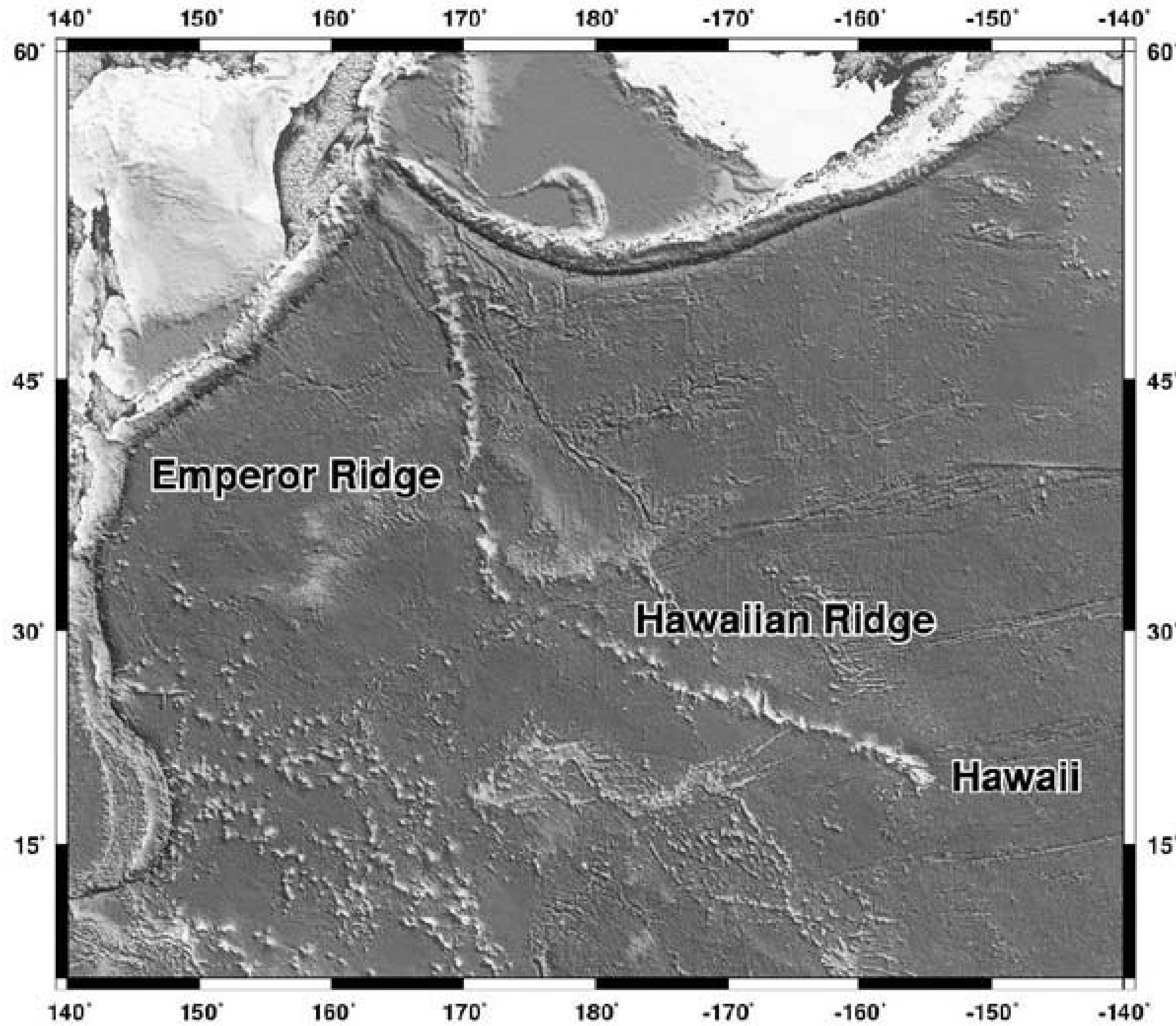
Hawaii, we thought we knew you

The classic Plate Tectonics story for Hawaii now appears to be mistaken. The Pacific plate did not suddenly change directions, and there is no deep, stationary plume. Other explanations fit the evidence better.

(This discussion is presented in the Plate Tectonics paradigm, referencing professional geologic journal papers. The Shock Dynamics perspective is described afterwards.)



Introduction

The chemical makeup of magma extruded at the surface is not all the same. Put simply, the recipes are Mid-Ocean Ridge Basalt (MORB) and Ocean Island Basalt (OIB), with variations on these two. Attempts to determine the sources of the different chemistries and why they appeared where they did was a principal inspiration for the plume theory. Earth was considered to have a number of distinct layers in it down to the core, each having a particular chemistry that was generally the same (homogeneous) throughout the layer. Thermal plumes were conceived to transport material from deep layers to the surface, and the Hawaiian plume became the main example. There have long been challenges to the plume concept, but these have intensified over the last 15 years as tomographic and chemical data have improved. The rebels have the smaller army in this battle, but they are energized. They offer new interpretations of Earth's interior that change everything we learned in school about Hawaii.

The original idea

In 1963 Wilson suggested that the Hawaiian Islands formed as the Pacific plate moved over continuously upwelling hot mantle. In 1968 Christofferson conjectured that the Emperor-Hawaii elbow records a change in direction of the Pacific plate over a fixed "hotspot". In 1971 Morgan speculated that the heat source is a stationary "plume" rising vertically through the deep mantle, and this has been widely accepted.[6]

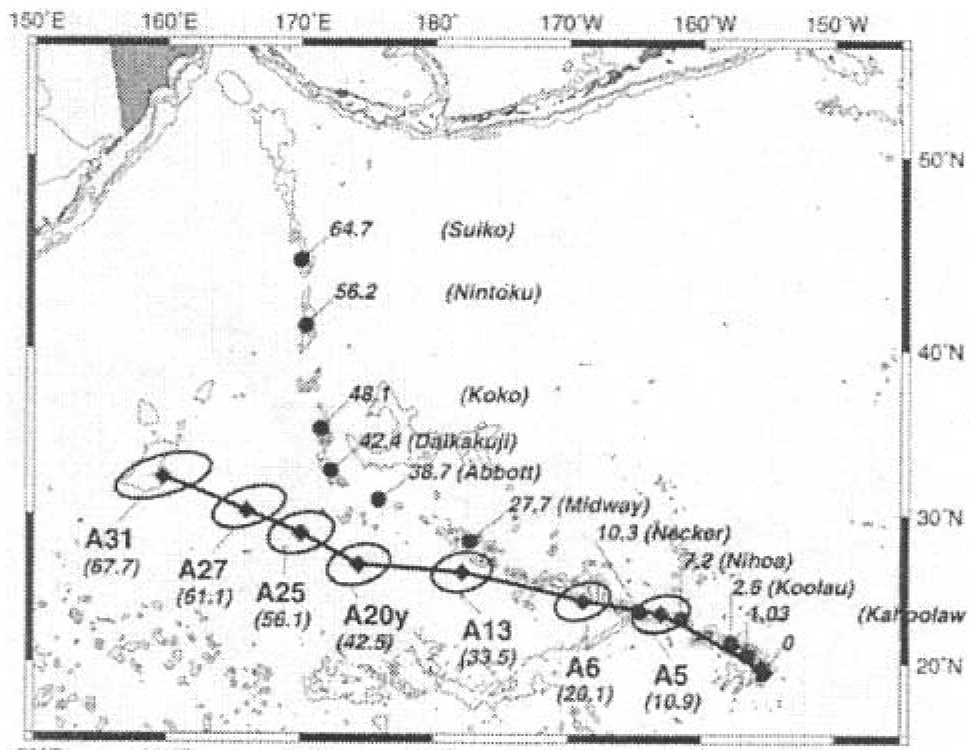
"The Hawaii-Emperor island and seamount chain is the most prominent morphologic feature on the seafloor, with a sharp 60 degree change in azimuth, called the Hawaii-Emperor bend (HEB). The HEB serves as a textbook example of the fixed hot spot hypothesis, in which changes in the azimuth of volcanic lineaments are explained by changes in plate motion, and the hot spots that created these volcanoes remain fixed beneath the moving tectonic plates."[9] "Hawaii is thought to be the strongest currently active plume."[13]

Challenging the original idea

"Simple tests falsify conjecture that the...Emperor-Hawaii system formed above a stationary plume. As this is the only testable purported plume, global speculation favoring fixed plumes falls with it."[6]

1) Pacific plate motion - no rapid change in direction

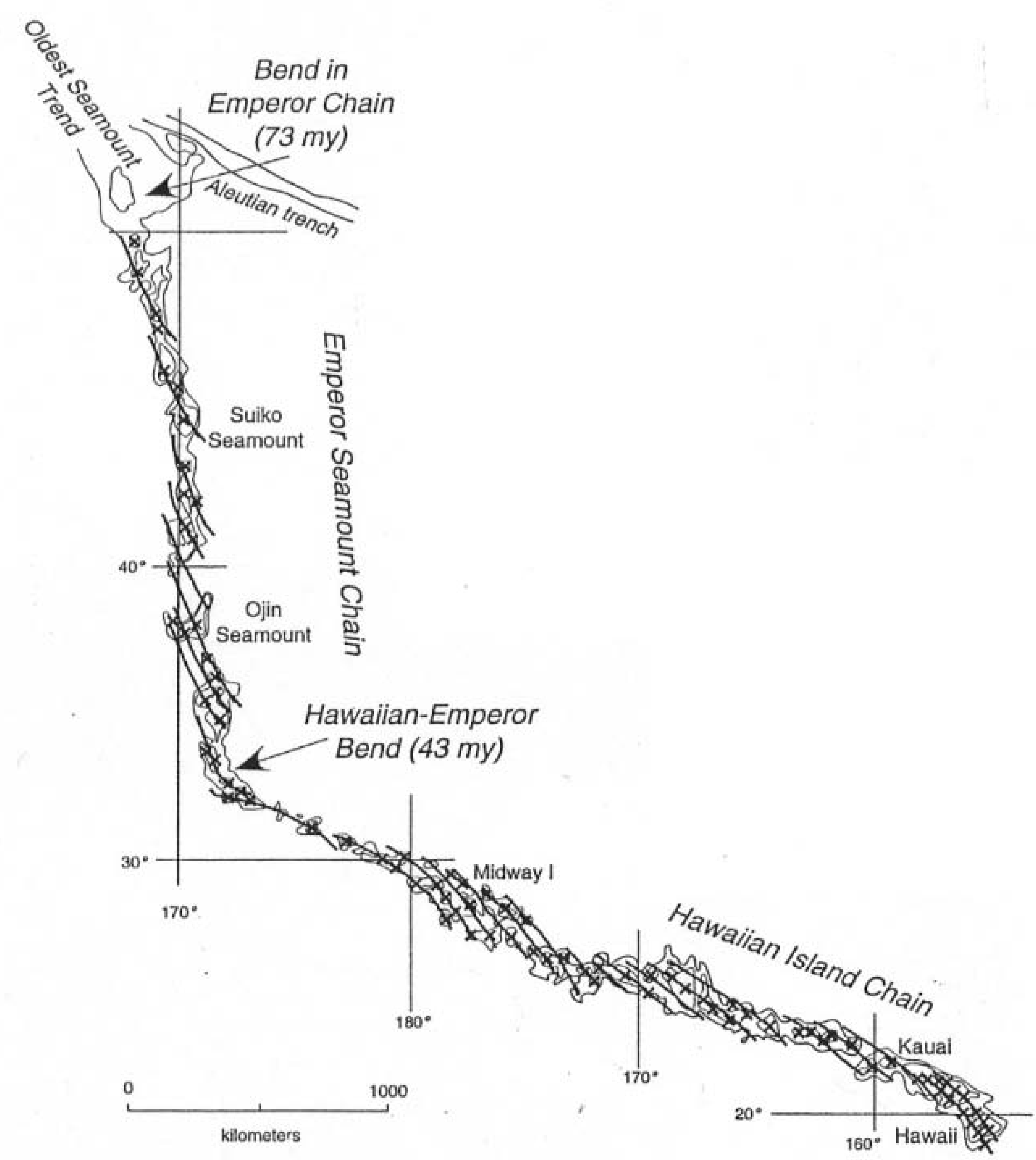
The concept requires "an enormous reorganization of Pacific Ocean plates 45 million years ago."[6] This is not found anywhere "along the northeast, east, or south sides of the Pacific plate," where crust of that age is preserved.[6] "The Pacific-Antarctic Ridge is the key link... tying the relative motion of the oceanic plates of the Pacific basin to the rest of the world."[2] A survey of the Pitman Fracture Zone along this ridge was carried out in 1992. The authors concluded that "predictions of the track of the Hawaiian hot spot based on global reconstructions fail, once again, to predict a large bend around 43 million years ago."[2] Next, "the Gilbert Ridge and Tokelau Seamounts are the only seamount trails in the Pacific Ocean with a sharp 60 degree bend, similar to the HEB." "The Louisville seamount trail is not useful... because it shows only a very broad curvature at its bend." Their study found that the Gilbert Ridge bend formed around 67 million years ago, while the Tokelau bend formed about 57 million years ago. They should have formed at the same time as the HEB, around 47 million years ago, "if they were formed by stationary hot spots, and assuming Pacific plate motion only." "Such asynchronous bends cannot be reconciled with the stationary hot spot paradigm."[9] In addition, "improved mapping of marine magnetic anomalies in the Pacific has failed to define the directional change at 43 million years ago." "There was also a general lack of circum-Pacific tectonic events documented for this time. Recent age data suggest a slightly older age for the bend, about 47 million years ago, but this revised timing still does not correspond to an episode of profound plate motion change recorded within the Pacific basin or on its margins."[15] "The textbook explanation for intraplate volcanism by fixed hot spots is either entirely wrong or insufficient to explain these phenomena."[9] The most recent study of volcanoes of the central and southern Emperor chain claims that the Hawaii-Emperor Bend started at 50 million years ago.[12] This is still far off of the 57 and 67 million years ago that are designated for the Gilbert Ridge and Tokelau Seamounts, and does not lessen the misfit between the predicted track of the Hawaiian hotspot, using magnetic anomalies at the Pitman Fracture Zone, and the actual island chain (below).



Predicted hotspot track (circles) using Indo-Atlantic hotspot reference frame.[2]

2) Segments en echelon - volcanoes not in one line

Instead of a straight line of volcanic islands, volcanic ridges are oriented en echelon.[7]



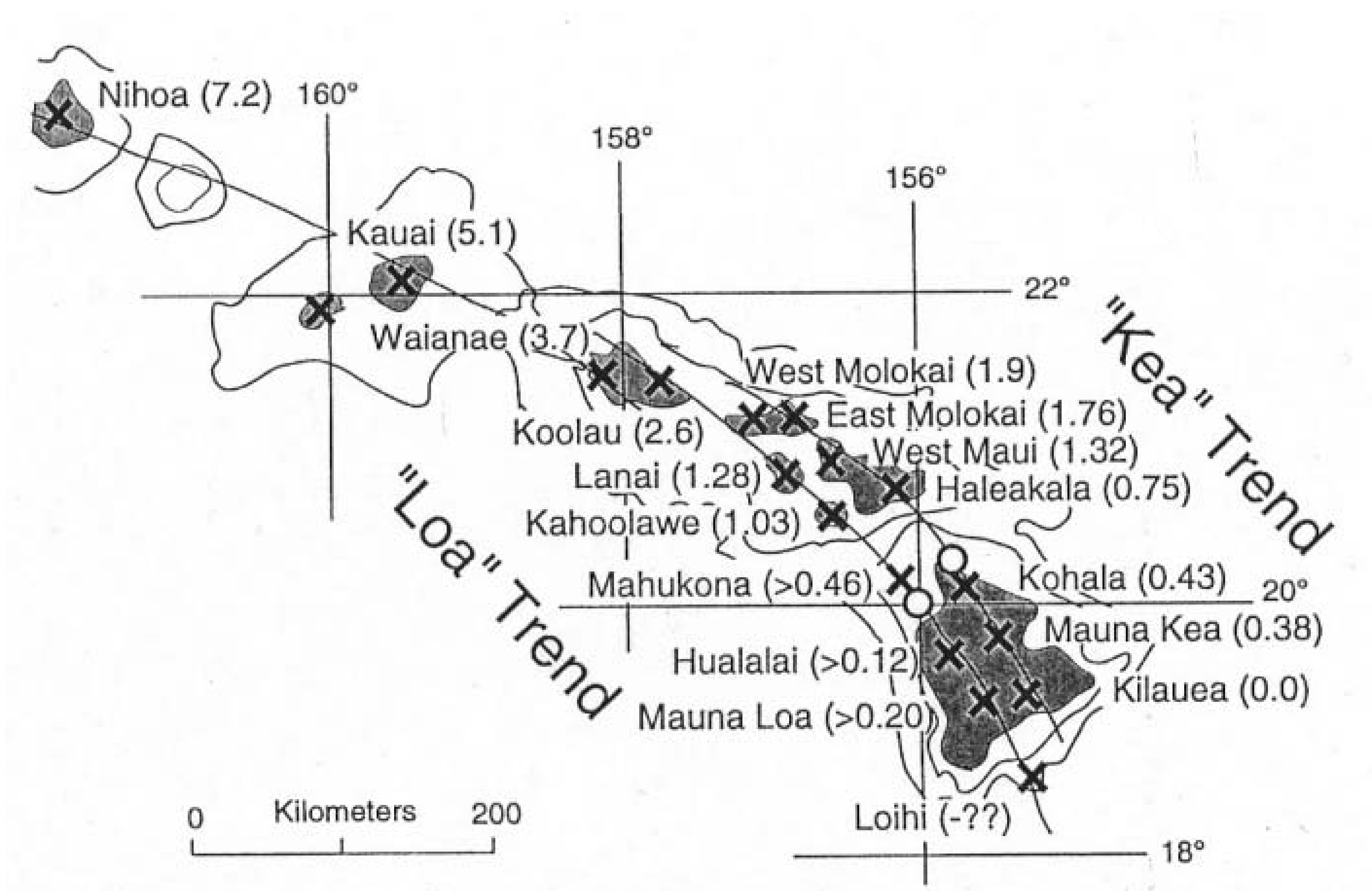
3) Plume swell (bulge) - not all there

A rising plume that reaches the lithosphere "would be expected to produce an uplift of the lithosphere which should be easily testable. Topographic swells such as those around the Hawaiian islands hence became evidence of the existence of plumes" As it turns out, "the size of the swell does not decline along the Hawaiian chain, and there is no corresponding swell associated with the Emperor chain."[13]

4) Plume heat - missing

"Unfortunately for the hotspot model, measurements along the axis of the Hawaiian swell suggested an increase in heatflow with distance away from the supposed site of the plume." Instead of a bulge, the swell may "merely represent a thick section of basalt".[13] "The concept of a Hawaiian plume is incompatible with detailed surface-wave tomography that shows Hawaii, and other purported hotspot swells southwest of it, to sit atop cool high-velocity mantle, not hot low-velocity mantle as required by plume conjecture. No plume-predicted thermal anomaly exists."[6]

5) Basalt chemistry - lots of variation



"The volcanoes along the Hawaiian Islands align along two distinct geographic segments (the 'Loa' and 'Kea' trends). Geochemical studies of the lavas that make up the Hawaiian Island volcanoes... point to the puzzling feature that two mature volcanoes situated only 40 km apart (Mauna Loa and Kilauea) are remarkably dissimilar in their geochemistry. In fact, geochemical variations... along the Loa trend show gradational changes with decreasing volcano age [see below], while the... volcanoes in the Kea trend are chemically distinct from adjacent volcanoes in the Loa trend."[7]

Geochemistry of mainstage tholeiites from Koolau, Mauna Loa, and Loihi representing Loa's "head" to "tail"

		Koolau (head)	Mauna Loa →	Loihi (tail)
Major Elements:	SiO_2*	53.0%	51.0%	49.5%
	Al_2O_3*	14.0%	13.5%	13.0%
	CaO*	9.0%	10.4%	12.5%
Trace Elements:	TiO_2*	1.8%	2.0%	2.5%
	Ba/La*	11	9.9	8.3
Radiogenic Isotopes:	$^{87}Sr/^{86}Sr$	0.7043	0.7039	0.7035
	$^{143}Nd/^{144}Nd$	0.51275	0.51285	0.5130
	$^{206}Pb/^{204}Pb$	17.8	18.1	18.4
Helium Isotopes:	$^{3}He/^{4}He$ (R_A)	10	15	28

* For lavas with MgO ~ 8.0 wt%.

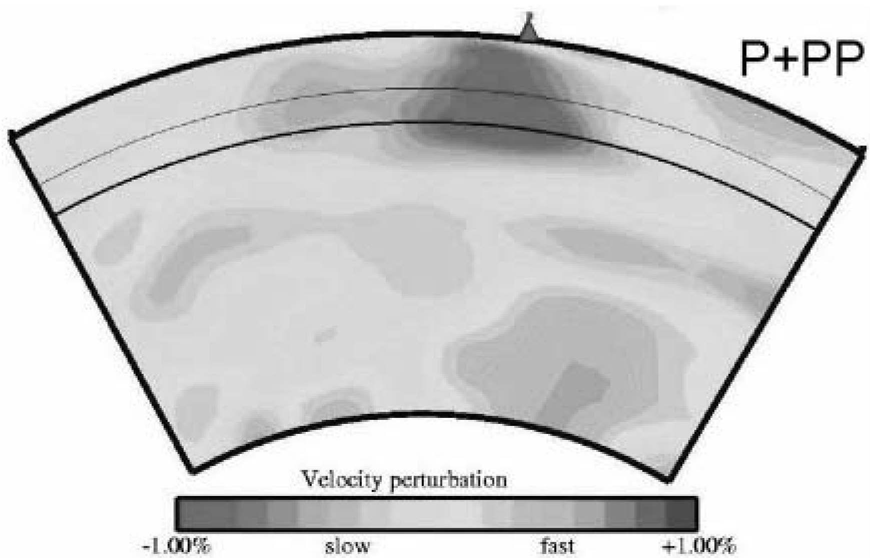
6) Hotspot stability - much motion

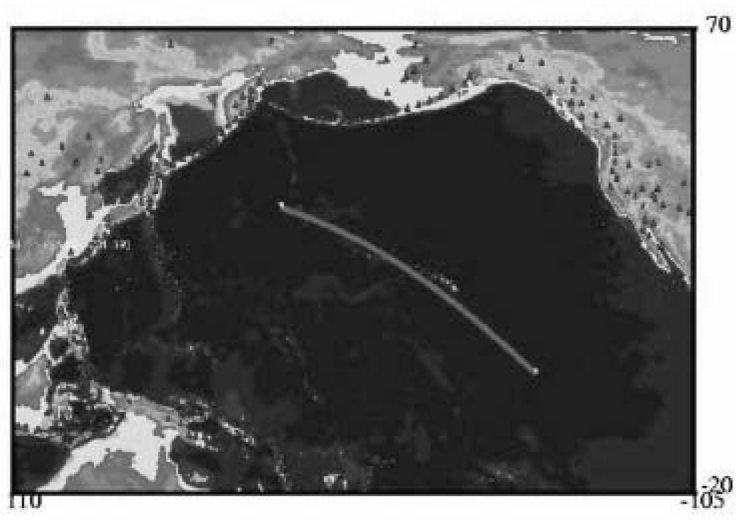
"It has long been known that purported hotspots move relative to one another."[6] "Comparison of an updated inventory of Pacific and non-Pacific paleomagnetic data... indicates that missing plate boundaries and other errors in the plate circuit play a relatively small role in the" relative movement. "Motions between East and West Antarctica can account for little more than about 20% of the apparent motion between the Hawaiian-Emperor hotspot and the Indo-Atlantic hotspots. The residual offset between the predicted and actual hotspot position cannot be explained by reconstruction uncertainties of the magnitude usually discussed." "We conclude that most of the apparent motion between the Hawaiian-Emperor and Indo-Atlantic hotspots is real."[5] Also, "global plate circuits suggest large relative motions between Hawaii and hotspots in the Atlantic and Indian Oceans.[15] Relative motions have been calculated to be "as rapid as 8 cm per year, faster than most relative motions between plates."[6]

Plume theory seems infinitely flexible. Researchers have proposed putting plumes in motion to solve the problem. Using paleomagnetic and radiometric age data, one group found that "the Emperor Seamount trend was principally formed by the rapid motion (over 4 cm per year) of the Hawaiian hotspot plume."[15]

Plumes are considered to advance in stages: first, the plume head and tail rise together. Then the head flattens and is assimilated, leaving only the tail. Finally, the tail is distorted by mantle flow, and may split into separate, winding segments. Melt zones "under hotspots usually do not show a straight pillar shape, but exhibit winding images, suggesting that plumes are not fixed in the mantle but can be deflected due to the influence of mantle flow."[18] Complicating the matter, "the distribution of seamounts in time and space... indicate that either the Pacific plate has undergone numerous short-term velocity changes or the path of the upwelling plume has been affected in some way."[7] One researcher proposed that hotspot motion southward may be due to deep mantle flow, but upper mantle convection cell return flow may be stringing out the top of the plume in the opposite direction.[3] Another proposed that individual "plumelets" rise from a single deep melt zone, each plumelet forming a seamount segment.[7] In the end he wondered why the supposed change in Pacific plate motion had so little effect on underlying mantle flow, and why "the generation of a new subduction zone (such as along the Tonga-Kermadec trench at about 45 million years ago) and subsequent intrusion of slab material exerted no observable impact on flow in the underlying mantle.[7]

7) Tomography (like a seismic MRI) - conflicting images





"Hawaii should have the most readily resolvable conduit [tail] as it is situated away from ridge systems and is supposedly the strongest plume." Two studies in 1998 "searched for low-velocity anomalies [melt zones] in the lower mantle beneath the hotspot, but found no low-velocity anomaly which correlated with the surface expression of volcanism." So both invoked plume deflection to resolve the issue. But while one "suggested the conduit to lie to the southeast of Hawaii," the other "claimed a double conduit to the northwest of Hawaii."[13] Similarly, the author of a 2004 tomographic study believes his cross-section shows the prominent melt zone beneath Hawaii connected by a thin melt zone to a moderate melt zone offset to the north and down to the core-mantle boundary (below 2700 km). However, his regional tomographic map shows the prominent melt zone thinning considerably below the transition zone (660 km), reappearing offset to the west at 1100 km depth, and disappearing below 1820 km. So the plume would be deflected by mantle flow to the south or to the east.[18]

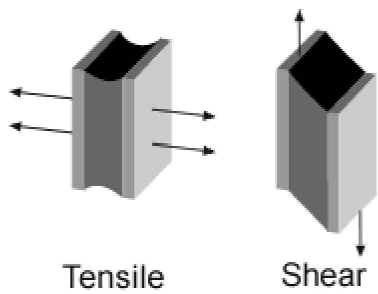
Tomography based on the travel-time of seismic waves has some inherent difficulties. "Seismic ray coverage is highly variable, and different types of rays are used to interrogate different depths." Tomography can show a false picture if the mantle is assumed to be uniform and it is not. Shallow heterogeneities (areas of varying density) and anisotropy (crystal alignment) can smear tomographic images when the mantle is assumed to be uniform, and most models do. Since most of the world's earthquakes occur in slabs, and many seismic stations are in their vicinity, the opportunity exists to smear this shallow anisotropy into an image of a deep slab. "Normal tomographic [images] cannot cancel out slab anisotropy, particularly in the deep mantle where seismic ray coverage is poor." Tomography shows that "in current subduction zones, descending slabs flatten out between 500 and 800 km." The supposed slabs in the deep mantle are separated, and up to 1500 km from expected locations.[1]

Return of an old idea - lithosphere crack

"The lithosphere crack model [is] the main alternative to the mantle plume model for age-progressive magma emplacement along the Hawaiian-Emperor volcano chain".[16] Calculations done in a 2007 study found the "incremental stress field has the form necessary to maintain and propagate a tensile crack... and is thus consistent with the crack model for the Hawaiian volcano chain."[16] In this model, "the cause of the Hawaiian-Emperor Bend may have been a rapid change in the thermoelastic stress field associated with the disappearance of ridge segments"[16] at plate boundaries.

"The obvious alternative" to plumes forming seamount chains is "extension that permits rise of partial melt from the asthenosphere" [between the mantle and crust]. Thus the en echelon segments in seamount chains are "extensional fissures", so that extension controls the propagation of the chain.[6] "The starting point for the construction of any counter-model has to be an acceptance of the evidence for amphibole and phlogopite in the source of OIB." "Intraplate volcanism results predominantly from compositional, not" heat differences. "The low melting point of such minerals would make them susceptible to shear melting to generate intraplate tracks." These have been called "wetspots" as opposed to "hotspots".[13] "The Hawaiian chain sits on a buoyant pad of mantle rich in magnesian olivine, and magmas must be rising in fissures, not broad plumes." "Volcanoes will form wherever this potential melt can be tapped: the problem is access to the surface, and there is no... need for unique heat sources, nor any geochemical need for deep sources of components of melts. Volcanoes are products of" "extension" and "propagating cracks".[6]

"The crack model... was suggested for the Hawaiian volcanic chain as far back as 1849."[4] In 1973, intraplate volcanism, including Hawaii, was proposed to be caused by lithospheric stress, with intermittent eruptions due to the shallowness of the source regions. "Cessation of volcanism in the absence of changes in the stress field can be explained by exhaustion of low-melting point minerals." On the other hand, opening a melt pocket would give the impression of the arrival of plume material.[14] In 1975, two authors wrote "we conclude that the trends and age correlations of volcanic loci in the Pacific accurately track and identify the evolution of states of stress in the Pacific lithosphere with time." There was "magma injection from a source in the asthenosphere into a rigid Pacific plate subjected to rotations of principal stress directions."[8] A 1987 study evaluated two other hypotheses, small-scale convection and compressive buckling, and decided in favor of tension (pull apart) cracks in the Pacific plate. The shape and positions "of the en-echelon ridges suggest that they result from filling of tensional cracks in the lithosphere." "Experimental and theoretical studies... show that plastic yielding occurs... oriented 55-60 degrees from the direction of tensile stress." "Extension opens the cracks and shear produces the en-echelon pattern." Pacific plate earthquakes "show plate-wide tension oriented NNE." However, their "data do not indicate the source of the tensile stress", and they speculated on several possibilities.[17]

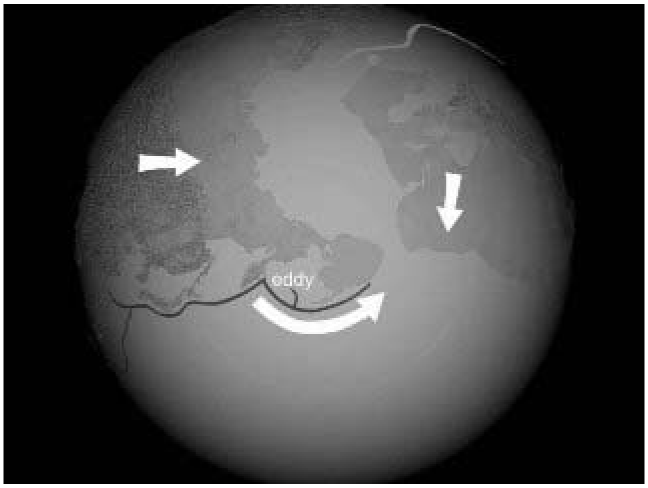


If one or more chains of linear volcanic ridges are shown to be formed by extension rather than by fixed hotspots as previously proposed, then the application of the fixed-hotspot model to other linear volcanic chains may be questioned.[11] The authors of the Gilbert Ridge/Tokelau Seamounts study mentioned above proposed "that the southwestern Pacific plate experienced two such short-term extensional phases."[9]

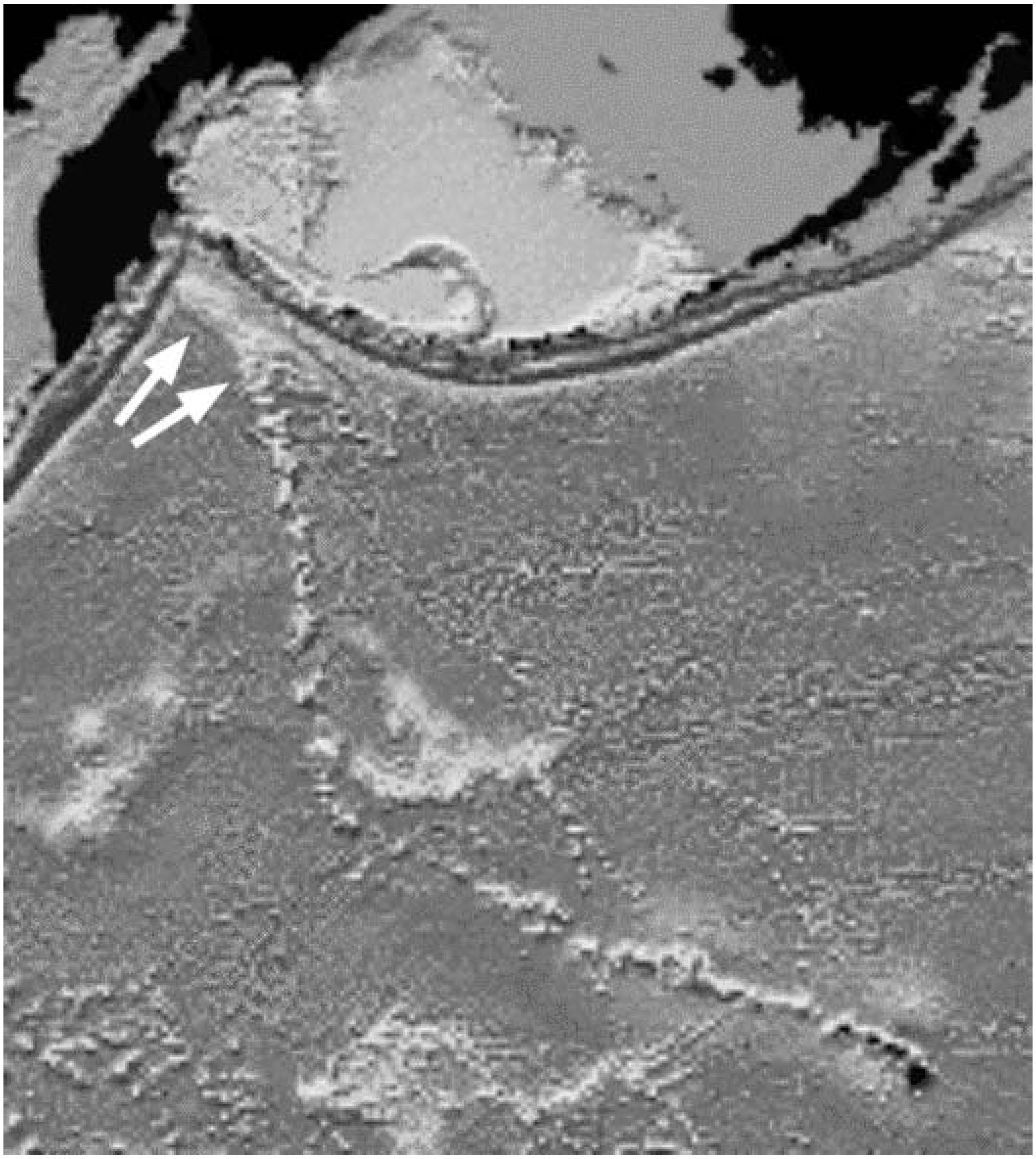
"The crack model is appealing because several first-order features of the Hawaiian and Emperor chains that are inconsistent with the plume model or require surprising coincidences may be consistent with the crack model. These include the inception of the Emperor chain on a ridge, the lack of a 'plume head' large igneous province, the ~60 degree change in propagation direction that occurred around 47 million years ago, the rapid southward migration of the Emperor hotspot prior to this, and the lack of the heatflow anomaly expected for a plume."[16]

Shock Dynamics interpretation

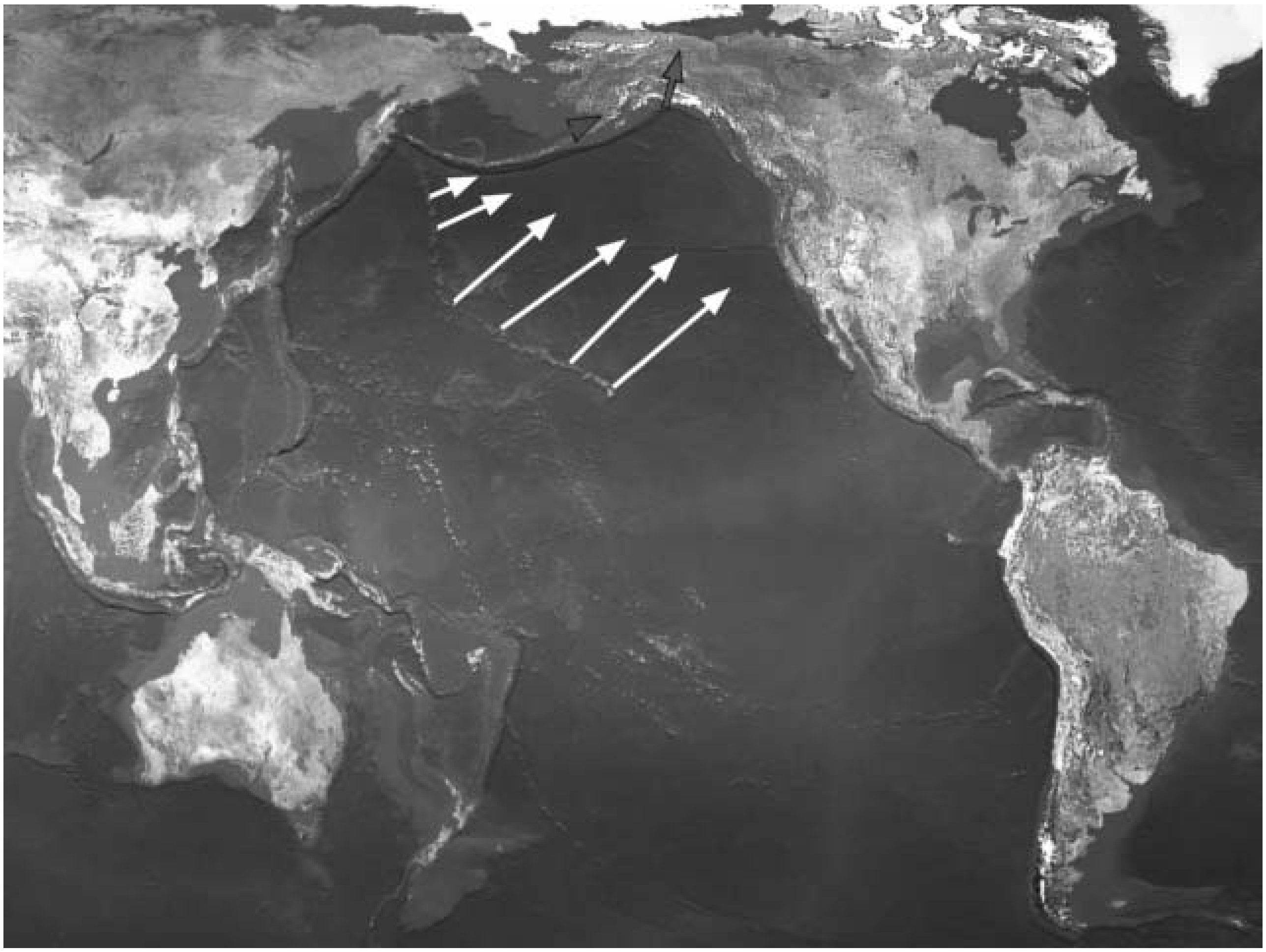
In the Shock Dynamics model, the starting point for the Emperor-Hawaii chain is next to the point where Alaska separates from Kamchatka and Siberia, so it is most likely connected with this move.



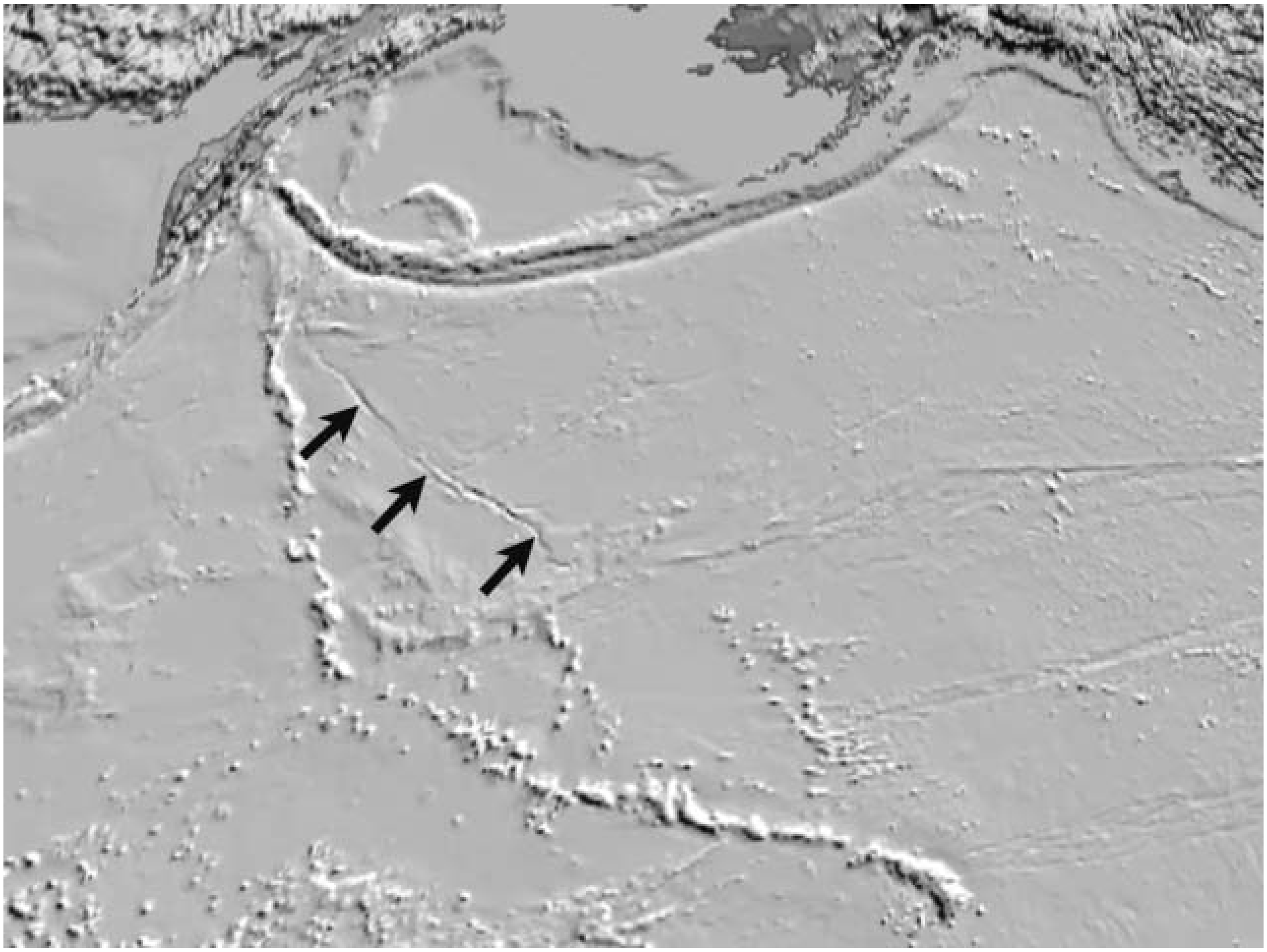
Notice that the first two eruptions, Meiji and Detroit seamounts, are the largest plateaus in the entire chain. The first is also oriented at a different angle from the rest of the Emperor chain.



Assuming the tensional stress-crack alternative to the plume model described above is correct, it becomes a matter of determining what pulled on the crust. Clearly it must be the motion of Alaska (red arrows, below). White arrows indicate the orientation of fissures along the chain. The sudden bend may mark the initial collision of Alaska with North America. Drag of the merged landmasses north would then have increased tension on the Pacific crust, leading to increased volcanism towards the end of the Hawaiian chain.



A long rift or fault, often overlooked, branches off of the Emperor Seamount chain. It also indicates pull-apart stretching towards Alaska.



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