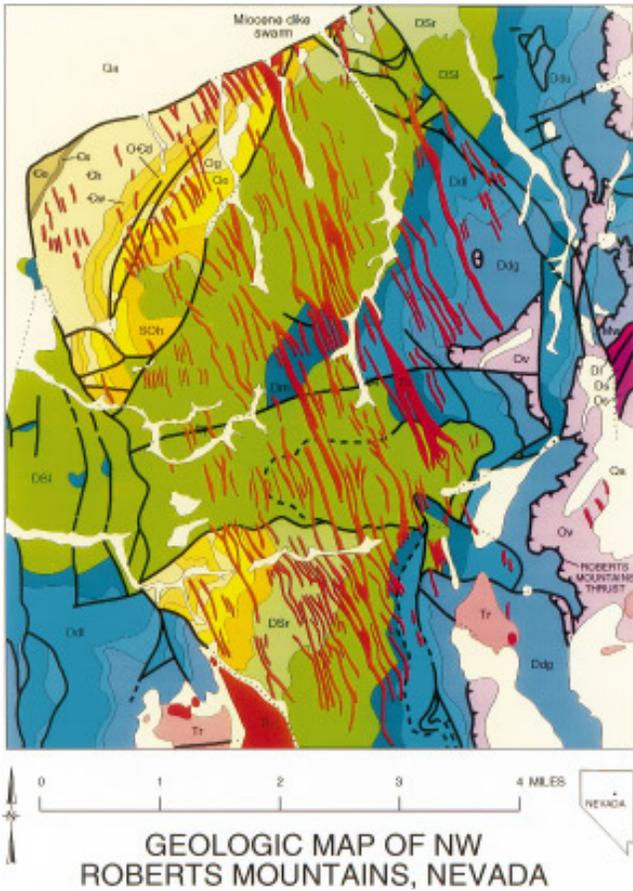


Figure 12. Dikes of the northern Nevada rift exposed in the Roberts Mountains. From Zoback et al. (1994).

culated by Parsons (Parsons et al., 1994) from seismic and gravity data. Meanwhile, the North American plate was moving southwestward, carrying much of the material of the plume head with it, while the plume tail or stem produced a remarkable volcanic track along the eastern Snake River Plain to its present location beneath the Yellowstone Plateau (Fig. 14; topographic track is 100 km wide).

Remarkably, as the Basin and Range terrane extended southwestward in this region, breaking into large normal-faulted blocks and producing large earthquakes, the Snake River Plain somehow extended along with the surrounding mountains but without large normal faults or earthquakes. The key to this puzzle is revealed by lines of basaltic vents and minor rifts, marking dike swarms that extend across the plain (Fig. 15). The plain stretched by dike injections in a process akin to ocean-ridge spreading (Fig. 16).

The Yellowstone mantle plume, in summary, powered much of the late Cenozoic tectonic and magmatic activity in a broad region.

CENTRAL ATLANTIC (CAPE VERDE) PLUME

Primary evidence for the giant Central Atlantic, or Cape Verde, plume (Fig. 17) is an extraordinary system of Jurassic diabase dikes (Fig. 18) that radiated from approximately the Blake Plateau off the southeastern U.S. coast for thousands of kilometers into North America, South America, and Africa at a time when these continents were still joined. May (1971) recognized the unity of this dike system in a paper, published, I'm happy to say, in the *GSA Bulletin*. Corresponding flood basalts are seismically imaged offshore (Lizarralde and Holbrook, 1997; Kelemen and Holbrook, 1995; Fig. 19 here), and along with intrusive rocks

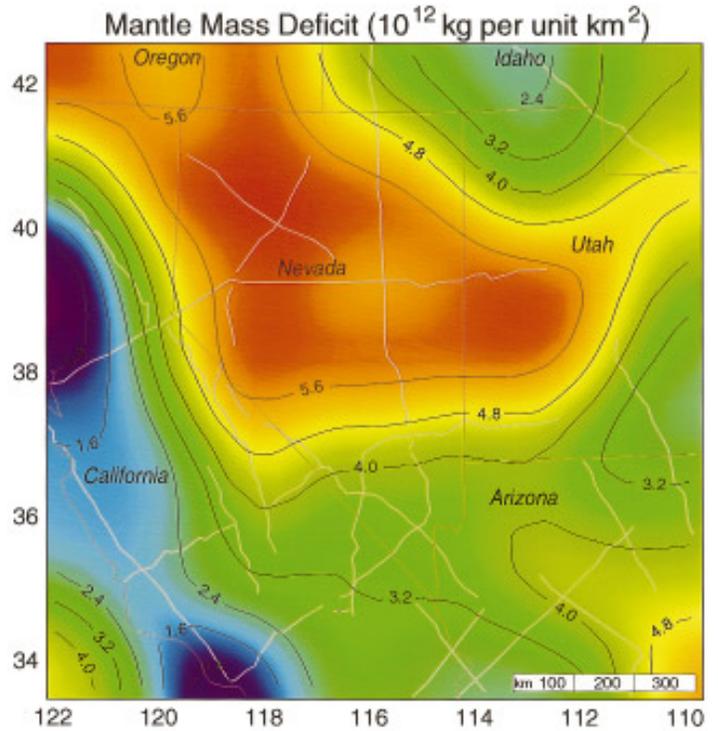


Figure 13. Probable location of the plume head of the Yellowstone hotspot, expressed as mantle mass deficiency (or excess buoyancy) per unit area, as calculated from crustal seismic data and gravity constraints. From Parsons et al. (1994).

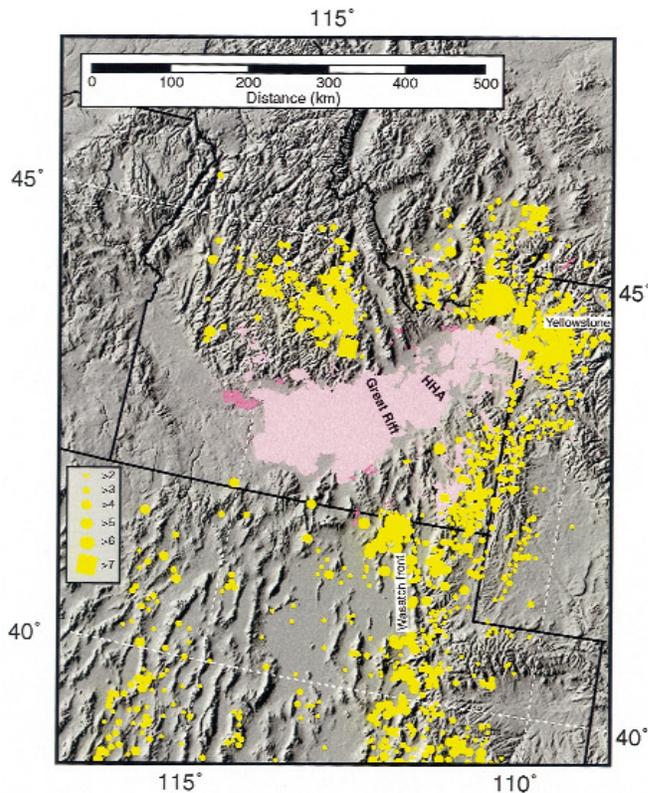


Figure 14. Plume track of the Yellowstone hotspot, forming the eastern Snake River Plain, and Basin and Range fault blocks to the north and south of the plain. Yellow marks earthquakes. From Parsons and Thompson (1991).

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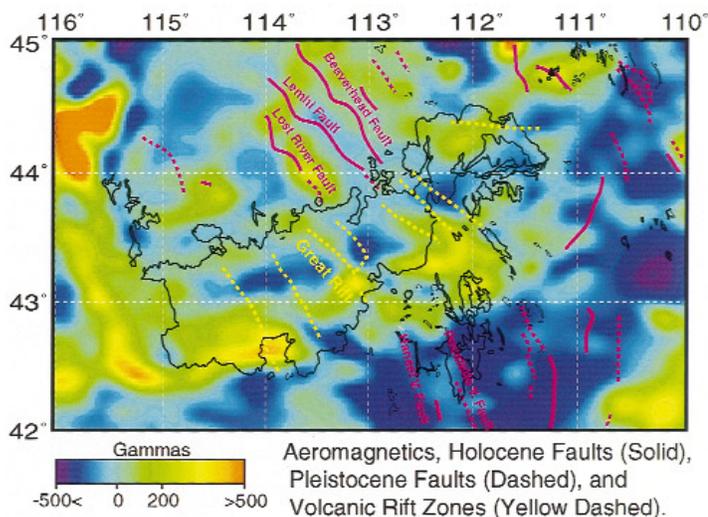


Figure 15. Lines of basaltic vents and minor rifts (dashed yellow lines) extending across the eastern Snake River Plain. From Parsons et al. (1998).

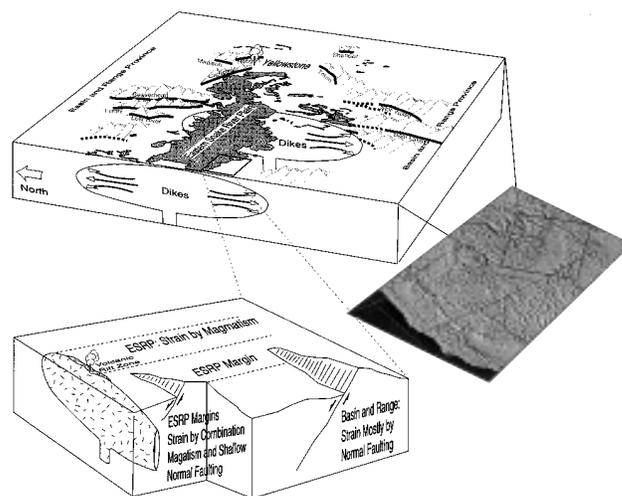


Figure 16. Model for aseismic strain by dike injection in the eastern Snake River Plain (ESRP) and transition to block faulting off the plain. From Parsons et al. (1998).

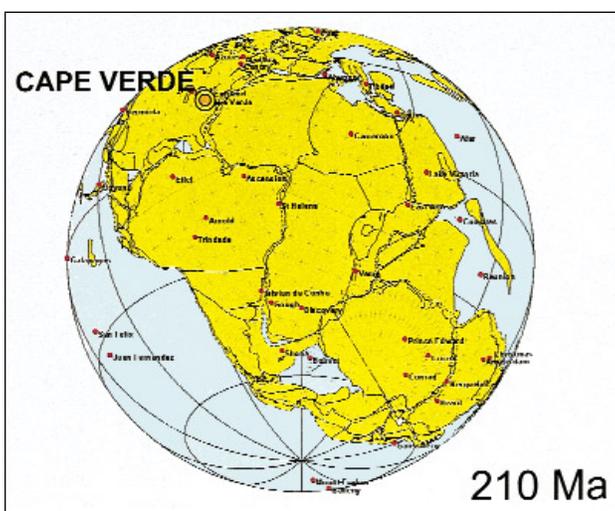


Figure 17. Location of the Cape Verde and other plumes at 210 Ma. From unpublished work of Stephen Gardoll (University of Western Australia) and Andrew Long (Stanford University).

201 Ma, Early Jurassic (e.g., Deckart et al., 1997; Weems and Olsen, 1997, p. 199). But well before the magmatic activity broke out, eastern North America began to pull apart in the extensive system of Triassic, sediment-filled rifts roughly parallel with the coast and with the earlier Paleozoic structures. The plume head underlay this region (Fig. 17). When magma broke through the lithosphere, radial and then rift-parallel dikes were injected for thousands of kilometers. The pattern is complex in detail; for example, in North America a pulse of magma generated a prominent subcenter of dikes radiating from near the coast of South Carolina (Ragland et al., 1983).

In the hard Paleozoic and older rocks, the pressurized magma fractured and injected the rocks as dikes. Figure 21 shows a part of the Virginia geologic map (Virginia Division of Mineral Resources, 1993) with generally straight dikes cutting the older rocks. But in the softer sedimentary rocks of the Triassic Culpeper Basin in Virginia (Fig. 22), the magma ballooned into huge irregular dikes, sills, and blobs. Similarly, in the Gettysburg Basin in Penn-

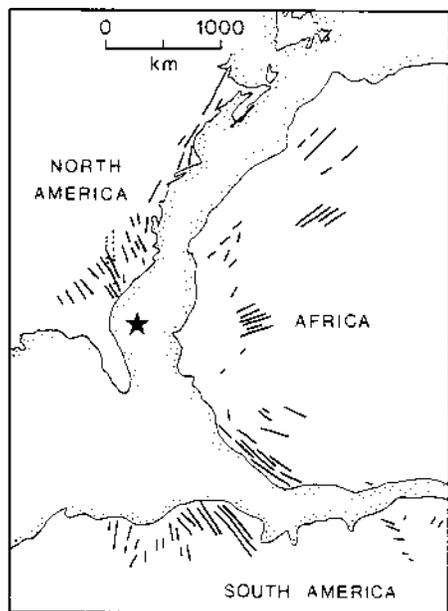


Figure 18. Giant swarm of Early Jurassic dikes radiating from offshore eastern North America (star) into the three continents before breakup. From Ernst et al. (1995).

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that inflated the crust, they are responsible for the East Coast magnetic anomaly (Fig 20). Here are the missing flood basalts! Modern, high-quality radiometric dates on dikes and flows on the three continents cluster around a starting time of about

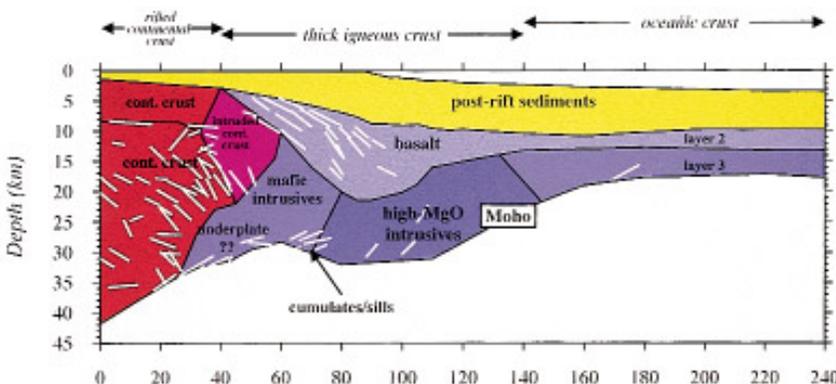


Figure 19. Cross section of the Atlantic margin of North America constructed from seismic images. From W. S. Holbrook (Lizarralde and Holbrook, 1997).

Figure 20. East Coast magnetic anomaly (ECMA), produced by the flood basalts and intrusions shown in Figure 19. From W. S. Holbrook (Lizarralde and Holbrook, 1997).

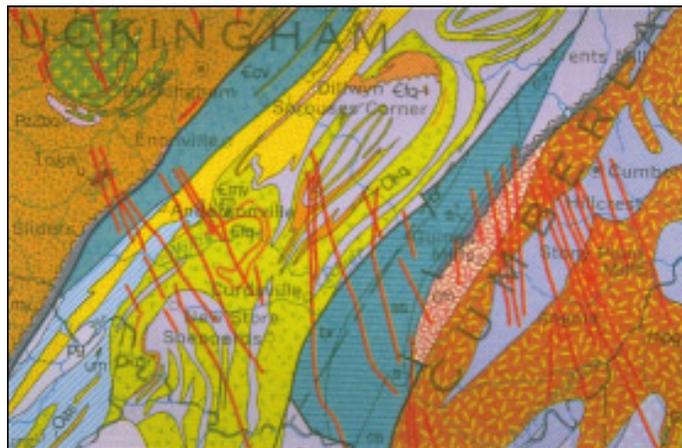
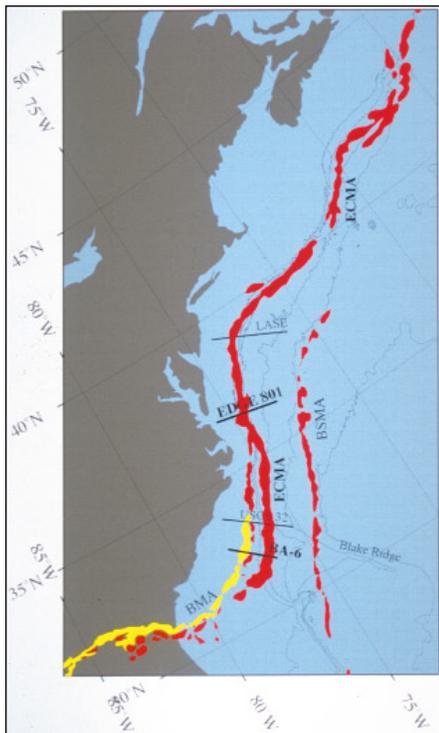


Figure 21. Part of the geologic map of Virginia (Virginia Division of Mineral Resources, 1993), showing the diabase dikes (red) cutting hard Paleozoic rocks. Width of area shown is 40 km.

sylvania, shown at a larger scale in Figure 23 (Pennsylvania Department of Environmental Resources, 1980), one sees the ballooning of the diabase intrusions. Here the master fault of the half-graben is on the north side and is now almost obliterated by the intrusive diabase. Also on the north side is the location of the great Cornwall magnetite deposit, which operated from well before the Revolutionary War until 1972, when a hurricane shorted out the power supply to the electric pumps. Ore deposits like Cornwall derived their iron and copper, as well as the heat for hydrothermal circulation, from the diabase intrusions, and

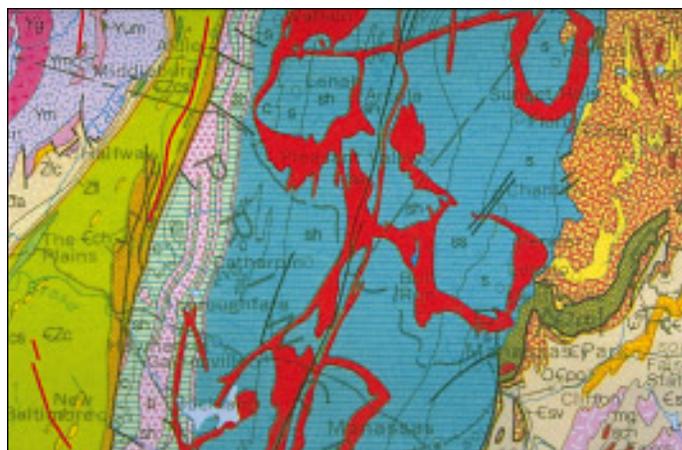


Figure 22. Another part of the geologic map of Virginia, also an area 40 km wide, showing the diabase ballooning in the Triassic sedimentary rocks of the Culpeper Basin.

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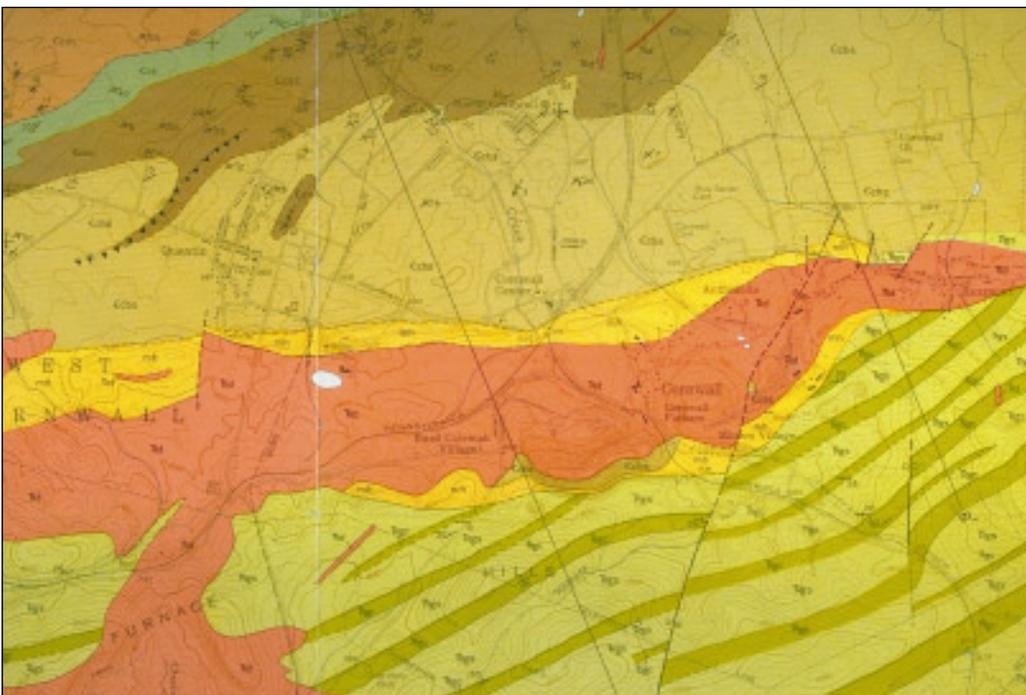


Figure 23. Part of the geologic map of Pennsylvania (Pennsylvania Department of Environmental Resources, 1980), 8-km-wide area, showing the northwest-dipping bands of Triassic sedimentary rocks (lower right) in the Gettysburg Basin. The huge irregular diabase intrusions (orange) balloon in the Triassic sedimentary rocks and mask the northern boundary fault of the half-graben. The northern boundary is the site of the historical Cornwall iron mine.

Figure 24. Location of the Cape Verde plume at 170 Ma, after initial opening of the Atlantic Ocean. From unpublished work by Stephen Gardoll (University of Western Australia) and Andrew Long (Stanford University).

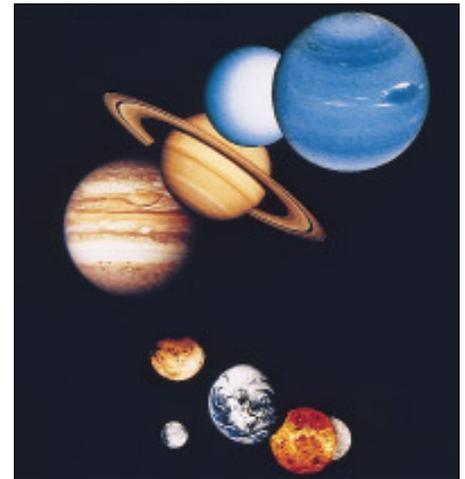


Figure 26. Earth, the blue-green water planet, is uniquely beautiful. From the National Academy of Sciences.

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Paleozoic carbonates precipitated the ore. Thus, a convective plume originating at the core-mantle boundary shaped our landscape and history in this region!

Meanwhile, the Atlantic had begun to open (Fig. 24). We can trace the path of the Central Atlantic plume and identify it clearly as the Cape Verde plume (Fig. 25). The Atlantic fracture zones (e.g., Kane; see Fig. 25) show the path of opening. The oldest magnetic stripes preserved in the ocean floor on both sides of the Atlantic date to about 170 Ma. As the African plate held nearly stationary in the hotspot frame of reference, North America sailed slowly away to the northwest at about the rate a fingernail grows. And the early Mid-Atlantic Ridge also moved northwest at half the North American rate, quickly

advancing across and beyond the Cape Verde plume. Thus, the plume was captured by the nearly stationary African plate around 150 Ma and remains on the African plate today.

CONCLUSIONS

The immense volume of the hot plume head, and the lesser ongoing flow of the Cape Verde plume column, profoundly influenced the tectono-magmatic events on three continents. In western North America, the Yellowstone plume head spread widely, burped out the Columbia River basalts, and reactivated Basin-and-Range uplift and extension. The Yellowstone plume column, or tail, left a spectacular track, the eastern Snake River Plain, on the moving plate, and on the way revealed to us another mechanical process besides normal faulting for the

continental crust to stretch, namely by emplacement of dikes, like the stretching at oceanic ridges.

These dramatic tectono-magmatic events are not mere passive consequences of the Atlantic opening or, in the west, passive consequences of older compression and subduction, but resulted from powerful new inputs of plume energy.

The paradigm of deep mantle plumes, like plate tectonics or asteroid impacts, supplies a wonderful unifying concept for geoscientists and for communicating our science to the world at large. Walter Sullivan said it well: "The discovery that there is order and logic in the seeming randomness of nature can be a quasi-religious experience. There is great beauty to be found there, and the successful teachers and writers who, having glimpsed it, are driven to share it with others." [Quoted by Bruce Alberts in address to National Academy of Sciences, April 1996]

Earth, our beautiful blue-green water planet (Fig. 26), is clearly the best of the lot and deserves all the care that we can give to it!

ACKNOWLEDGMENTS

I am indebted to many colleagues who, sometimes unknowingly, served as inspiring teachers. I am especially indebted to Norm Sleep and Tom Parsons for illuminating discussions of the growing knowledge about mantle plumes. The support of a talented and generous GSA staff made my year as president enjoyable and, I hope, productive.

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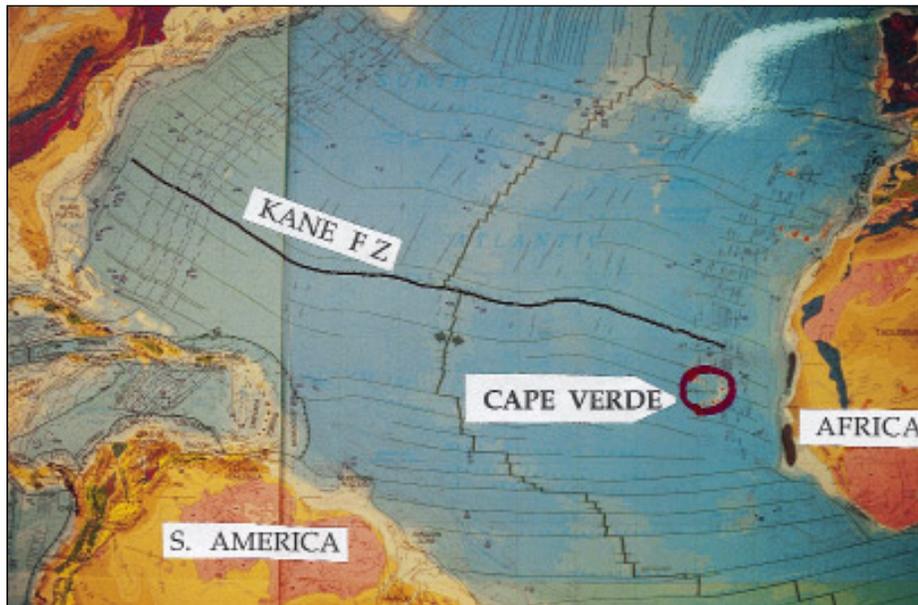


Figure 25. The present-day Atlantic ocean, showing fracture zones and magnetic chrons in relation to the Cape Verde hotspot. The fracture zones, marking the path of opening, lead clearly from the center of the Jurassic radial dike swarm (approximately at the Blake Plateau) to the Cape Verde hotspot. See text for further explanation. From Exxon Production Research (1985).

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LETTER

The recent article by Eugenie Scott on "Creationism and Evolution" in the January *GSA Today* (SAGE Remarks) prompts this comment. As one who has been teaching for many years an undergraduate course on Darwin and the *Origin of Species*, I would like to provide another, rather different perspective on the creationism and evolution debate.

The approach I have found most useful for my students is to make clear the distinct epistemological differences between the rival claims of creationists and evolutionists. The epistemology of each side is diametrically opposed: what they know, how they know it, and the limits of their knowledge. The creationist is unequivocally committed to textual *content*, namely the literal meaning of Biblical Genesis, and disbelieves anything that contradicts that content. The evolutionist, by contrast, is thoroughly committed to *method*, namely drawing logical inferences from reproducible observations. Whereas the evolutionist will revise current content if the results of the method so dictate, the creationist has no method and simply relies on an inerrant text.

It is not rational, therefore, for the well-meaning evolutionist to expect that there is some critical body of evidence,

external to literally interpreted Biblical claims, that will win over a creationist, because there is none, for the rules by which one assesses "truth" are fundamentally different for each side of the debate.

I have found that focusing on the underlying epistemologies of different realms of knowledge—science, religion, the arts—is more instructive for students as a way for their discovering what is more likely credible and useful with respect to certain aspects of human experience. Thus, one should rely on the epistemology of science for the removal of a cancer; religious belief might console after the death of a loved one; and the arts can enrich aesthetic experience.

This emphasis on an epistemological approach to knowledge will win over many more adherents to evolution in particular, and science more generally, than the fruitless debates about creationism that too often degenerate into "is"/"isn't."

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