Extensional Tectonics and Global Volcanism

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ABSTRACT

Most of the world's hotspots occur on or near plate boundaries. Proposed 'hotspot tracks' are primarily along pre-existing linear features, and volcanism is controlled by extensional stress. These linear features are transform faults, fracture zones and abandoned ridges. Almost half of the 'midplate' volcanoes occur on young (<30 My) lithosphere. The correlations of volcanoes with seafloor age, topography, fracture zones, gravity and focal mechanisms show that tensional tectonics is essential for volcanism, supporting the hypothesis that volcanism is controlled by lithospheric architecture and stress, not by hot narrow jets. Non-thermal explanations for focused magmatism are consistent with absence of heat flow, uplift and subsidence anomalies. Extensional stresses and lithospheric fabric are the controlling influences on the timing and location of 'midplate' volcanism. Island and seamount chains provide maps of stress and fabric, not plate motion.

INTRODUCTION

The tectonic plates on the Earth's surface are primarily under horizontal compression [Zoback et al., 1989; Zoback and Zoback, 1987]. The physics of dikes and volcanic eruption require extensional stresses or a horizontal least compressive axis [Rubin, 1995]. We explore the hypothesis that pre-existing fabric of the plate [fracture zones (FZ), transform faults (TF), ridges, abandoned ridges and sutures], plus tensile stress controls the locations of 'midplate' volcanoes. Magma buoyancy can break through a plate that is under the appropriate local stress conditions. If large regions of a plate are not under horizontal compression, then a new plate boundary is likely to form, preceded by linear volcanic chains.

Conditions for dike intrusion and volcanism include: a) temperatures above the solidus in the asthenosphere, b) the direction of the least-compressive stress is horizontal, and c) the magma pressure exceeds the least compressive stress by some tensile strength [Rubin, 1995]. If the lithosphere is under horizontal compression, or if the least-compressive stress direction is not horizontal, or if the fluid pressure is low, then dikes and volcanoes will not be able to penetrate the plate, even if, as seems likely [Anderson and Sammis, 1970; Anderson and Bass, 1984] the upper mantle is near or above the melting point almost everywhere. We use the term "tensional tectonics" to refer to stress conditions which are appropriate for normal-faulting, rifting, or diking [Parsons and Thompson, 1991].

Tensile stresses around most volcanoes are inferred from focal mechanism (FM) solutions, dike swarms, and topographic features such as grabens. Volcanism is associated with extension in various tectonic environments, including ocean island basalt (OIB) - like volcanism at convergent margins [Smellie, 1994]. Hotspots also tend to occur in extensional environments and near cracks and other lithospheric discontinuities [Jackson and Shaw, 1975; Vogt, 1974; Bailey, 1992; Anderson, 1998a]. It is natural then to assume that processes that cause regional tensile forces are those that allow and focus volcanism. These processes include thermal stresses, membrane and flexural stresses [Turcotte and Oxburgh, 1973; Sandwell et al., 1995], and far-field stresses [Sandwell et al., 1995]. A combination of forces, including slab-pull and ridge-push may give, to first order, the state of stress in the oceanic lithosphere. Localized loads due to bending and topographic features, including volcanoes, are also important. This localized effect can be seen both in continental and oceanic areas, and it may distort the large-scale stress field of the plates [Okal et al., 1980; McNutt et al., 1997]. The continental lithosphere stress situation is complex [McKenzie and Fairhead, 1997], but it appears that continental volcanism may also be a manifestation of far-field extensional stresses [Bailey, 1992] rather than local uplift.

In addition to plate driving forces, there are also resisting forces. These include 1) slab resistance, which counters, to some extent, the slab-pull force; 2) bottom drag which mainly operates in the opposite direction to slab-pull and ridge-push, and 3) transform resistance. The latter is probably the only force that can change rapidly. For example, when South America fully separated from Africa, the South Atlantic was free to open at a different angle, and stresses across pre-existing FZ and TF changed. This occurred at about 80 Ma, a time of global plate reorganization and changes in mountain building and volcanism. Slab-pull and ridge-push are basically gravitational body forces, reflecting density anomalies, and are not expected to change rapidly. This is one reason why multiple rapid changes in the motions of the Pacific plate, proposed to explain changes in trends of ‘hotspot tracks’ [Wessel and Kroenke, 1997] are unlikely. Bottom-drag does not cancel out ridge- or trench-parallel stresses and far-field stresses can cause localized extension in plate interiors. Hawaii may be at such a point because of divergent pulls of the western Pacific slabs.

The occurrence of OIB-like basalts in extensional situations in many tectonic contexts [Smellie, 1994], including convergence zones, throws doubt on the generally accepted idea that such chemistry must be imported into the shallow mantle by deep plumes. The universal existence of a shallow-enriched layer is indicated [Anderson, 1996; 1998a, b].

‘Hotspots’ are regions of localized magmatism not obviously related to plate margins. A region of excessive volcanism or unusual chemistry at or near a plate margin is also called a hotspot. The implication is that a narrow region of hot mantle is controlling the location of the volcanism. However, in 3D simulations [Morgan and Forsyth, 1988], there are localized upwellings both along and off-axis, and such features as fracture zones can also introduce lateral changes in melt productivity and focusing. If the upper mantle is at or above the melting point [Anderson and Sammis, 1970] then these effects can localize eruptions and cause increased thicknesses of basalt without the need for localized regions of high temperature [King and Anderson, 1995, 1998; Boutilier and Keen, 1999].

Jackson and Shaw [1975] argued that linear volcanic chains record the state of stress in the lithosphere. Vogt [1974] proposed that volcanoes occur on reactivated seafloor structures due to local stress variations. Solomon and Sleep [1974] and Turcotte and Oxburgh [1973, 1976] argued that propagating fractures are due to plate boundary or plate interior stresses. The source of magma in these cases would be from an already partially molten upper mantle [Anderson and Sammis, 1970; Anderson and Bass, 1984]. Bailey [1992] calls this “opportunistic volcanism.” The control of magmatism by fractures and by stress may explain short-lived volcanic chains and why volcanism is episodic and sometimes simultaneous over large distances ('hotlines'). It can also explain the absence of uplift and, in many areas, absence of evidence for reheating and thermal swells.

Turcotte and Oxburgh [1973] suggested that if the Earth’s lithosphere were a homogeneous plate, and if tensile forces were responsible for volcanoes, then one should expect plastic failures on the surface at angles of 35^o from the direction of maximum tensile stresses, and $60\text{-}65^o$ for the inclination of the fracture on a cross-sectional view. If lithospheric stress is responsible for volcanism, one may expect strike-slip and normal focal mechanisms near volcanoes. Sibson [1981] showed that fluid induced fracture is more likely for these faults than for thrust faults. Since it has been found in a number of instances that the tensional axes of intra-plate earthquakes are nearly perpendicular to transform faults and to the directions of plate motion away from ridge crests [Okal et al., 1980; Wilcock et al., 1990], then one of the planes in the focal mechanisms (FM) should be equivalent to tangents on the fracture zones, along linear volcano trends. The presumed fault planes tend to be aligned with zones of weakness, [Bergman and Solomon, 1992]. It will become evident that most active volcanoes and seamount chains follow fracture zones or occur near ridges or on abandoned ridges. Transform faults and spreading ridges form a generally orthogonal pattern. The orientation of volcanic chains is controlled by pre-existing fabric and present stress state. This is often parallel to plate motions. In the fixed plume hypothesis, volcanic chain orientations are controlled by plate motions rather than by stress or fabric.

These early suggestions of stress-control of propagating fractures have received little recent attention because of the perception that the active volcanoes in the chains define a fixed reference system and that volcanic chains are co-polar. These constraints have been removed [Norton, 1995; Stock and Molnar, 1987; Steinbuger and O'Connell, 1998; Wessel and Kroenke, 1997], and the evidence for repeated volcanism at the same sites (lithospheric coordinates) [McNutt et al., 1997] and simultaneous volcanism along some tracks has reopened the stress-and-crack vs. fixed plumes debate.

The purpose of this paper is to put global ‘midplate’ volcanism and volcanic chains into a tectonic context. Most global ‘hotspot’ maps denote proposed hotspots as points or circles and they appear to be randomly distributed over the Earth’s surface, as appropriate for the plume or deep mantle hypotheses. When plotted along with bathymetric, gravity, age and earthquake data, however, it becomes evident that surface tectonics may control the locations and activity of volcanoes, as proposed in the stress, crack and EDGE theories [Jackson and Shaw, 1975; King and Anderson, 1995, 1998; Boutillier and Keen, 1999; Anderson, 1998b].

DATA

We have plotted the world's active volcanoes on the Sandwell-Smith maps of gravity and estimated topography. The Smithsonian Institute’s Global Volcanism Program database [http://www.volcano.si.edu/gvp/] criteria for a volcano ranges “from individual vents, measured in meters, through volcanic edifices measured in kilometers or tens of kilometers, to volcanic fields measured in hundreds of kilometers”. Volcanoes in the list are thought to have been active in the last 10,000 years. These features will be referred to as “active volcanoes”. Many proposed hotspots are not on the active volcano list, such as the Caroline, Cape Verde, New England, St. Helena, Circe, Shona, Bermuda, Juan de Fuca, and Ascension. The hotspot list was created by using data from Crough [1983], Morgan [1981], and Crough and Jurdy [1980]. The currently active volcanoes that are considered hotspots were put on the hotspot list. In plate A, hotspots are shown in white; on other plates, hotspots are shown in red. Active volcanoes are given in black in all plates.

Many proposed hotspots are not evident in bathymetry or volcano catalogues, being based on hypotheses regarding hotspot fixity, age-progression of older volcanic constructs or inferred positions of ridge-axis geochemical anomalies. The locations of the Easter, Bowie, Circe, Bouvet, Heard, New England, Foundation, Louisville and other "plumes", and even their existence, is uncertain. We investigate the alternate hypothesis that active volcanism is controlled primarily by the stress-state and architecture of the lithosphere, and only secondarily by the underlying mantle. If this is true, many of the problems and paradoxes of the plume hypothesis are resolved. These include the short duration of most volcanic chains, the widespread, even global, synchronism of volcanism [Vogt, 1972], reuse of existing fractures and volcanoes at later dates, long-sustained volcanism in some areas long after the plate has moved off the ‘fixed hotspot’, the non-parallelism of volcanic chains, and so on.

We use focal mechanism (FM) solutions from the Harvard catalogue [for example, Dziewonski et al., 1994]. Sea-floor age data is from Müller et al. [1997]. In the gravity plates, 10 My age contours are given. The topographic data, in the figures, is Etopo-5 [National Geophysical Data Center, 1988], the gravity data is from Sandwell and Smith [1997]. We also use the Sandwell-Smith estimated bathymetry maps (not shown). The focal mechanisms are given in purple for earthquakes with depths of 10 to 20 km, red for earthquakes at depths of 20 to 40 km, and peach for earthquakes from 40 to 100 km depth.

The term “hotspot” is seldom defined. Sometimes the term “midplate volcano” is used, but many such features are actually on, or near, or were formed at, plate boundaries. Most “hotspots” are on young oceanic lithosphere, regions which are generally in extension, or along young fracture zones which are on thin lithosphere and can experience rapid differential thermal contraction. Many others are near, or formed near, continental margins, where stress gradients and magma focusing are likely. Focusing of magma, three-dimensional effects, lithospheric architecture and stress are also parameters, in addition to high-temperature, that may control the location and magnitude of magmatism. We prefer not to define, nor defend, the definition or concept of a hotspot, but accept, for discussion, features which previous authors have called “hotspots”. If volcanic regions are due to lithospheric conditions, then they may be neither “hot” nor “spots”. In fact, we are investigating phenomena and associations that bear on the fundamental question of “What are hotspots?”

Plate 1 gives volcano and hotspot locations and earthquake focal mechanisms superposed on the Sandwell and Smith [1997] gravity map. The plates discussed are labeled with a number if they are provided in the paper and with a letter if they are provided on the World Wide Web ("http//www.gps.caltech.edu/~javier/research/globalvolcanism/globalvolcanism.html").

TENSIONAL STRESSES

Lithospheres of different ages are adjacent at transform faults. In addition to thermal and buoyancy stresses, a transform fault may be the locus of extension or compression. A transform fault can be assumed to be "leaky" if volcanism occurs along a significant segment of it. It should be noted that age progressive volcanism can occur along leaky transforms, or any tensile crack, so "age progression" is not a unique indicator of mantle plumes, as commonly asserted [e.g., O'Connor et al., 1999].

Thermal stresses contribute significantly to the extension across transforms [Wilcock et al., 1990]. This is consistent with the fact that almost half of the proposed hotspots occur on young lithosphere (<30 My). Thermal stresses can be large and are volumetric in nature [Zoback et al., 1989; Haxby and Parmentier, 1988], but are generally less than slab-pull and ridge-push forces [Okal et al., 1980]. Their importance may increase during major plate reorganizations (such as ridge jumps or stress reorientations), or at fracture zones (FZs) with large displacements, or on large lithospheric plates with significant distances between major fracture zones. Plate reorganizations are of great importance since transform faults can be activated (made leaky), and create linear volcanic chains [Sykes, 1978; Bonneville and McNutt, 1992]. Weak spots along FZs can be linked to regions of excess volcanism, and major plate reorganizations with large changes in direction are not necessary to trigger (or suppress) such volcanism. The stresses in a plate can change even if the motions do not, or change little.

If thermal stresses play an important tectonic role, one should expect to see a time window for ongoing volcanism in young oceanic plates of about 20 My [Bratt et al., 1985]. For this time-span, the temperature change in the lithosphere causes significant stresses and rapid subsidence. This agrees with the observation [Bergman, 1986] that "most oceanic seismicity occurs in young lithosphere (< 35 My old) and appears to be dominated by stresses related to the early evolution of the lithosphere, particularly thermoelastic stresses". The effect is likely to be most noticeable within the first 5 Ma, when the differential thermal stresses will be largest. This is in agreement with the typical volcano lifetime of ~3 My [Haase et al., 1996].

Lithospheric contractions along a transform mostly occur nearest the ridge, “opening” the lithosphere (Fig. 1), in a process that permits magma ascent. Wilcock et al. [1990] show that normal faulting in young lithosphere is in agreement with net subsidence at transform faults (Fig. 2). The result of this process can be time progressive volcanism or synchronous volcanism, linear trends in volcanic chains, and trends that mostly parallel plate motions. An additional effect is the flow of magma toward thin lithosphere, both toward the ridge and toward the young part of the FZ. This directed flow is most pronounced at triple junctions.

Cooling lithosphere near a ridge produces stresses from subsidence and shrinkage. Since seismicity occurs to a depth corresponding to the 600^o to 800^oC isotherm [Chen and Molnar, 1983; Bergman, 1986], thermal stresses are probably significant to depths of 30 to 40 km. Okal et al. [1980] show that seismicity preferentially occurs in pre-existing zones of weakness such as faults and fracture zones (FZs), which means that volcanism should be expected there. Many FZs are characterized by numerous volcanoes, indicating weakness or extensional stress [Lowrie et al., 1986], and melt focusing. Furthermore, Turcotte and Oxburgh [1973] demonstrate that thermal stresses corresponding to a temperature change of 800^oC are enough to fracture the lithosphere. Volcanic loads and magma buoyancy can also fracture the lithosphere. Large volcanoes create membrane stresses that maintain parts of the lithosphere in tension, keeping volcanism active for times longer than expected from purely thermal stresses. An alternative way to reactivate volcanism is to form regional tensile stresses, due to large scale inhomogeneities in the lithosphere or plate reorganizations, which will in turn help “unlock” the FZ [Lowrie et al., 1986]. Also, tensile stresses from far-field stresses due to subduction can be oriented in the direction to open FZs (as seems to be the case in the Pacific and Nazca plates) [Sandwell et al., 1995]. Near subduction zones, changes in strike or dip of the slab can also generate tensile stresses.

In general, plate interiors are under compression [Zoback et al., 1989; Zoback and Zoback, 1987]. Volcanism is unlikely in these circumstances. Midplate volcanoes then would be rare because the normal state of midplate environments is compressional or, at least, does not have a horizontal least-compressive stress orientation. We therefore investigate the possibility that midplate volcanism is a result of local or regional extension.

STRESS CONDITIONS FOR MAGMATISM

Fluids can hydrofracture their way toward the surface, even if the fluid is under less than lithostatic pressure, along strike-slip and normal faults [Sibson, 1981]. The condition for hydraulic fracture is that the least principal stress be horizontal (i.e. normal and strike-slip fault environments) and approximately equal to the pore pressure. In compressional regimes the pore pressure must exceed lithostatic, and vertical magma transport is unlikely [Sibson, 1981]. The orientation of the least principal stress is horizontal at transform margins, and this favors vertical fluid flow [Martin et al., 1997]. Strike-slip and normal faults can provide efficient fluid conduits [Tobin et al., 1993], and these are the type of faults we expect from horizontal tensional stresses. FZs, abandoned ridges, and ocean-continent boundaries can be thought of as former and potential plate boundaries. They concentrate stress and also provide channels for magma transport, as well as potential channels to the surface. Large buoyant plume heads, in principle, can uplift and extend the lithosphere, but there is no evidence that this is the source of tensile stress.

LINEAR VOLCANIC TRENDS

WESTERN UNITED STATES (Plate 2)

The tectonic stresses and evolution in the inland part of the region are discussed by Dickinson [1997] and Turcotte and Oxburgh [1978]. Cenozoic volcanism in western North America is related to ridge-trench encounters, slab windows and block rotations induced by shear of the Pacific margin [Dickinson, 1997]. Migration of volcanism in this case has a straight-forward tectonic explanation, not involving plumes.

Dickinson [1997] attributes the mid-Miocene (17-14 Ma) pulses of volcanism in coastal California and the interior of the Pacific Northwest to the demise of offshore microplates (19-17 Ma) and a coupling of the Pacific plate to the North American plate. Tectonic rotations within the Pacific Northwest were complete by 15 Ma [Heller et al., 1987] and extensional tectonism was initiated in the Great Basin during the interval 18-16 Ma. Block faulting initiated along the Rio Grande rift during the interval 21-15 Ma. The volcanism immediately followed initiation of basin and range extension. Dickinson [1997] attributes all of these processes to shear on the continental interior owing to plate-boundary interactions along the margin.

The Juan de Fuca hotspot (~45^0N, 231^0) clearly lies near a dying ridge or a transform fault of the dying ridge, as do the two volcanoes east of it. No track is evident near the proposed hotspot, but the features to the north can be explained by the Sila FZ at about 52^0N and other parallel FZs. The fact that all these FZs have volcanism of approximately the same age might be due to local stress changes between 20 and 40 Ma, which Smoot [1985] speculates happened at 17 Ma. “Jamming” of the subduction zone of the western Aleutian trench may have occurred at 17 Ma [Smoot, 1985; Dalrymple et al., 1987]. There is much volcanic activity of this age in western North America [Dickinson, 1997], consistent with a regional stress change.

There may also be a more global explanation for changes in the stress-state and magmatism of western North America and the adjacent plates. Volcanic chains in the Atlantic become activated at this time [O’Connor et al., 1999] and volcanic activity in the African plate increased [Bailey, 1992]. Changes in stress can also shut off volcanism. Among the global events occurring between 18 and 25 Ma are: volcanic activity picks up at Yellowstone, Snake River Plain, Fernando, Azores, Kerguelen, Bouvet, Hawaii, Cape Verde, Bowie and Africa;

volcanic activity ceases in Bermuda and the Louisville chain. Possible causes of a global plate reorganization and change in plate stress include; hard contact of Africa and India with Eurasia, Gulf of Alaska opening, Farallon plate breakup, W. Pacific backarc basin opening and Ontong-Java Plateau contact with the Solomon Arc. There are also rifting events of this age in Africa and North America.

The Bowie hotspot (~51^0N, 231^0E) which is believed to be located near the Tuzo-Wilson volcanic field (TWVF) lies in a complex triple junction involving a spreading center and the Queen Charlotte fault. Allan and Chase [1993] argue that the TWVF and the Bowie "hotspot track" are due to a leaky transform fault and present data supporting tensional tectonics in the region. The lack of a thermal swell, the lack of large eruptive volumes, and the need for a cool thermal environment relative to other spreading ridges argue against a plume origin. Tensional tectonics can also be inferred from the focal mechanisms (plate 2). The rest of the proposed hotspot track are seamounts on FZs. There are about 9 seamounts that generally form a trend. The northernmost lie on two FZs, and another is near the clearly defined Aja FZ (~57^0N). Due to the subduction bulge and sedimentation, it is hard to see the oceanic fabric in this region, but our interpretation is that there is no need for a plume. Dalrymple et al. [1987] showed that several seamounts in the Bowie chain (Danson, Davidson, and Hodgkins) are of clear near-ridge origin. Dalrymple et al. [1987] propose that Dickens, Giacomini, and Kodiak seamounts are formed by mid-plate volcanism, being 16-21 My younger than the underlying crust and regionally compensated, but the ages correlate with Smoot's [1985] stress change. Kodiak and Giacomini lie closest to the zone associated with the stress change. Changes in boundary stresses also affect stresses throughout the plate. In order to make the chain fit the hotspot theory and make the ages match, "at least two, and probably more, distinct episodes of mid-plate volcanism" [Dalrymple et al., 1987] have been proposed. Each of these episodes has a lifetime less than a few million years. Also of importance is the fact that difference in age between the lithosphere and the seamounts is less than 21 My, and the chain has an average lifetime of ~10 My [Dalrymple et al., 1987]. The seamount ages are based on K-Ar dating, which should be considered as lowerbound ages, but the samples are taken from dredges, which means that only the younger eruptions are dated. As a result, the age difference may be smaller than given by Dalrymple et al. [1987]. The Bowie seamount chain appears to be consistent with fracture and stress control of magmatism.

GALAPAGOS AND EAST PACIFIC (Plate 3)

The Galapagos Islands do not form a linear chain nor are there any obvious age progressions. Instead, the general area appears to be fragmenting due to divergent pulls on the young Nazca plate. The small plates in the eastern Pacific were, in turn, formed by fragmentation of the Farallon plate. The area is characterized by multiple ridge jumps. The Galapagos Islands are midway between the East Pacific Rise and the South American trench, and are near the Cocos-Nazca plate boundary. The mantle in the vicinity is not particularly hot [Ito and Lin, 1995], as would be expected from a plume process. Estimates of the temperature excess at the Galapagos, from bathymetry, are only 51°C, well within the 200°C variability found along normal ridges [Feighner et al., 1995; Kaula, 1983; Anderson, 1998b]. Also, the Cocos and Malpelo ridges, often interpreted as hotspot tracks related to a hotspot, appear instead to be abandoned ridges [Meschede and Martin, 1997; Mammerickx and Sandwell, 1986]. The Malpelo Ridge may be a fracture zone, while there is young volcanism along the Cocos ridge. This is consistent with tensile or membrane stresses reactivating an old plate boundary, but not with a hotspot track.

Plate 3 shows the volcanoes around the Galapagos Islands. As can be seen from Plate 3, the fabric emanating from the EPR is fan shaped and tends toward perpendicularity with the subduction boundaries, and the volcanoes follow no linear trend and instead are bunched together at the tip of a triangular extensional feature off the west coast of South America. The tip of an extensional feature is the point of largest tensile stresses, and is likely to be the newest part of the system, and hence more susceptible to volcanism. It should also be noted that the volcano considered to be the current location of the Galapagos hotspot lies near the margin of the Nazca plate and the Cocos plate, the margin being roughly denoted by the focal mechanisms (FMs). These two plates are diverging slightly, and as a result, tensional features arise. The most obvious tensile feature in the region is a triangular rift. The FMs in the region indicate tension, being predominantly strike slip. The observed FMs are due to subduction stresses in this wedge shaped region off the coast of South and Central America. Two predominant modes of tension are present, one along the rift boundary and the other towards the point where South America meets Central America. The FMs clearly show this pattern, as the tension axis of the FMs are predominantly E-W for the FMs inside the wedge, while the tension axis are primarily perpendicular to the lines defined by the wedge.

The convergent margin volcanoes along the north coast of South America begin at a latitude of ~5^0N. The volcanoes continue south until they reach the southern part of the Galapagos Wedge. The on-shore volcanic chain follows the mountain chain, and the FMs under the volcanoes are primarily strike slip with some normal mechanisms. The fault planes in the FMs follow the volcanic chain as expected, and are extensional. Below the southern part of the wedge, the FMs are mainly reverse, implying compression, consistent with no volcanism being present. The tensile forces under the volcanoes might be due to the South America plate being sucked over the Nazca plate by the ongoing subduction in the west. The volcanic gap south of the Galapagos wedge is probably due to the shallow subduction of the Nazca plate under South America in this region. Thus, subduction zone geometry affects stresses and magmatism in both the continental and oceanic plates.

MEXICO AND CENTRAL AMERICA (Plates B and 3)

Plate B shows part of Mexico and Central America, and plate 3 shows the gravity data for a similar region that extends farther south. The Baja volcanic region (~27^0N, 247^0E) is on some hotspot lists but is probably not a hotspot. An apparent hotspot track at the Guadalupe hotspot (~28^0N, 242^0E), is an abandoned ridge. The Gulf of California is an extensional regime, and the proposed Baja hotspot is more likely due to spreading of the Gulf than to a plume. The strike-slip FMs and the volcanoes define a straight line up the Gulf of California. This suggests a tectonic rather than a deep thermal, i.e. plume, origin.

From the gravity signal, it can be seen that the two volcanoes on the Socorro Islands (~19^0N, 248^0E) lie on an abandoned ridge (the Mathematicians seamounts), just south of the Clarion FZ. This appears to be the same abandoned ridge that Guadalupe is on, although the segments are offset from each other by FZs. The other volcano in this region of the Pacific (~9.5^0N, 256^0E) is clearly in an extensional tectonic region, as it lies on the current ridge, near the Clipperton FZ, and the FMs are strike slip, even at depth (20-40 km). All of the volcanoes and proposed hotspots in the eastern Pacific are within about 800 km of the coast and are related to FZs or transform faults, ridge jumps or ridge-trench interactions. They are all on young lithosphere. Young lithosphere is not only thin and weak, but it is also contracting. Magma drains "uphill", towards thin lithosphere. There are other examples of proposed hotspots lying at the intersections of abandoned ridges and transform faults, e.g. Reunion and Mauritius. Such regions concentrate stress and focus magma.

The volcanoes inside Mexico are a puzzle; they are too far inland to be explained purely by shallow subduction. The Trans-Mexican volcanic belt lies on the extension of the off-shore FZ and off-shore volcanoes. A FZ may therefore be implicated for all volcanoes near 18^0N. This may explain why the volcanoes are further inland than expected. The volcanoes on the Central American coast have stronger lithosphere being subducted at a steep angle (verified by the higher gravity signal before subduction) and as a result the volcanoes appear where expected.

NAZCA (Plate C)

This area contains the Easter (~27^0S, 110^0W), San Felix (~27^0S, 80^0W), and Juan Fernandez (~33^0S, 79^0W) islands. This area is in the fastest spreading region on Earth and is characterized by microplates and ridge propagators. The Easter chain lies on the Easter FZ / Sala Gomez ridge, and the FMs near the hotspot are extensional. Volcanism should therefore be expected. Sandwell et al. [1995] propose that the Pacific plate is under extension due to the divergent pull of subducting slabs. Mammerickx and Sandwell [1986] note that the Sala y Gomez ridge is in the early stages of rifting, thinning and uplift. The concave shape of the Peru-Chile trench gives divergent pulls on the plate. Also, the existence of the Easter and Juan Fernandez microplates is attributed to a change in spreading direction by Bird and Naar [1994], which would open up FZs near the region and cause leakage. These mechanisms explain the hotline volcanism in the region and the normal FMs occurring in the FZs, as they are most likely the result of unlocking of the FZs. This implies that FZs are weak, as suggested by Lowrie et al. [1986]. The Easter chain is on young lithosphere and near plate reorganization boundaries, supporting the idea that volcanic events occur on near-ridge transforms during stress changes. Contemporaneous young volcanism has occurred over a distance of 2700 km along the Easter-Sala Gomez Ridge, which supports a regional stress explanation [Bonatti and Harrison, 1976]. The western side of the proposed Easter hotline or hotspot track has volcanic ages which young towards the west, in conflict with the hotspot hypothesis [Kruse et al., 1997]. Migration of magma from the hotspot to the ridge has been proposed, but the more straightforward explanation is that the “Easter hotline” is related to the East Pacific Rise, propagating ridges, leaky transform faults, and tensile stress. Volcanic chains radiate both east and west from the southern boundaries of the Easter and Juan Fernandez microplates (Plate C).

The San Felix chain lies in what appears to be a tensile region similar to that found in the Galapagos area. There are no FMs available in this area, but the gravity signal is similar to that in the Galapagos area. The Galapagos tensile region was formed by subduction in two different directions, which is also the case in this region.

The Juan Fernandez islands also lie on a FZ (Challenger FZ). The volcanoes are on the older side of the FZ, and appear to exert a significant load on the lithosphere, perhaps providing the necessary membrane stresses to create the seamounts visible in the gravity picture, which are adjacent to the islands. The origin of this volcanism is probably due to a tear in the lithosphere, as south of the volcanic line there is volcanism in the South American coast, while north of the volcanic line there is no volcanism. This implies a change in subduction angle for the Nazca plate occurring at the Challenger FZ, where the volcanism occurs. The Juan Fernandez and San Felix chains bracket the shallow dip portion of the Nazca slab and the on-shore volcanic gap. As with most other proposed hotspots in the eastern Pacific, the active volcanoes on the Nazca plate are close to the coast and can be related to interaction of young lithosphere with nearby subduction zones. The linear features off the coasts of Central and South America tend toward perpendicularity with the plate boundaries, as if the trench were controlling stresses in the oceanic plate. Tearing stresses are associated with change in dip (San Felix, Juan Fernandez) or strike (Galapagos) of nearby subduction zones. On the other side of the Pacific, the Samoan island chain is associated with both a change in dip and strike of the Pacific plate.

KERGUELEN (Plate D)

There are three proposed hotspots in this region; Crozet (~47^{0}S, 50^{0}E), Christmas (~38^{0}S, 78^{0}E), and Kerguelen (~49^{0}S, 70^{0}E). Heard Island is sometimes attributed to “a Kerguelen plume.” Kerguelen lies in a convoluted region between FZs. Crozet is also in a complex area, but may have a simple interpretation. The two isochrons next to the one that crosses the proposed hotspot have offsets on them that act in opposite directions. Furthermore, the isochron near Crozet does not have an offset. Our interpretation is that the area is in compression in a northeasterly direction, and has “tensile” stresses in the perpendicular direction, consistent with the observed volcanism to the NW and SE of the region. The Kerguelen Plateau appears to be underlain by a continental microplate [Operto and Charvis, 1995], which may explain both the shallow bathymetry and the enriched chemistry of the basalts. There are many oceanic plateaus and some are of clear continental affinity [Nur and Ben-Avraham, 1982]. Such plateaus, along with fracture zones and abandoned ridges, may also localize magmatism, such as at Jan Mayen, another continental fragment. Broken ridge may also be such a fragment.

Christmas Island (~38^{0}S, 78^{0}E) and the volcano adjacent to it lie next to a spreading center and at the tip of a FZ emanating from the ridge. Because of the proximity of both these volcanoes to the ridge, thermoelastic stresses are probably responsible for both volcanoes. The other two volcanoes in the picture (~47^{0}S, 37^{0}E) lie on a FZ, as do other seamounts surrounding them. The Kerguelen Plateau formed at a triple junction after the separation of Africa, Australia and Antarctica and may be an edge effect [Vogt, 1991].

DISCOVERY (Plate E)

Discovery seamount (~42^{0}S, 0^{0}E) lies on a FZ. As can be seen from the isochrons, there is a FZ at ~43^{0}S, just south of the seamount. At the 70 My isochron (which crosses the seamount) the FZ displacement is discontinuous from the two isochrons next to it, and part of the slip is taken up by what may be a tear in the lithosphere about a degree above the main FZ. This rip is bounded by the 60 and 80 My isochrons. Discovery seamount lies at the tear’s center and it also places a volcanic load on the lithosphere, as can be seen from the gravity data.

Bouvet (~56^{0}S, 3^{0}E) and the adjacent volcano lie on a ridge, and near FZs. Note the complex geometry that occurs on the ridge. Bouvet is near a ridge-ridge-ridge (RRR) triple junction, and excess magmatism is to be expected in this tectonic setting. It should be noted that both of these proposed hotspots and the other active volcano in this plate lie in the center of seamount chains, not at one end as would be expected from a plume source. This is also the case for Easter island. Moreover, Martin [1987] associates the volcanism with a rift that propagated along the Falkland-Agulhas FZ. This fracture zone has a 1300 km offset, and may be responsible for part of the Bouvet “hotspot track” (ages > 70 Ma). Martin [1987] also relates Tristan da

Cunha to a rifting event propagating towards the island. The rifting event is also supported by O'Connor [1991] who dates it at 70 Ma and this could be the stress change event that facilitated seamount formation for dates older than 70 My in the South Atlantic. The northern part of the Walvis ridge is clearly fault related, and extends into a mobile belt in Africa.

Most of the volcanoes in the South Atlantic volcanic chains formed on 19 to 29 My old lithosphere, about 440 to 800 km from the ridge axis [O'Connor et al., 1999]. This is a typical mantle scale length [Anderson, 1998a; Wessel et al., 1996] and may reflect small-scale convection associated with the ridge-FZ system. The age progression of volcanisms along the St. Helena and Tristan da Cunha chains has been taken as proof of a stationary plume [O'Connor et al., 1999], but cracks, fracture zones and transform faults can also have age progressive volcanism. Volcanoes forming at a constant distance from a migrating ridge, as in the Atlantic, are most likely controlled by plate stresses rather than by a feature fixed to the deep mantle. The apparent age progression on a near-ridge volcanic chain may reflect ridge-migration rates rather than absolute plate rates. The increased volcanic activity on the African plate in the past 20 My has been taken as evidence that the plate slowed down [O'Connor et al., 1999] or stopped [Burke, 1996], but most likely reflects a change in the stress-state of the plate [Bailey, 1992], probably associated with changing boundary conditions. Changes in the stress of a plate can modulate magmatism. It is not clear how changes in the motion of a plate can do so.

EAST AFRICAN RIFT (Plate F)

This entire area is under tensile tectonics, and appears to be a classical triple junction [Turcotte and Oxburgh, 1978]. However, all the rifts are not the same age and they are not all propagating away from the center as predicted in plume theory. The stress regime in this area is complicated, but the volcanoes follow the fault planes given by the FMs. The Red Sea and the Gulf of Aden are propagating toward Afar, in conflict with the plume hypothesis [Manighetti et al., 1997]. Rifts in Ethiopia and Yemen follow pre-existing lithospheric boundaries separating thin from thick lithosphere, and propagate at up to seven times the spreading rate [Manighetti et al., 1997]. Coleman [1993] argues against the presence of a plume in the Red Sea / Afar region since there is no uplift prior to the magmatism. Passive rifting initiated by the movement of the Arabian plate, appears to be an adequate explanation for this region. From time to time, much of

Africa experiences extension and widespread magmatism, attributed by Bailey [1992] to changing boundary conditions. When a spreading ridge propagates end-on into a continent, exceptional magmatism can be expected. This is also the expectation at a new RRR triple junction. Transient and 3D effects, as well as focusing, can be as much involved in excessive magmatism as high temperatures.

The Gulf of Aden, Afar and East African Rift area can be thought of as the present manifestation of a ridge (Central Indian Ridge) penetrating into a continent. The North Atlantic can be thought of as a more advanced version of a ridge propagating into a continent. A new ridge, or the tip of a propagating ridge, cannot be expected to have the same melt productivity as a mature ridge. Focusing and lateral temperature gradients, and dumping of ponded melts are three of the differences.

Other regions that represent new ridges or new cracks include the Easter microplate propagator region, the Juan Fernandez FZ, the Samoa FZ and the Galapagos region. These all have basalts with low ^{3}He concentrations but high and variable ^{3}He/^{4}He ratios. Thus, there may be a tectonic correlation with “high-^{3}He” (possibly low-^{3}He, high ^{3}He/^{4}He ratio) regions.

CENTRAL AFRICA (Plates G and H)

The Cameroon volcanic chain has been attributed to a hotspot track but there is no age progression and there has been recent volcanism over most of its length. Plate G shows the topography of the Cameroon line, while plate H shows the gravity data. There are not enough FMs to make any conclusions about the state of stress, but the age and gravity data suggest that two FZs are present where the volcanoes are located. The two islands NE of the proposed hotspot track are part of other linear trends which strike approximately N60^{0}E. Meyers and Rosendahl [1991] point out that magmas and uplift that formed the main volcanic centers seem to occur preferentially where major FZs transect the proposed Cameroon volcanic line, which suggests that the South Atlantic plate had a major reorganization at the time of seamount formation, allowing magma to leak through the FZs and form the volcanic chain. Sykes [1978] arrives at the same conclusion and dates the reactivation of the FZ at the early opening of the south Atlantic.

The FZ related to the Central African shear zone is an old accretionary suture separating lithospheres of quite different thicknesses [Plomerová et al., 1993; Sykes, 1978]. There is no age progression for the continental volcanoes [Djomani, et al., 1997] and sporadic volcanism has continued into recent times throughout the line [Meyers and Rosendahl, 1991]. The Adamawa plateau and the continental part of the Cameroon chain are related to deep lithospheric structure and ancient plate boundaries [Plomerová et al., 1993]. Lithospheric architecture and stress control the magmatism along the Cameroon line.

BRAZILIAN BASIN (Plate 4)

This area contains five proposed hotspots, of which three are inactive. Two linear chains (~4^0S and ~20^0S) are parallel to FZs and die off away from the coast of South America. Several other chains, between these two, are at about 45^0 to the FZ fabric. Note the shallow bathymetry about 800 km east of South America, between the seamount chains. Swells at about this distance from the coastline are common in the Atlantic and Indian oceans and may be related to an edge effect, important in the early stages of spreading [Vogt, 1991]. The two active volcanoes in this region are Trinidade (~20^0S, 29^0W) and Ascension (~9^0S, 14^0W). Ascension has no track, it lies next to a FZ, and is located very close to a ridge. This volcano rests on the younger (thinner) side of the FZ. Since Ascension is so close to the ridge and the FZ, it is reasonable to expect that thermoelastic stresses are the reason that this volcano is at its present location. Ascension and Circe are related to the Ascension FZ and the Mid-Atlantic Ridge with convection possibly controlled by the strong lateral temperature gradients [Freedman and Parsons, 1990]. According to Schilling [1991] Circe is the hottest hotspot (+ 278^0C) although there is little evidence for its existence or location. There is no geophysical or geochemical evidence for a plume near Ascension or Circe [Minshull et al., 1998].

Ascension and Circe are between the Ascension and Gabon FZs, and there is also a geochemical spike on the midatlantic ridge between these FZs [Schilling et al., 1985]. Ascension and Circe may be related to tectonic adjustments in the region, involving ridge jumps and ridge-transform stresses. Schilling et al. [1985] favor a Circe plume rather than an Ascension plume since their model of hotspot-migrating ridge interactions requires the plumes to be east of the ridge. Alternatively, ridge migration and asymmetric spreading could place the ridge-related upwellings and the maximum extensional stresses to the east of the ridge [Houseman, 1983; Anderson et al., 1992]. Considering all the evidence, a tectonic rather than a thermal explanation seems to be indicated for near-ridge (and near-FZ) Atlantic volcanism.

Of the other three proposed hotspots, Arnold (~18^0S, 25^0W) has the smallest gravity signal. This is probably not a hotspot as it is not active and has no nearby seamounts. Fernando (~4^0S, 32^0W) lies on the older side of the FZ, but the proposed hotspot track can be explained by three FZs.

St. Helena (~17^0S, 6^0W) is also inactive, and can be explained by leaky FZs. The present location is on 40 My lithosphere and a seamount lies on the older side of a FZ. The proposed hotspot track is oriented about N45^0E, and all the seamounts that compose the track lie on the older side of FZs. The older and more prominent seamounts (~10^0S, 0^0E) lie on lithosphere 80 My old. There is a secondary gravity signal that runs NE on the western side and NW on the eastern side of the mid-Atlantic ridge. O’Connor et al. [1999] demonstrate age-progression along the “St. Helena track”, but St. Helena itself violates the trend. All the volcanoes formed on 19-29 Ma lithosphere; the age-progression may represent the westward migration rate of the MAR.

AZORES PLATEAU (Plates J and K)

As the FMs in the area show, the Azores Plateau is characterized by tensile stresses. The proposed Azores hotspot (~38^0N, 28^0W) and the surrounding volcanoes lie on a major FZ that continues into the Mediterranean as the boundary between the European and African plates. The FMs end at the pre-existing FZ (~37^0N), and follow a linear trend where the volcanoes are located. A similar trend in FMs (mostly normal, very few strike-slip) is also found in the Kane transform fault, for which thermal stresses are a possible source of the stresses necessary to produce the observed mechanisms [Wilcock et al., 1990].

The gravity data shows that the Azores plateau is at the southern end of an anomalously hot North Atlantic oceanic mantle which extends down to a latitude of approximately 38^0N [Anderson et al., 1992] at or near a FZ. The Azores plateau lies at a latitude slightly north of the FZ. The hot Atlantic region (high gravity) extends north, past Iceland, but is broken by a major FZ at a latitude of about 50^0N. The lithospheric block between 38^0N and 50^0N is of significant size and contraction from thermal stresses will be large at the center of the block. There appear to be FZs in the gravity map but there is no age offset, and the FZ only appear on the western side of the ridge. If thermal stresses are responsible for creating this FZ where the volcanism is occurring, the FZ should be expected to be near the end of the block and close to the ridge, the region of maximum temperature gradient, and where the tensile stresses will be maximum. An alternative explanation is that this FZ is leaky, as is the case for some FZs in the South Pacific. The Azores region could also be described as a triple junction.

According to Bonatti [1990] and Grevemeyer [1999], the Azores platform is not a hotspot. In fact, it is cold and wet [Bonatti, 1990]. Grevemeyer [1999] argues that the New England seamounts, the Great Meteor seamount and the Corner seamounts are formed by non-hotspot processes.

The proposed New England hotspot (~29.5^{0}N, 29^{0}W, no longer active) appears to lie at the tip of a FZ, which places it in a high stress area susceptible to volcanism. The proposed track for this hotspot consists of many seamounts, but only two are clearly visible in the plate (~32^{0}N, 29^{0}W), and there is a strong correlation of the seamounts with FZs [McHone and Butler, 1992]. Both of these visible seamounts lie next to FZs, which are evident from the isochrons. The gravity signal shows that the two seamounts impart a large load on the lithosphere which in turn provides the membrane stresses necessary to create the Great Meteor seamounts at the FZ tip. These seamounts are on 80 and 90 My old lithosphere.

Although the New England seamounts are usually referred to as being a well-established hotspot track, there is no evidence that a hotspot track exists [McHone, 1996]. The problems with the hotspot model are described by McHone. Duncan [1984] provides radiometric ages for the seamounts assuming a plume model, but his predictions are dependent on the Bear and Corner Seamounts being dated at 101 and 70-75 Ma respectively. Swift et al. [1986] provide stratigraphic evidence to date Bear seamount at >120 Ma, which makes Duncan’s proposed hot spot track too fast since volcanism lasted too long (>19 My) at Bear seamount. Duncan [1984] also refers to Vogt [1973] to discard the possibility of volcanism occurring along a FZ, as Vogt mentions that there is no offset in magnetic anomalies in the proposed track. But later, Vogt [1974] argues for “control by fractures, many of which exhibit the same or closely similar trend as the sea-floor 'fabric' of northeast-trending normal faults and southeast-trending transform faults." Plate K shows that the seamounts considered by Duncan [1984] lie in an area with FZs.

McHone [1996] and Swift et al. [1986] also find mid-Tertiary time (~25-45 Ma) oceanic seamounts along the proposed hotspot track, suggesting a stress change in the region at the time, and control of magmatism by seafloor fabric.

The four other volcanoes in the picture, which are not related to either of these proposed hotspots, clearly lie next to or on FZs. The seafloor fabric data support the contention of McHone [1996] that the New England seamounts are not a hotspot track. Furthermore, this chain is not parallel to other volcanic chains on the same plate.

The only proposed hotspot swells in the central north Atlantic that may be thermal in origin are Cape Verde, Bermuda, Canary and Madeira [Grevemeyer, 1999], but these are all near continents and can be explained as a continental edge effect, associated with a narrow ocean [Vogt, 1991; King and Anderson, 1995, 1999; Boutilier and Keen, 1999]. This is also described as 'rift induced convection', or 'dynamic melting'. Convection induced by rifting and lateral temperature gradients drives material through the upper mantle melting zone and uplift and transient excess magmatism result with no need for excess temperature.

LITHOSPHERIC AGE CORRELATIONS

About half of the active ‘midplate’ volcanoes are, in fact, on lithosphere younger than 30 My, and about two-thirds of those are on lithosphere younger than 10 My. The near-ridge environment is characterized by spreading induced 3D convection, tensile stresses in the lithosphere, and thin lithosphere. There is a tendency for near-ridge volcanism to cease when the lithosphere exceeds 30 My in age [O’Connor et al., 1999]. Many currently extinct volcanoes were emplaced on seafloor of age 20 to 30 My. These correlations strongly suggest a plate tectonic and shallow explanation rather than the conventional deep mantle plume explanation.

OTHER PROPOSED HOTSPOTS

There are many proposed hotspots that we have not discussed at length but which have been treated by others. Volcanism on the Canary Islands correlates with extension in the nearby Atlas mountains and is consistent with a FZ model [Anguita and Hernan, 1975]. There is no evidence for a plume [Filmer and McNutt, 1989]. The Kerguelen Archipelago is related to widening shear fractures [Giret and Lameyre, 1985] and lithospheric dynamics. Both of these may be edge effects [Vogt, 1974]. Burke [1996] provides evidence against most of the proposed hotspot tracks on the African plate. The Shona hotspot is associated with a ridge jump during a plate reorganization [Martin, 1987]. The central Atlantic hotspots on older lithosphere appear to be related to instabilities along the ocean-continent boundary [Vogt, 1991; Schmincke, 1982; Grevemeyer, 1999]. The relationships of continental magmatism to stress changes, lithospheric fabric and off-shore FZ volcanism are discussed by Sykes [1978] and Bailey [1992]. The Samoan chain is at the northern terminus of the Tonga arc, the fastest convergence zone on Earth, and is parallel to the Pacific-Australian plate boundary. It may represent a tear in the Pacific plate [Natland, 1980; Dickinson and Green, 1998; Millen and Hamburger, 1998] due to the large change in dip and strike angle of the plate at the end of the Tonga trench. The island chains in the South Pacific do not have any of the characteristics predicted by the plume hypothesis [Okal and Batiza, 1987; McNutt et al., 1997; Dickinson and Green, 1998]. These characteristics include swells, age progressive volcanism, parallelism with plate motions and other island chains. Auxiliary hypotheses have been proposed, such as multiple plumes, rejuvenated volcanism, long distance lateral transport of magma and pulsating plumes, but these modifications may stretch plume theory too far and suggest that alternative and simpler hypotheses might be appropriate. Volcanism controlled by stress state and pre-existing fabric seems to explain most of the proposed hotspots. Loading by volcanoes may also cause volcanic chains to propagate.

YELLOWSTONE, ICELAND AND HAWAII

These are three of the best known features that have been called ‘hotspots’. Yellowstone is located at a complex juncture of diverse features including Rocky Mountains, Basin and Range, Wyoming craton, Snake River Plain and Idaho batholith. The only archean craton in the western part of the Americas and the only ‘hotspot’ are juxtaposed in Wyoming, and this is the edge of the region being affected by Pacific plate-North American plate interaction, and the interaction of the continent with the underlying Farallon plate. Tomography indicates that the high seismic velocities of the Wyoming craton, and the low velocities under Yellowstone extend to 200 km depth [Dueker and Humphreys, 1994]. A plate tectonic (non-plume) explanation for Yellowstone is provided by Dickinson [1997]. A deep mantle plume explanation would require many spatial and temporal coincidences. Lithospheric extension and focusing of stress and magma at the edge of the craton seem to be the essential features of any explanation for Yellowstone. The inferred trajectory of the Yellowstone “hotspot” track does not conform to the “fixed hotspot” reference frame, and the connection to the Snake River Plain and the Columbia River Flood Basalts is tenuous. Fracture zones and rifts are magma conduits in these areas and overall extension is evident.

Smith and Braile [1994] review the various non-plume explanations for Yellowstone and attribute the 'Yellowstone hotspot' to Basin and Range extension, although they also favor a 'thermal plume', extending to about 200 km depth. The association with the 200 km thick Wyoming craton and the stresses associated with rotation of the Pacific Northwest [Dickinson, 1997] would then be coincidental.

Iceland straddles the youngest part of the Atlantic ridge system, and is centered in the narrowest part of the ocean. Focusing, lateral temperature gradients and initial transients are important at the onset of rifting. Archean cratons are not far from Iceland. Although it has been claimed that deep continuous low-velocity cylinders have been tomographically imaged under Iceland, the interpretation is not unique [Keller et al., 1999]. Bermuda, and other Atlantic and Indian Ocean plateaus may be related to edge-effects, and the initial opening of an ocean basin [Vogt, 1991]. A large fraction of ‘hotspots’ are on or near ridges and are therefore not ‘midplate’. Chemical gradients away from Iceland are strongly influenced by fracture zones (FZ), suggesting a shallow origin. The role of new ridges, nearby cratons, focusing and fracture zones must be understood before a deeper explanation is invoked.

Hawaii, on the other hand, is a midplate construct, by any definition. It is not obviously related to pre-existing fracture zones or transform faults. The Hawaiian chain, is ‘parallel’ (co-polar) with the northern (Alaskan) boundary of the Pacific plate, the southwestern boundary (Pacific-Australian) and the Eltanin FZ in the South Pacific. It is nearly parallel to several of the FZs along the EPR, and the Chile Rise. There are few volcanic chains on the Pacific plate that are parallel to the Hawaiian chain [Wessel and Kroenke, 1997]. The ‘fixed hotspot’ reference frame does not seem an appropriate description of the loci of volcanism [Norton, 1995; Wessel and Kroenke, 1997]. The Emperor chain started on a ridge, and may be built on a pre-existing feature [Handschumacher, 1973]. The Mendocino FZ separates the Emperor and Hawaiian chains and these may be separate features. The change in trend is also associated with a large decrease in productivity. The chemistry and productivity of the Hawaiian chain is influenced by the FZ south of and parallel to the Mendocino FZ [Basu and Faggart, 1996].

In order to explain the various trends of the volcanoes in the Emperor and Hawaiian chains, one must assume numerous changes in plate motion [Wessel and Kroenke, 1997], high-angle flow of the underlying mantle [Ihinger, 1995], true polar wander, large latitudinal shift [Tarduno, 1995], and group motions of Pacific hotspots. A propagating fracture or leaky transform fault mechanism would not require these adjustments.

It is unknown whether the Hawaiian Swell is a pre-existing feature or if it has an ancient root. The origin of Hawaii is an open question since the plume explanation encounters serious difficulties [Von Herzen et al., 1989; Woods et al., 1991; Cande et al., 1995; Davies, 1992; Jackson and Shaw, 1975; Cordery et al., 1997].

The Hawaiian Swell has a seismically fast root and no heat-flow anomaly. It does not have the attributes predicted from plume theory. The swell is, more-or-less, bracketed by FZ. Some oceanic plateaus have ancient continental roots and have been subsequently covered by basalts. We do not know the age of the underpinnings of the Hawaiian Swell. If Hawaii is built on a pre-existing structure, then much of the geophysics and geochemistry can be understood without importing material from the core-mantle boundary. Finally, the productivity of the Hawaiian chain (and directions of volcanic lineaments) are highly variable in time. The present high productivity is a recent phenomena and may be related to the presence of the swell or the related fracture zones.

Older ideas about Hawaii involve propagating fractures, or stress modulated volcanism [Jackson and Shaw, 1975; Clague and Dalrymple, 1989], and these should be revisited considering the numerous features that are unexpected or unpredicted from plume theory, and even inconsistent with it.

Yellowstone, Iceland and Hawaii are known as "high-^{3}He" hotspots, although the ^{3}He/^{4}He ratios exhibit enormous scatter, and the actual ^{3}He contents of the magmas are very low compared to midocean ridge basalts. High ^{3}He/^{4}He ratios may involve high ^{3}He/^{238}U sources such as ancient lithosphere. Iceland and Yellowstone are near such ancient lithosphere. If the

Hawaiian Swell is an ancient feature, like the Kerguelen Plateau,the Seychelles and Jan Mayen, then the inferred high ^{3}He/^{238}U source may have a common shallow explanation.

CONCLUSIONS AND DISCUSSION

In the 1970's, volcanic chains were attributed to lithospheric fractures, stress concentration zones, volcanic loading and so on. These mechanisms were criticized for not accounting for the perceived fixity of hotspots, the parallelism of island chains and the source of magma. These objections have been removed [Cande et al., 1995; Norton, 1995; Wessel et al., 1996; Anderson and Bass, 1984; Steinbuger and O'Connell, 1998], and there are now good reasons for once again considering lithospheric control, rather than asthenospheric or deep mantle control, on the timing and locations of volcanism, and the origins of volcanic chains. The lithosphere apparently can act as a valve, permitting or denying the ascent of underlying magma, depending on the state of stress.

The role of subhorizontal extension and lithospheric focusing in controlling the locations of volcanoes is well understood at divergent and convergent margins [e.g., Smellie, 1994; Apperson, 1991]. The enriched nature of magmas at all newly extending regions has led to the concept of a shallow enriched layer, the perisphere, overlying the depleted midocean ridge reservoir [Anderson, 1996]. Some newly extending backarc basins even have high ^{3}He/^{4}He ratios, suggesting a shallow source [Anderson, 1999]. The source of extension can be far field or local sources in the plate or an underlying buoyancy. A large buoyant upwelling (plume) as opposed to local magma buoyancy gives rise to regional uplift and heating of the lithosphere. This possible source of extension does not seem to be responsible for midplate volcanism [Hill et al., 1992; Czamanske et al., 1998; Sheth, 1999; Smith and Lewis, 1999].

The data presented in this paper clearly demonstrate that volcanoes correlate with linear features in the gravity data, with the age and fabric of the seafloor, and with thermoelastic stresses. None of these correlations are predicted by the plume hypothesis. It should not be surprising that most hotspots and volcanoes occur on young oceanic lithosphere, as this is where the plate is thin and under tensile stresses.

If plumes are the cause of these volcanic chains, then many questions need to be addressed: 1) Why are there no continental hotspot tracks older than 200 Ma?; 2) Why are the Indian plate and continents such as South America, eastern North America, Asia, and Antarctica exempt from hotspot volcanism if plume locations are random?; 3) Why do most hotspots occur in oceanic lithosphere?; 4) Why are continental hotspots associated with shear zones, rifting events, and located near the coast?, 5) Why are many hotspots and oceanic swells within 1000 km of coastlines? The answers to these questions are simple in terms of the hypothesis that volcanism is controlled by extension and lithospheric architecture. The answer to all questions is that most continental interiors are under horizontal compression, and as a result no volcanism occurs, while young oceanic lithosphere is thin, weak, and under extension (from gravitational and thermal stresses) and as a result easily penetrated by magma. Volcanoes in the continental lithosphere occur in regions that show clear signs of extension [Sheth, 1999; Dickinson, 1997], usually as a result of ocean-continent interactions or slab-window formation. The proximity of "hotspots" to ridges, continental margins and ancient sutures must be explained. Pre-existing lithospheric features are implicated for most volcanic chains. New tears may be responsible for volcanic chains on oceanic plates exposed to divergent stresses, such as those on the Nazca plate.

If volcanism is controlled by lithospheric architecture and stress, then its association with ridges, young lithosphere and fracture zones is easily understood. Young lithosphere is thin, weak and rapidly contracting. The convection induced by spreading ridges is intrinsically three-dimensional, not sheet-like as commonly assumed in 2D modeling. On-axis and off-axis variations in upwelling are expected and are part of the near-ridge environment. On the other hand, hot buoyant plumes rising from the core-mantle boundary should be indifferent to the surface plates.

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FIGURE LEGENDS:

Figure 1: Cooling of the lithosphere with age along a transform fault (not under strong compression) shows that thermal stresses will “open-up” the crust so as to let melt flow through.

Figure 2: Vertical cross section perpendicular to the Kane transform (from Wilcock et al., 1990). This figure shows how tensional stresses perpendicular to the transform zone create normal faults, which then cause net subsidence of the lithosphere. The approximate locus of the Principal Transform Displacement Zone (PTDZ) as deduced by Pockalny et al. [1988] is also shown.