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Driving mechanism and 3-D circulation of plate tectonics

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ABSTRACT

A conceptual shift is overdue in geodynamics. Popular models that present plate tectonics as driven by bottom-heated whole-mantle convection, with or without plumes, are based on obsolete assumptions, are contradicted by much evidence, and fail to account for observed plate interactions. Subduction-hinge rollback is the key to viable mechanisms. The Pacific spreads rapidly yet shrinks by rollback, whereas the subduction-free Atlantic widens by slow mid-ocean spreading. These and other first-order features of global tectonics cannot be explained by conventional models. The behavior of arcs and the common presence of forearc basins on the uncrumpled thin leading edges of advancing arcs and continents are among features requiring that subduction provides the primary drive for both upper and lower plates. Subduction rights the density inversion produced when asthenosphere is cooled to oceanic lithosphere: plate tectonics is driven by top-down cooling, but is enabled by heat. Slabs sink more steeply than they dip and, if old and dense, are plated down on the 660-km discontinuity. Broadside-sinking slabs push all sub-lithosphere oceanic upper mantle inward, forcing rapid spreading in shrinking oceans. Down-plated slabs are overpassed by advancing arcs and plates and, thus, transferred to enlarging oceans and backarc basins. Plate motions make sense in terms of this subduction drive in a global framework in which the ridge-bounded Antarctic plate is fixed: most subduction hinges roll back in that frame, plates move toward subduction zones, and ridges migrate to tap fresh asthenosphere. This self-organizing kinematic system is driven from the top. Slabs probably do not subduct into, nor do plumes rise to the upper mantle from, the sluggish deep mantle.

Keywords: forearc basins, geodynamics, global tectonics, plate tectonics, rollback, seafloor spreading, subduction

INTRODUCTION

The reality of plate tectonics, as a description of relative motions of those parts of the Earth's outer shell that are internally semirigid, has been proven. Analogy with the systematic relationships of many geologic and magmatic features to modern plate settings demonstrates that plate tectonics has operated in something like its present style for, at most, the past billion years (Stern, 2005, 2007). A key indicator of low-temperature conditions in subduction systems, lawsonite eclogite, has formed only within the past half-billion years (Tsujimori et al., 2006). In still-older assemblages, relationships are progressively less like those now developing, and, in my view (Hamilton, 2003; 2007), neither rigid plates nor subduction—i.e., nothing resembling even a precursor of plate tectonics—operated before two billion years ago. Secular cooling of the upper mantle by 75°C or 100°C per b.y. is likely (Anderson, 2007; Hamilton, 2007).

Plates commonly are visualized as driven by whole-mantle convection in a mostly-unfractionated mantle: bottom-heated hot mantle rises beneath ridges, diverges, carries lithosphere passively along as it flows laterally while cooling, and sinks at trenches (e.g., Figure 1). These concepts derive from hypothetical models, not from

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data, and appear in many variants. Most geodynamic numerical modeling, and all fish-tank modeling, incorporates properties and parameters that enable favored results but that otherwise are incompatible with much information, including the great effects of pressure on physical properties. Observed plate interactions are also among factors largely missing from these popular models. Among the minority of geoscientists arguing instead for an irreversibly fractionated mantle, a top-down drive, and plate circulation limited to the upper mantle are Anderson (2002a, 2002b, 2007), Hamilton (2002, 2003), Hofmeister (2005), and Hofmeister and Criss (2005a).

<<Figure 1. Simkin cartoon>>

This paper emphasizes the actual geologic and geophysical products of plate interactions. These features are incompatible with bottom-up mechanisms whereby plates are driven by bottom-heated convection cells with or without plumes, and instead indicate plates to be self-organized and driven by subduction due to top-down cooling. Subduction represents the righting of the density inversion caused by cooling from the top of sub-oceanic asthenosphere. Plate tectonics is enabled by Earth's internal heat, but convection associated with plate motions is a product, not a cause, of plate motions. Anderson (e.g., 2002a, 2007) has long argued, on geophysical, mineral-physics, and thermodynamic grounds, for a top-down drive, a few other geoscientists now do so also (e.g., Schellart and Lister, 2005) , and some geodynamicists add a top-down complication to their dominantly bottom-up explanations. Anderson and I agree that plate-tectonic circulation is largely or entirely limited to the upper mantle—for him, shallower than ~1000 km, for me, shallower than the discontinuity near 660 km. This essay continues the analysis carried on in prior papers (e.g., Hamilton, 1979, 1988, 1995, 2002, 2003).

The conventional assumption that plate-tectonic circulation involves the entire mantle and is driven by bottom heating has been repeated and embellished in hundreds of textbooks at all levels, and in thousands of scholarly papers, and has been widely taught as dogma for 30 years. Contrarians face great inertia in ingrained biases when arguing that none of the conjectural variants of this conventional wisdom is soundly based. I recall my pre-plate-tectonic years as a continental drifter, when most of the American geoscience community was impervious to the powerful evidence for drift because several fine mathemeticians had proved (starting from false assumptions) that crustal mobility was impossible.

GLOBAL SPREADING PATTERN

Bottom-up drives are incompatible with the characteristics of plate boundaries and the ages of oceanic crust (Fig. 2)—the broadest features of plate tectonics. The Atlantic spreads slowly and has no subduction about its margins, except for the small Caribbean and Scotia arcs, and the subduction-free Arctic Ocean spreads slower yet. The Pacific spreads rapidly, is mostly rimmed by subduction systems except in the south, and yet is getting smaller by a large fraction of the amount by which the Atlantic gets larger because bounding subduction hinges roll back oceanward. The Indian Ocean spreads slowly in the west, where there is little peripheral subduction, but rapidly in the east, where subduction systems bound it. Antarctica is ringed by spreading ridges that lengthen and change shapes as new increments of oceanic lithosphere are added: the ridges migrate relatively away from the continent with varying velocities and initiation ages. The African plate is rimmed on west, south, and east by spreading ridges that similarly lengthen and change shape as they migrate relatively away from the continent as required to stay midway between diverging continents. Ridges enter trenches in a number of places along the east side of the Pacific, and abruptly cease spreading as plate boundaries change to accommodate motions between plates separated previously by subducting oceanic plates. For example, the Gulf of California-San Andreas boundary system has developed progressively between migrating ridge/trench intersections. In the western Pacific, by contrast, some arcs migrate away from continents, opening backarc basins in their wakes, even though the total area of the Pacific plus backarc basins is shrinking.

<<Figure 2. Seafloor ages map>>

Such behavior cannot be explained by conventional models (e.g., Fig. 1), and it shows instead that upwelling beneath ridges is a consequence, not a cause, of plate motions. Ridges are not fixed, and cannot mimic shapes of deep-mantle upwellings. (Plume conjecture is anchored to the assumption that much of the Mid-Atlantic Ridge is fixed in whole-Earth space.) Ridges continue to spread primarily at the places where young lithosphere has almost no strength, between plates diverging as a consequence of subduction, and halt when the subduction drive halts. Transform faults minimize the heat loss consequent on spreading. The lack of compressive deformation in young, thin oceanic lithosphere precludes the shortening that would occur were there a ridge-push force. Ridges form where oceanic plates slide apart, and subduction provides the drive. Ridges are in the middles only of non-subducting oceans, and "mid-ocean ridge" is a misnomer in subduction-bounded oceans.

HINGE ROLLBACK—KEY TO SUBDUCTION

Trenches mark dihedral angles between the tops of subducting oceanic plates and of thin accretionary wedges riding in front of overriding plates (Fig. 3). Seismicity and seismic reflection and refraction show subducting lithosphere to dip gently beneath forearcs, and to steepen gradually, through broadly curved hinges, beneath arcs and backarcs. Magmatic arcs typically form ~100 km above subducting slabs.

<<Figure 3. Sumatra/Calif. section>>

Subduction is the falling away of oceanic lithosphere, for hinges roll back into subducting plates. Subduction hinges are fundamental structures whereas trenches are very gentle-sided surficial features, so I use the terms "hinge rollback" and "hinge retreat" in preference to "trench retreat" (e.g., Rizzetto et al., 2004) and "trench migration" (e.g., Faccenna et al., 2001); and "slab rollback" (e.g., Lucente et al., 2006) for me conveys an ambiguous geometry. The shrinking of the Pacific requires hinge retreat on a very large scale. Retreat at smaller scales is shown by many specific interactions: collisions of facing arcs (e.g., Halmahera-Sangihe: Hamilton, 1979), collisions of arcs with passive-margin continents (e.g., Banda with Australia and New Guinea: Hamilton, 1979; Maghrebides with Africa: Lucente et al., 2006; Carpathian with eastern Europe; Manila with Taiwan), advance of small arcs into oceanic plates (e.g., the several Mediterranean arcs, Faccenna et al., 2001, Lucente et al., 2006, Rizzetto et al., 2004; Caribbean; Scotia), migration apart of oppositely-facing arcs (e.g., New Hebrides and Tonga), arc reversals (e.g., Sangihe-Mindanao-Sulawesi, and part of Banda, Hamilton, 1979), and arc rotations (e.g., Fiji and New Hebrides: Taylor et al., 2000). The subsurface behavior of sinking lithosphere requires the same conclusion; for example, the sunken slab of the tight-horseshoe Banda Arc defines an inward-shallowing basin continuous from south to north rims (Widiyantoro and van der Hilst, 1997).

Hinge retreat requires that subducting slabs sink more steeply than they dip, and that their seismic zones mark transient positions of slabs, not trajectories. Slabs are not injected down inclined slots, although this is the way they commonly are visualized and modeled (e.g., Fig. 1), but instead sink broadside.

Forearcs

Magmatic arcs commonly are depicted incorrectly (e.g., Fig. 1) as rising directly and steeply from trenches, whereas in fact broad, systematic structural belts intervene, and have characteristics that constrain the process of subduction and hence the driving mechanism of plate tectonics.

The Sumatra-Java-Banda arc of Indonesia (Fig, 4) has a well-defined and continuous active forearc system. The trench, the outermost part of the system, is continuous for 4500 km within the area of the figure, and it extends northward in the west another 2500 km, the north half of which is onshore in Bengal and Burma. The trench has typical deep-sea character along Sumatra and south-central Indonesia, but it shallows in the east where the arc has ramped onto continental crust of Australia and New Guinea. Within the area of Figure 4, a continuous forearc ridge (mostly submarine) and, behind it, a continuous forearc basin separate trench and magmatic arc, which typically are 300 km apart. The forearc ridge marks the crest of the accretionary wedge: the partly emergent Mentawi ridge off Sumatra in the northwest, the submerged ridge along central Indonesia, and Timor and other islands around the Banda Arc in the east. Many reflection profiles across this arc system were presented by Hamilton (1979, 1995). One of these lines, which has great vertical exaggeration but extends from the outer swell seaward of the trench across accretionary wedge, forearc ridge, and forearc basin, is shown here as Figure 5. (See Figures 3, 6, and 9 for unexaggerated views of such features.) Beaudry and Moore (1985), Kopp et al. (2001, 2002), and Matson and Moore (1992), among others, have published reflection profiles, some of which are accompanied by seismic-refraction and gravity surveys, across this system.

<<Figure 4. Indonesian physiography>>

<<Figure 5. Sumatra profile>>

The major shallow earthquakes of subduction systems are caused by ruptures that nucleate at the tops of subducting slabs back under the fronts of overriding plates, follow the tops of the slabs forward, and break up through the accretionary wedges as thrust faults (Wells et al., 2003). The rupture that caused the great Sumatra-Andaman earthquake of December 2004, moment magnitude 9.2, was of this type, and broke along 1500 km of the length, and 150 km of the width, of the top of the gently inclined subducting Indian Ocean plate (Chlieh et al., 2007; Lay et al., 2005). The rupture initiated under the Sumatra forearc basin and broke up further forward, through the accretionary wedge, as thrust faults. The large coseismic slip on the December break, and on the rupture of the moment-magnitude 8.7 earthquake that continued the break 300 km southward three months later, was directed toward the trench, oblique to the plate-convergence direction. Lay et al. (2005) ascribed this obliquity to a strike-slip torque, but because such obliquity characterizes coseismic deformation of accretionary wedges where trenches are not perpendicular to convergence directions (e.g., Estabrook and Jacob, 1991; McCaffrey, 1991; Subarya et al., 2006), I take it to indicate instead that strain was released by coseismic slip toward the trench—the gravitationally driven direction—after having accumulated by thickening of the wedge in the plate-convergence direction.

Accretionary wedges

Thinly tapered accretionary wedges display extreme imbrication (Fig. 6) and internal disruption of trench and pelagic sediments and other surficial, island, and crustal components scraped from subducting plates. Wedges are snowplowed in front of overriding plates and typically have upper surfaces whose slopes steepen toward trenches (Fig. 5), presumably indicative of dynamic equilibrium between thickening in plate-convergence directions and thinning in gravitational, trenchward directions. "Uphill" thrusting within the wedge (as within foreland thrust belts) is driven by the lithostatic head of increasing surface altitude arcward. Not apparent in Figure 6 is the abundant broken formation and polymict melange that typify wedges where drilled at sea or exposed on land. See Hamilton (1978,1979) for representative field photographs. Many thousands of kilometers of subduction may be recorded by shearing within a wedge.

<<Figure 6. Nankai trench profiles>>

The shearing and imbrication of the cool, wet, forward parts of accretionary wedges are mostly aseismic. The many thrust faults that deform them typically have trench-parallel strikes (Fig. 7), which confirms that slip within wedges is primarily in the gravitational direction, not the plate-convergence direction. Incoming oceanic plates are flexed as they ride through the standing waves of outer rises and outer trench slopes, and are broken by many small down-to-the-trench, trench-parallel, normal faults (Fig. 7; Ranero et al., 2003).

<<Figure 7. Midle-American trench>>

Many accretionary wedges contain blocks or imbricated sheets of exotic high-pressure, low-temperature metamorphic rocks of blueschist and eclogite facies that require depression to depths of 20, 50, or more kilometers, followed by return back up the subduction channel to the surface. Metamorphic ages of such rocks cluster in narrow ranges within a sector, so the upward return flow is episodic, not continuous. This sporadic return flow may be enabled by relatively rapid periods of hinge retreat and correlative falling away of the subducting slab in front of the advancing plate.

Forearc basins

Most active arc systems display continuous (Fig. 4) or discontinuous sedimentary basins atop the thin fronts of their overriding plates. Among summaries of basin characteristics are those by Dickinson and Seely (1979) and Dickinson (1995). The basins may be bathymetric as well as sedimentary basins (Figs. 4, 5, 8, 11), or they may be filled to (Figs. 7, 9), or above, sea level. They may resemble continental shelves or coastal plains in topography, but their basinal character is seen in reflection profiles and outcrop. The characteristics of these basins have profound, but commonly overlooked, implications for the mechanism of subduction. The presence of such a basin demonstrates that the front of the plate has not been crumpled (cf. Fig. 1) during the period recorded by deposition of basin strata. In the case of the Cretaceous and Tertiary forearc basin of central California, that duration was about 100 m. y. (Constenius et al., 2000; Dickinson and Seely, 1979; Hamilton, 1978).

A sampling of other forearc basins, and their equivalent "deep sea terrace" basins in some arcs, around the Pacific includes many western Melanesian, Indonesian, and southern Philippine examples (Hamilton, 1979), and a basin, >700 km long, paired to the Manila Trench of the west Philippines (Hayes and Lewis,1984; Lewis and Hayes, 1984). That Philippine basin continues north to Taiwan, where it disappears in the collision of the arc with Asia. A similar basin continues north from Taiwan, in the oppositely-facing Ryukyu arc (Shyu et al., 2005). The segmented basins of southwest Japan were depicted by Wells et al. (2003; Fig. 8 herein). Suyehiro and Nishizawa (1994) illustrated the forearc basin of Honshu. For forearc basins of the Kuril Islands, Kamchatka, and Aleutian Islands, see Wells et al. (2003); for southwest Alaska, see Dickinson (1995) and Von Huene et al. (1979); for Washington and Oregon, Wells et al. (2003; Fig. 9 herein); and for Central America, see

Hinz et al. (1996), Shor (1974), and Wells et al. (2003). The beaded forearc basins of South America are illustrated in Collot et al. (2002) for Colombia and Ecuador; Krabbenhöft et al. (2004) for Peru; Moberly et al. (1982) for Peru, Ecuador, and Chile; and Mordojovich-K. (1974) for Chile. The reflection profiles of the latter paper were calibrated by drilling: a broad basin underlying the continental shelf has a clastic section thicker than 3 km that extends from Late Cretaceous through Holocene.

<<Figure 8. Physiography of SW Japan>>

<<Figure 9. Oregon margin>>

The two small active Atlantic arc systems display forearc basins. The forearc basin of the Scotia (South Sandwich) arc is shown by Vanneste et al. (2002). The Tobago Basin is the forearc basin of the southwest part of the Caribbean arc.

The marked profile of Figure 10 extends from the Peru-Chile trench to a forearc basin of northern Peru, which is known from drilling to contain strata at least as old as Paleocene. Figure 11 is a stratigraphic analysis of the Arica forearc basin of northernmost Chile, showing landward displacement of depocenters with time. Both illustrations are from Moberly et al. (1982). Similar depocenter migration in other South American forearc basins was demonstrated by Coulbourn and Moberly (1977). Such depocenter progressions are recorded by reflection profiles across a number of other forearc-basins, and by stratigraphic studies of onshore forearc basins including that of the Cretaceous and Paleogene in California. Depocenter migration is conspicuous, for example, in the thick basin section south of western Java (Kopp et al., 2002), and in the northwest Luzon basin, for which Lewis and Hayes (1984) made a stratigraphic analysis similar to that of Figure 11.

<<Figure 10. Peru trench>>

<<Figure 11. Chile forearc>>

As Coulbourn and Moberly (1977), Hamilton (1978, 1979), and Moberly et al. (1982) emphasized, these landward-migrating depocenters show that forearc basins typically evolve in response to progressive jacking up of leading edges of overriding plates by accretionary-wedge material stuffed beneath them. Hamilton (1979) explained the great water depths of the forearc basin around the tightly curved Banda Arc (east part of Fig. 4) as an elastic response to the much greater frontal uplifts where the leading edge of the overriding plate ramped up on to continental crust of Australia and New Guinea.

Forearc basin strata frequently are seen in reflection profiles to lap on to basement rising to the forearc ridge, but contacts, both top and bottom, of that basement with accretionary wedge materials are not obvious in the profiles alone. I infer both from submarine topography and from on-land exposures that bedrock fronts commonly are thinly tapered and override wedges (Fig. 3). This accords also with the progressive uplift of the frontal parts of basins by underplated melange. Trenchward-sloping backstops for accretionary wedges are often postulated (e.g., Fig. 9) but do not accord with this constraint. Basements beneath the deep-water portions of the few forearc basins well characterized in on-land exposures are of oceanic basalts (e.g., Cretaceous California, and Eocene Oregon), though whether of spreading-ridge or backarc origins is disputed. The landward parts of basins overlie varied continental and accretionary assemblages.

Deformation of forearc basins

The fronts of forearc basins frequently show modest deformation (e.g., Fig. 5). I infer from the many reflection profiles I have seen that this deformation represents variously slight crumpling of the far front of the system, overflow of accretionary-wedge materials into the oceanward part of the basin, diapiric rise of basin shales, extension, and responses to changed plate-motion regimes (such as the Neogene California change from subduction to strike-slip). Subduction erosion from beneath can remove the entire forearc and much overriding lithosphere, as in latest Cretaceous and Paleocene time in southern California and adjacent regions.

Shortening across arc systems, discussed in a subsequent section, commonly has little effect on forearc basins, and apparently is accomplished by drag on the bases of overriding plates. Forearc basins, whether continuous or discontinuous, prove a general lack of crumpling of the thin leading edges of overriding plates (cf. Fig. 1).

Extensional Arc Systems, Backarc Basins, and Complex Flow

As marine geologists are aware but many landlocked geoscientists are not, arc systems commonly undergo extension. Plate convergence need not produce upper-plate shortening. Karig (1971, and many subsequent papers) early recognized that island arcs extend internally—even splitting into parts left behind and parts advancing—and migrate and increase their trenchward convexity in response to hinge rollback. Oceanic backarc basins open behind the migrating arcs. Hundreds of papers by others since (including many of my own; e.g., Hamilton, 1979) have added documentation and further examples. Intra-arc extension, both oceanic and continental, can involve hundreds of small normal faults (Suter et al., 2001; Taylor et al., 1991). Geodetic data confirm that the Mariana arc is lengthening and increasing its curvature as the Mariana Trough opens behind it (Kato et al., 2003). The highest reported velocities are for the Tonga system: satellite geodesy shows that the north end of the Tonga arc is converging with the subducting Pacific plate at 24 cm/yr, and the northern Lau Basin is opening at 16 cm/yr in the lee of this end of the arc (Bevis et al., 1995). Lengthening and shape change of the New Hebrides arc, as expected from arc-migration analysis, also are shown by geodesy (Calmant et al., 2003). Schellart and Lister (2005) and Schellart et al. (2006) explain various Pacific-margin plate interactions in terms of rollback controls.

The internally deforming Aegean-Turkey plate, with the Aegean arc system in its southwest part, is advancing with curved trajectory (Fig. 12) over the African plate as the subduction hinge in front of it rolls back toward the African continent (Chaumillon and Mascle, 1997; Dilek, 2006; Reilinger et al., 2006; Reston et al., 2002; ten Veen and Kleinspehn, 2003). The overriding plate is bounded by strike-slip faults and diffuse high-strain zones, and is deformed internally by distributed and miniplate-bounding extension and strike-slip (Nyst and Thatcher, 2004). Internal extension increases toward the subduction hinge: the plate is being pulled toward the retreating hinge, not pushed into it. The trench, in front of the hinge from which Mediterranean lithosphere of the African plate subducts relatively northward, is advancing rapidly southward across the Nile abyssal fan in the east, and has reached the base of the Libyan continental slope in the west. The accretionary wedge broadens rapidly as Nile sediments are added to it, so the trench is migrating faster than the hinge. Curvature—southward convexity—of arc components increases as they migrate. Africa and the subducting plate are moving much more slowly northward, relative to stable northwest Eurasia, than the Aegean arc system and hinge are migrating southward. (The misnamed Hellenic Trench is a series of extensional features north of the forearc ridge, and is far behind the subduction-front trench of the system, the also-misnamed Hellenic Trough: Reston et al., 2002.)

<<Figure 12. Aegean GPS>>

The Tyrrhenian-Apennine arc system has steadily lengthened, increased its curvature, rotated counterclockwise, and left continental fragments and newly-opened small ocean basins in its wake, as it has advanced toward a subduction hinge rolling back into Adriatic and Mediterranean lithosphere (Facenna et al., 1996, 2001; Lucente et al., 2006). Again, migration of the overriding plate toward a hinge that is retreating oceanward is indicated.

The most complex interactions occur in East and Southeast Asia and the Indonesian region. As India crowds northward into central Asia, extruded crust flows primarily toward free sides and subduction systems—eastward toward the Pacific, relative to stable Eurasia, and also in a giant glacierlike flow southeastward and southward into Southeast Asia, thence westward toward the retreating Andaman-Sumatra hinge (cf., Chen et al., 2000, 2005). Hamilton (1979) and Schellart and Lister (2005) emphasized that this flow is toward retreating extensional subduction systems, which thus provide part of the drive. Socquet et al. (2006) confirmed with satellite geodesy my (Hamilton, 1979) analysis, from observed onshore arcuate strike-slip faults and offshore trenches, of rotating Sulawesi microplates driven by hinge rollback.

Interseismic Locking

Although arcs and plates advancing over subducting oceanic plates are not crumpled from the front, many are shortened by drag at the bottom. The most complete data come from Japan's dense network of permanent Global Positioning System (GPS) stations (e.g., Mazzotti et al., 2000). The northwest (Japan Sea) margin of central Japan, like nearby mainland Asia to the west, is moving slowly eastward relative to stable northwest Eurasia, whereas the southeast part is converging with Eurasia with 1990s velocities of up to 2 cm/yr. That the net migration of the arc system nevertheless is eastward relative to stable Eurasia is shown by the downplating in the mantle transition zone of subducted Pacific lithosphere beneath China, as discussed subsequently.

GPS data from a number of other continental and composite arc systems also show interseismic shortening. Sumatra and Java may be similar, though much less well documented (Michel et al., 2001). Complex New Zealand is rotating clockwise, propeller-fashion about a hub, as strain is transferred from an east-facing arc system, wherein the forearc is moving rapidly eastward away from the rest of the system, in the north, to a west-facing one in the south; the intervening region is subjected to strike-slip faulting and shortening (Beavan and Haines, 2001).

In such cases, only the bottom-frontal part of the overriding plate can be coupled to the slab, for tomography (e.g., Wang and Zhao, 2005; also see subsequent discussion and Fig. 14) shows a low-velocity mantle wedge that intervenes between plate and slab farther back under the plate. Sumatra modeling by Simoes et al. (2004) indicates that coupling may extend only to a depth of 40 or 50 km.

CAUSE OF SUBDUCTION

Oceanic lithosphere is generated by cooling of asthenosphere from the top. This conversion produces a density inversion, for dense, strong lithosphere overlies light, weak asthenosphere. This inversion is righted by subduction. The temperature of the top of the lithosphere is regulated by the ocean to be little above 0°C, whereas the bottom of the lithosphere is defined approximately by the solidus temperature of basalt, which increases with pressure. Oceanic lithosphere does not randomly founder, for its strength and mass-supported compression hold it together, and the mass of a plate instead drives it toward a subduction hinge that provides an escape from the surface. The lithostatic head of seafloor relief and of the trenchward inclination of the base of the dense oceanic lithosphere atop the light asthenosphere, products of the thickening of lithosphere with time as a result of top-down cooling, provides an additional gravitational body force, ridge slide. Oceanic lithosphere is strong in compression but weak in tension, so pull by the sinking slab (although often invoked as "slab pull") is only a minor complication. "Ridge push" is another popular misconception. Body forces do the job.

An overriding plate is carried and driven forward to maintain contact with the retreating hinge and falling slab. This concept is expanded later in this chapter.

MANTLE CIRCULATION

Both seismicity and high-amplitude tomography show that subducting slabs widely reach the 660-km discontinuity. Only ambiguous evidence, which I question, supports the common view that slabs penetrate this discontinuity, sink deep into the lower mantle, and are balanced by upward flow of hot deep-mantle material as currents including plumes and megaplumes, and thus that all or most of the mantle circulates together. Like Anderson (2002a, 2002b, 2007), Hamilton (2002, 2003), and Hofmeister and Criss (2005a, b), I argue that, instead, plate circulation is closed within the upper mantle, and that heat, but not material, rises from the deeper mantle. I see the deep limit of circulation as the discontinuity at about 660 km, whereas Anderson prefers a limit near 1000 km on the basis of geoidal wave-length arguments and of his acceptance of tomographic modeling of some subducted material to that depth

Many arguments given for rise of plumes from the deep mantle to the lithosphere are rationalizations of assumptions, and many testable predictions in the conjectures have been disproved. See, for example, papers by various authors in Foulger et al., 2005a, and Foulger and Jurdy, 2007, discussions appended to papers in the latter volume, and the extensive discussions and links to published papers, pro and con, at www.mantleplumes.org. Downward flow by subduction into the deep mantle, has, however, been illustrated with cross sections from seismic tomography that have convinced many geoscientists. If such deep subduction indeed occurs, there of course must also be upward flow, and thus circulation through all or most of the mantle. Despite its widespread acceptance, tomographic evidence for deep-mantle subduction is, at best, ambiguous and has often been presented in ways that mislead casual observers.

Slabs in the Upper Mantle

The upper-mantle positions of subducting slabs are clearly shown by inclined zones of earthquakes that reach a maximum depth of 690 km where the subducting lithosphere is older than ca. 60 Ma (Fig. 13). Oceanic lithosphere younger than this when it enters a subduction system typically is seismogenic only to a depth of 200 or 300 km (compare Figs. 2 and 13). Young slabs, which are thinner than old ones, lose negative buoyancy and apparently are mixed into the middle upper mantle as they are overriden by advancing arcs and upper plates.

<<Figure 13. Sandwell quakes map>>

Oceanic lithosphere older than ca. 60 Ma can be tracked in both seismicity and high-amplitude tomographic anomalies into the transition zone, which is bounded by seismic discontinuities at depths of about 410 and 660 km, the lower of which is now taken to be the boundary between upper and lower mantle. Many slabs are clearly defined by high-amplitude tomography as subhorizontal on the 660 km discontinuity. This downplating is a manifestation of the migration of hinges at both tops and bottoms of inclined slabs and is not a result of horizontal injection, although it often is so represented. Fukao et al. (1992) showed that subducted lithosphere of most East and Southeast Asian systems is laid down on or near the 660 km discontinuity for lateral distances of 1000-2000 km beyond the hinges at the bases of inclined slabs, which in turn are 500-1000 km laterally distant from the upper hinges that are rolling back into the Pacific. Huang and Zhao (2006) confirmed this pattern and added still more to the areal extent of laid-down slabs. Deal et al. (1999) found cross-strike downplating of ~1000 km behind the Tonga subduction system, in addition to the 600-800 km of horizontal distance between lower hinge and trench. Piromallo and Morelli (2003) showed that subducted lithosphere is stranded atop the 660 km discontinuity across a broad Alpine-northern Mediterranean-Balkan-Turkish region. The entire sunken slab of the migrating Apennine-Maghrebide arc is still recognizable in the transition zone (Lucente et al., 2006).

Body-wave tomography is relatively insensitive to horizontal anomalies, and this is critical with regard to whether or not the 660 km discontinuity is penetrated by sinking slabs. To minimize this problem, Zhao (2004) solved independently for velocities within the transition zone, thereby much sharpening depiction of the settled slabs. Three figures from his global P-wave model are reproduced here, modified slightly in labeling. Note that the colors on Figures 15 and 16 are saturated at calculated P-wave velocity anomalies of less than 0.5 or 1%, although upper-mantle anomalies reach 5% (Fig. 14). Zhao presented both layer maps and vertical sections through his models and regarded them as showing that, although most slabs indeed are plated down on the 660, some penetrate far into the lower mantle, and that broad upwellings (not the narrow stovepipes of some plumologists) rise from deep in the mantle and are responsible for some volcanic "hotspots"; I question these inferences that voluminous material crosses the 660 km discontinuity..

Figure 14, Zhao's upper-mantle profile across central Honshu, shows the position and seismicity of Pacific lithosphere sinking beneath the Japanese arc system. The slab sinks, more steeply than it dips, from a retreating hinge. The low-velocity region midway between slab and magmatic-arc crust may be hot mantle sucked up above the sinking slab, and may be the heat source for arc magmatism (Hamilton, 1995; Zhao, 2001). The hot, low-velocity mantle wedge precludes interseismic locking of the slab to the overlying lithosphere plate below shallow depth (see also Wang and Zhao, 2005).

<<Figure 14. Honshu tomography>>

Figure 15 crosses the entire mantle of a larger region that includes Japan. Pacific lithosphere subducted beneath Japan is imaged as plated down on the 660 km discontinuity for 1500 km beneath China, and, with the 1000 km horizontal length of the inclined part of the subducting slab, it records 2500 km of hinge retreat into the advancing Pacific. (The common assumption that flat slabs within the transition zone represent lateral shoving of a beam overlooks hinge rollback.) Active Changbai volcano and other young basaltic tracts of northeast China obviously owe their magmatism to crustal or upper-mantle processes, not to hot material rising beneath them from the lower mantle (Zhao et al., 2004).

<<Figure 15. Changbai-Japan tomography>>

Zhao's velocity variations within the transition zone are shown in map view by Figure 16. The broad high-velocity patches presumably include much of the relatively young subducted lithosphere plated down on the 660 km discontinuity in Tethys, Australasia, East and Southeast Asia, and southwest North America. Ritsema's shear-wave tomography (body waves plus surface waves, in spherical harmonic rendition: Ritsema, 2005, Fig. 6C) yields similar images for the East Asian-Australasian region, with lesser horizontal resolution, and shows a continuous slab in the transition zone beneath western South America and no major anomaly beneath North America.

<<Figure 16. Tomography at 550 km>>

No Proven Subduction into Lower Mantle

A widely accepted argument for whole-mantle circulation comes from seismic tomography that purportedly shows a great slab inclined downward through most of the lower mantle. This would require that compensatory rising material (plumes are currently favored) come back up through the 660-km discontinuity elsewhere. There is only one visually impressive example of this possible deep subduction; blobs depicted elsewhere are nondescript. Many tomographers regard the low-amplitude positive velocity anomalies calculated in the lower mantle that are near regions of surface subduction to record deeply subducted slabs, and conclude that although indeed most old slabs are parked in the transition zone, much other subducted material descends through the 660 km discontinuity and goes varying distances into the lower mantle. Penetration of the 660 km discontinuity is visualized as direct in some cases, the upper-mantle slab continuing into the lower mantle at a semiconstant angle, but, more commonly, it is thought to require accumulation of subducted lithosphere in the transition zone until large masses break away downward. Thermal, mechanical, and petrologic rationales given for such subduction are strained.

Tomography

The tomographic anomalies attributed to deep slabs can be interpreted alternatively as artifacts of methodology and sampling deficiencies and as illusions of selective presentation. No deep subduction need be indicated. The illustrations that convince many readers are tomographic profiles that are too often placed only where desired results are shown and too often truncated are downward and laterally to omit anomalies that misfit the message. "Cross sections are for tourists", Bradley Myers, expert geologic-map reader and my longtime colleague, often said with regard to structural geology, and the same applies to much tomography. Colors or patterns on tomographic maps and profiles commonly are saturated for very small velocity differentials, which make ambiguous low-amplitude lower-mantle anomalies look similar to upper-mantle ones with amplitudes 10 or 15 times greater. Many ambiguities are inherent in the tomography itself. Most body-wave tomography divides the solid Earth into compartments or grid nodes, calculates raypaths from earthquakes to recorders, determines departures of actual travel times from those expected from a standard-Earth radial-velocity model, and inverts to solve for the contribution of velocity within each compartment, or in the vicinity of each grid node. Various smoothing, damping, and sharpening algorithms are applied, and the final result accounts for some fraction, usually unspecified but commonly small, of the observed travel-time variations. The methodology is viable mathematically when each compartment or nodal vicinity is crossed by many rays in many directions, but this requirement often is not met. Earthquakes (Fig. 13) and recorders are very irregularly distributed. Most of the mantle beneath the oceans, and the deep mantle almost everywhere south of about latitude 20°S, is poorly sampled. Much other mantle is sampled primarily by subparallel rays from which tomographic methodology generates artifacts. Calculated anomalies are smeared out. No-data regions are populated with interpolated values, or with near-zero default values, or with artifacts required by symmetry in spherical-harmonic renditions. Illusory local anomalies can be generated from actual regional anomalies where coverage is meager.

Profiles showing an irregular low-amplitude anomaly, 500 km or so in typical thickness, the top of which is inclined eastward deep into the lower mantle beneath the southernmost United States (e.g., Grand et al., 1997) are widely accepted as imaging the subducted Farallon plate, and thus as proving whole-mantle circulation. Gu et al. (2001) and Dziewonski (2005), however, presented longer profiles, through the same tomographic models and other similar ones, which show the "Farallon anomaly" to be merely part of a highly irregular regional regional positive anomaly that extends vertically through the entire lower mantle, and that extends horizontally 2000 km or so west of North America where no relation to subduction is plausible. Further, an inclined "Farallon anomaly" can be designated only within a narrow latitudinal band because to both north and south, where it should be present if correctly interpreted in terms of long-continued deep eastward subduction, no tidy anomaly is depicted. The near randomness of such deduced anomalies below the 660 km discontinuity, and the lack of coherent anomalies suggestive of subducting slabs, is obvious on the small-scale global tomographic maps, at various mantle depths in several different tomographic models, presented by Montelli et al. (2006). (For an elaborate rationalization of highly irregular low-amplitude positive velocity anomalies, deduced in the lower mantle beneath the Americas and the Caribbean, as representing the Farallon and other slabs, see Ren et al., 2007; they did not show their model beneath the adjacent eastern Pacific Ocean, nor did they address the sampling bias discussed next.).

Artifacts due to inadequate sampling may account for the "Farallon anomaly". About 80% of the earthquakes used in tomography occur in subduction systems (Fig. 13), primarily near the upper surfaces of subducting slabs and in accretionary wedges (Fig. 14). Teleseismic raypaths from these quakes mostly exit obliquely downward through the slabs and thereby gain traveltime advances. Most of the waves from which the purported Farallon anomaly is calculated originated near the top of the subducting Andean slab and are recorded at North American stations. The raypaths are clustered, so their shallow near-origin time advances are not cancelled out by the simultaneous-inversion process. The Andean slab varies greatly in strike, inclination, and configuration (Brudzinski and Chen, 2005), so within-slab travel distances of diving rays vary complexly on route to different recorders. Also not factored into tomography is the strong velocity anisotropy of slabs. The purported Farallon slab anomaly likely is a methodological artifact due to the scarcity of the crossing rays required for viable body-wave tomography.

Van der Hilst (1995) presented three tomographic profiles, but no maps, across the Tonga and Kermadec arcs. He inferred slabs subducting deeply westward, beneath lithosphere laid down in the transition zone. As in the "Farallon" example, selective viewing is needed to postulate that slabs are present within irregular regional positive anomalies, which in this case are gaining volume and complexity where they are truncated at the ends and bottoms of the short and shallow profiles.

Other purported tomographic examples of deep subduction are primarily of low-amplitude positive anomalies, in discontinuous tracts of the upper third or half of the lower mantle, along the great Tethyan orogenic systems from southwest Asia to Indonesia (e.g., Piromallo and Morelli, 2003; Replumaz et al., 2004; Van der Voo et al., 1999; Widiyantoro and van der Hilst, 1997; Zhao, 2004). These non-slablike anomalies are mostly irregular blobs that are depicted beneath, or across strike from, only parts of the subduction-generated orogenic terrains, and that have tops often hundreds of km beneath the 660 km discontinuity. The common explanation is a byproduct of erroneous visualization of slabs as pushed laterally along, rather than plated down on, the 660 km discontinuity: the discontinuity resists penetration but is subject to sporadic breakthroughs by piled-up slabs. (Similar blobs elsewhere that have no conceivable relationship to young subduction, as beneath East Antarctica and the central Pacific, are not given subduction interpretations.) The earthquakes from which these deep, discontinuous Tethyan anomalies are calculated occur mostly in active subduction systems and in continental orogenic systems that contain or overlie upper-mantle slabs, but, in contrast to the simple Andean-Farallon case, geometries are too complex for casual analysis of raypaths and sampling artifacts. Tomographers could resolve this problem by analyzing raypath directions through their mantle boxes.

Heat

Conventional models of geodynamics require assumptions of temperatures at depth, and of easy vertical rise of hot material, that are biased in the high directions.

Global Heat Flow

The heat loss from the solid Earth indicated by heat-flow measurements, integrated for continental and oceanic crustal age, is approximately 31 TW. This is about the maximum amount that can be accounted for as generated concurrently by cosmologically reasonable contents of radioactive elements (Hofmeister and Criss, 2005a). The voluminous numerical-modeling literature nevertheless incorporates a speculative value of ~44 TW, which represents the age-integrated measured heat flow from the continents plus a conjectural amount for the oceans, derived with a half-space cooling model, that is approximately twice the age-integrated measured oceanic heat flow. This factor-of-two discrepancy between measurements and model is popularly rationalized as due to loss of half of the oceanic heat flow to circulating seawater, and is enormously important for evaluating the composition, properties, and behavior of the deep interior. Hofmeister and Criss (2005a, b, 2006) showed that the half-space cooling model grossly overestimates heat loss because of its invalid physical assumptions. One false assumption is that three-dimensional thermal volume expansivity can be used in evaluating the age-dependent subsidence of oceanic lithosphere, whereas the actual problem is of essentially one-dimensional vertical expansivity. This consistent error, repeated in scores of papers over the last 30 years, exaggerates by a factor of three in effect of lithosphere temperature on seafloor depths. Another false assumption in conventional papers is that thermal conductivity of oceanic lithosphere is constant at its near-surface value, whereas in fact conductivity decreases with temperature and is only about one-third as large at the base of oceanic lithosphere as at the top. These two errors greatly increase heat flow calculated with the half-space-cooling model. Von Herzen et al. (2005) reasserted the [invalid] assumptions of the half-space model and showed that several of the minor arguments of Hofmeister and Criss (2005b) can be regarded as ambiguous, but they did not address, and hence in effect conceded, the important issues, as Hofmeister and Criss (2005c) made clear. Wei and Sandwell (2006a) deduced, from a variant of the half-space model, a global heat loss of ~42 or 44 TW, but Hofmeister and Criss (2006) demolished this rationale for its mathematical errors, its misuse of 3-D expansivity, and its implicit assumption of constant thermal conductivity. In their response, Wei and Sandwell (2006b) reasserted their assumptions, made further errors, and did not address the Hofmeister and Criss points—and thus, in my view, conceded the debate. Many conventional modelers of other aspects of lithosphere behavior (e.g., Sleep, 2006) also base their calculations on the false assumptions of constant thermal conductivity and of 3-D expansivity.

Global heat loss probably is near the measured 31 TW, not the hypothetical 44 TW, and far less of the total can come from the core than is assumed in popular bottom-heating conjectures.

Magma Temperatures

Another required, but invalid, assumption, commonly misstated as fact, of conventional geodynamics and plumology is that rising columns of hot material produce temperatures at the base of the lithosphere that are several hundred degrees Celsius hotter than ambient asthenospheric mantle (Campbell and Davies, 2006; Sleep, 2006). This assumption commonly incorporates the additional assumption, also misstated as fact, that "hot-spot" basalts (e.g., ocean-island basalts, OIB) erupt at much higher temperatures than "normal" midocean-ridge basalts, N-MORB. In fact, the temperatures of the chemically contrasted end-member N-MORB and OIB magmas are essentially the same (Falloon et al., 2007), as is to be expected from the limited range of seismic properties of oceanic asthenosphere globally.

Geochemistry

The misleading term "normal", which is applied to only about half (N-MORB) of all ridge basalts, reflects model-driven speculation that proper MORB should be derived from "depleted [upper] mantle". The other half of MORBs are geographically interspersed and trend continuously in composition from N-MORB to "ocean-island" (e.g., plots by Debaille et al., 2006, and Fitton, 2007). Rationales in Debaille et al. typify much basalt geochemistry by invoked mixing of melts from upper and lower mantle sources to explain all local variants, no matter how closely intercalated in space and time. Fitton, by contrast (and despite his conviction that plumes from the deep mantle do rise to the crust), demonstrated that *most* basalts of OIB type, which conventionally are assigned to plume sources, "occur in [many diverse continental and oceanic] situations where mantle plumes cannot provide a plausible explanation."

Two families of explanations provide obvious alternatives to explanations that require lower-mantle sources, and hence whole-mantle circulation, to account for enriched igneous rocks. One family, which is fast gaining in popularity although it is still a minority view, is that both subduction and crustal delamination recycle fractionated material downward into the upper mantle, where it is selectively melted and is disproportionately represented in small-batch melts (e.g., Anderson, 2007; Herzberg, 2006; McKenzie et al., 2004; Natland, 2007). The second family, which is not exclusive of the first, is that much of the contrast between enriched and depleted basalts is due to different pressure-temperature-composition histories of fractional melting, fractional crystallization, and zone refining in contrasted lithospheric settings (e.g., Hamilton, 2002, 2003).

Other Arguments Against Whole-mantle Circulation

There are many reasons for thinking that through-the-mantle circulation does not operate and that the lower mantle circulates only very sluggishly. Irreversible fractionation of a largely molten planet very early in its history is likely, radioactive heat sources may be almost entirely in the crust and upper mantle, temperature of the lower mantle may be much lower than commonly assumed, and deep-mantle thermal conductivity plus diffusivity may be high, minimizing transfer of heat in material (Anderson, 2002b, 2007; Hofmeister, 2005; Hofmeister and Criss, 2005a, b). The deep mantle has very low thermal expansivity, so buoyancy effects of lateral temperature variations are minimal. Viscosity increases greatly with pressure, and if temperature of the lower mantle is lower than the high values commonly assumed to enable rapid convection and plumes, its viscosity may be in part a thousand or more times higher than that of upper mantle, precluding all but the most sluggish circulation. That the low-seismic-velocity regions of the basal mantle, close to the core, owe their velocity retardation to high iron content and high density, not to high temperature, is made likely by their relatively low Vp/Vs ratios and by data from experimental petrology and mineral physics (Ishii and Tromp, 2004; Jacobsen et al., 2004; Trampert et al., 2004); and, if so, they cannot provide the rising hot material attributed to them by plumologists. The conventional assumption of great bottom heating of the mantle by the core may be invalid. The discontinuity near 660 km separates domains of profoundly different seismic patterns that are inconsistent with easy passage of material through it (Gu et al., 2001). The 660 km discontinuity is a phase-change boundary with negative pressure/temperature slope: descending material must be heated to penetrate it, and ascending material cooled, thus cancelling out thermal buoyancy—although whether this effect is enough to block penetration, if the boundary has not also become compositional as a result of layered circulation, is disputed (e.g., Chucinovskikh and Boehler, 2004). Earth's enormous present heat content must mostly be retained from its early history, although current heat loss may be little more than current radioactive heat generation. Top-concentrated and interrnal radioactive heat sources, and cooling by subducting slabs, may produce far-from-adiabatic mantle temperatures (Anderson, 2007). Motions of surficial plates and subducted lithosphere have simple possible explanations in terms of flow restricted to the upper mantle, as I elaborate in following sections.

Most current geodynamic (e.g., Jellinek and Manga, 2004) and geochemical models (e.g., Debaille et al., 2006) incorporate the contrary view that there are no significant barriers to whole-mantle circulation and that the evolution and properties of the lower mantle must be such as to enable such circulation. This view is anchored to the dubious assumptions that the lower mantle is mostly unfractionated "primitive mantle" (despite very early and hot separation of the core), whereas the upper mantle has become "depleted mantle" by separation of crust. This notion originated with chemists in the 1950s and early 1960s, when little was known about isotopes or the solar system, and was adopted by dynamicists in the late 1960s to explain plate motions with whole-mantle convection. These assumptions have since become dogma by repetition and self-citation. The common geochemical assignment of "enriched" oceanic volcanic rocks to sources that have risen from hypothetical "primitive [lower] mantle" is one of many circular rationalizations of these assumptions.

Dual Circulation?

Whether or not my skepticism regarding deep-mantle subduction is warranted, the 660-km discontinuity clearly impedes circulation between upper and lower mantle, the properties of the lower mantle require its circulation to be much more sluggish than that of the upper mantle, and simplistic cartoons of whole-mantle flow loops, and of deep-mantle subduction geometrically and temporally similar to that in the upper mantle, cannot be valid. There might, however, be both flow that is mostly less restricted to the upper mantle, and flow involving lower and upper regions together. That the shallow-flow-only option permits an elegantly simple representation of plate motions makes it my strong preference.

MECHANISM OF PLATE TECTONICS

The broad patterns of seafloor spreading, rolling-back hinges and down-plating subducted slabs, and the characteristics of convergent margins all accord with a simple explanation of plate tectonics as top-driven circulation closed within the upper mantle (Fig. 17; Hamilton, 2002, 2003). Oceanic lithosphere is formed by top-down cooling of asthenosphere, and the resulting density inversion is righted by subduction. Oceanic plates are propelled by their mass toward their sinking sides, their only exits from the surface, aided by the lithostatic head represented by seafloor bathymetry and by the common trenchward slope of the base of oceanic lithosphere. Subduction hinges roll back as slabs sink, more steeply than they dip, into the mid-upper mantle if young and thin, but into the transition zone if old and thick. Overriding arcs and plates are pulled toward the retreating slabs and pass over subducted lithosphere plated down in the transition zone or mixed into the middle upper mantle..

<<Figure 17. Plate model>>

This process transfers lithosphere from shrinking to expanding oceans. Because slabs sink more steeply than they dip, the entire upper mantle beneath incoming oceanic lithosphere—asthenosphere, transition-zone material, and whatever is between them, an aggregate thickness of 550 km or so—is pushed back under that lithosphere, forcing rapid spreading within shrinking oceans. Advancing arcs and upper plates, by contrast, pass over only subducted lithosphere, perhaps 100 km thick where not doubled up, and a modest amount of entrained material, and only that proportion of mantle material is thus transferred to expanding oceans and backarc basins, which accordingly widen only slowly. The striking contrast (Fig. 2) between the rapidly spreading, yet more rapidly shrinking, Pacific Ocean, and the slowly spreading, yet expanding, Atlantic, has a simple explanation.

In these terms, hinges advance relative to a sluggish lower mantle, and, in the framework that accords with such advance, plate motions should make quantitative sense in terms of subduction as the primary drive. These conditions can not be satisfied with conventional frameworks, as discussed next, but are satisfied with an alternative framework.

FRAMEWORK OF PLATE TECTONICS

If plate tectonics indeed is driven by subduction due to cooling from the top, and its circulation indeed is confined to the upper mantle, then there should be a framework, relative to decoupled and sluggish lower mantle and hence approximately an "absolute" reference frame, of plate motions within which plate interactions make sense. Hinges should roll back, plate motions should relate coherently to subducting margins, and the passive ridges spreading between plates should migrate to tap fresh asthenosphere. These conditions are not remotely met by the popular hotspot and no-net-rotation frameworks, but are mostly satisfied by an Antarctica-fixed framework.

The geometry of seafloor-spreading anomalies younger than a few million years constrains much of the relative-motion pattern, although it poorly defines the behavior of internally deforming parts of plates and of small-plate interactions. The rapid development of satellite geodesy, and in particular GPS, in the past 20 years has done much to close this gap. Despite their short time line, GPS vectors generally accord with the several million years of motion incorporated in seafloor-spreading deductions, showing that most motion is remarkably smooth and continuous (e.g., Sella et al., 2002). Major irregularities are introduced by preseismic and postseismic creep, and interseismic locking.

Published GPS studies relate motions to local frameworks, or to internally stable parts of chosen major plates, or to the International Terrestrial Reference Frame (ITRF), a no-net-rotation frame that incorporates seafloor-spreading data. The result is a confusing array of data sets in different frames. Help is available in the interactive UNAVCO Web site http://jules.unavco.org/VoyagerJr/Earth, maintained by Lou Estey. Either individual GPS velocity vectors or vectors of generalized models of plate velocity can be displayed on a zoomable world map in a no-net-rotation framework or in a framework wherein any major plate as fixed. The Antarctica-fixed map, Figure 18, is from this source.

<<Figure 18. Antarctica fixed>>

No Fixed Hotspots

Evaluation of the driving mechanism of plate tectonics has been long retarded, in my view, by widespread but uncritical acceptance of speculation that plumes of hot, buoyant material rise from fixed positions in the deep mantle and produce surface magmatism and other thermal effects on overpassing lithosphere plates, and thus that a reference frame for motions of plates relative to most of the mantle can be established from surface imprints of those effects. Despite disproof of many aspects of this speculation, the basic conjecture has hardened into dogma; see historical reviews by Anderson and Natland (2005) and Glen (2005). Visualization of plumes and their products varies widely and incompatibly between groups and subgroups of investigators—plate dynamicists, geodynamic modelers, fluid dynamicists, seismologists, geochemists, structural geologists—because there are few constraints save imagination. Much conjecture represents ad hoc evasion of disproved predictions: whatever is observed where a plume is postulated to operate is a product of the plume even if unique to that locality, and so the speculation cannot be tested. Some groups (e.g., McKenzie et al., 2004) define all buoyancy-driven upwellings and downwellings as plumes (hence dikes, midocean ridges, salt domes, and subducted slabs), which divorces the term from its common geoscience application to hypothetical narrow upwellings from deep thermal boundary layers. In an ultimate non sequitur, Bourdon et al., 2006 claimed that their evidence for a shallow example of this all-inclusive definition was evidence for the concept of deep-mantle thermal plumes.

Much recent ballyhoo has accompanied the depiction of through-the-mantle plumes with finite frequency ("banana-doughnut") seismic tomography by Montelli and associates. (e.g., 2004). For evaluations of the defects in the methodology and in its basis and inconsistent results, and for statistical demonstration that the purported plumes are artifacts of sampling deficiencies, see Julian (2005) and the chronological review, and linked published papers, by four groups of seismologists at www.mantleplumes.org. (Montelli et al., e.g. 2006, retain confidence in their method.)

The hotspot reference frame of Gripp and Gordon (2002) is tied to three purportedly fixed hotspots, Hawaii, Yellowstone, and Iceland, to which are added, because they approximately fit the same frame, two more hotspots regarded as approximately fixed for >5 Myr, and six more as fixed but inaugurated only within the past several million years. This short list minimally overlaps the many conflicting lists of hotspots designated by various other groups, for most other postulated hotspots are unstable within the framework of the accepted few. I see this selection of a small array because they approximately fit the concept as mere wish fulfillment

Plate kinematics makes no sense in this hotspot reference frame. As many subduction hinges migrate forward as retreat in this frame, and some change along strike from advancing to stationary to retreating. Each mode requires different propulsion mechanisms and mantle flow in fixed-hotspot terms, which nevertheless have been thus rationalized by Conrad and Lithgow-Bertelloni (2004), Heuret and Lallemand (2005), and Schellart et al. (2007). The complex mechanisms postulated for such interactions do not account for the observed major and minor features of plate motions and interactions discussed earlier in this essay.

Powerful evidence contradicts the notion of fixed hotspots. The purported spots most important for the hotspot reference frame are Hawaii, Yellowstone, and Iceland. The relative positions of these can be rationalized, by selection from ambiguous parameters along the plate circuits between them, as fixed relative to one another—but none is viable as the top of a plume fixed relative to the lower mantle.

Hawaii

Geophysics of the Hawaiian region misfits plume predictions (Anderson, 2005). Pacific spreading patterns (Atwater, 1989), paleomagnetism of Emperor seamounts (Tarduno et al., 2003), and paleomagnetic latitudes of cores from the floor of the Pacific plate (Sager, 2007) show independently that the Pacific plate did not change direction by 60° above a fixed hotspot at the time of the Emperor elbow, 50 Ma, as required by fixed-Hawaiian-plume speculation. Other island and seamount chains once conjectured, in the absence of data, to fit a Hawaiian trajectory in fact misfit it badly in chronology, trends, and geometry (e.g., Clouard and Bonneville, 2005; Natland and Winterer, 2005). Hawaii and the other chains are properly explained as responses to within-plate stresses (Natland and Winterer, 2005; Norton, 2007; Stuart et al., 2007).

Yellowstone

The east-northeastward progression of late Neogene volcanic centers in the eastern Snake River Plain and Yellowstone region is an anchor for advocates of fixed plumes. Nevertheless, the thermal anomalies, as constrained by high-resolution tomography, are confined to the upper mantle (Humphreys et al., 2000). Plume proponents Waite et al. (2006) made a detailed tomographic study with local seismic arrays and also found no evidence for low velocities deeper than 400 km. A series of magmatic centers that progress west-northwestward-into Oregon from the same origin during the same period, and that display a more regular time-distance progression, commonly is ignored by plume proponents because it does not "fit", although plume-advocate Jordan (2005) speculated that the aberrant trend formed by long-distance squirting from the fixed Yellowstone plume.

Iceland

The Iceland thermal anomaly on the northern Mid-Atlantic Ridge also is confined to the upper mantle (Foulger et al., 2001, 2005b). The contrary depiction by Bijwaard and Spakman (1999) of a broad, highly irregular, through-the-mantle low velocity plume required placement of a cross section in the one orientation through their tomographic model that afforded continuity. Bijwaard and Spakman depicted the hypothetical plume with velocity differentials of only ~0.4% (which are below the actual resolution of their model), and they truncated the profile at both ends where continuation would have shown other low-velocity anomalies in their model where none are plausible in plumological terms (Foulger et al., 2005b). There is no time-progressive hotspot track, and conjectures positing initiations of seafloor spreading by a hotspot are contradicted by geophysical characteristics of the relevant tracts (e.g., Foulger et al., 2005b).

No-Net-Rotation Frame

A framework in which plate motions sum to zero makes a convenient reference, absent other information, although there is no compelling reason to presume such a zero-sum frame to depict "absolute" motions, relative to a sluggishly moving deep mantle, of surficial materials on a spinning Earth. DeMets et al. (1990) depicted plate motions in the framework wherein rotations defined by ridge-spreading magnetic anomalies less than 3 million years old summed to zero, and Sella et al. (2002) depicted frame the generally similar relative motions defined by space geodesy in a similar frame. Best-station motions in parts, not undergoing internal deformation, of six large plates, as defined within a slightly modified geodetic zero-sum framework, mostly can be fitted to the ridge-anomaly frame within ~2 mm/yr (Altamimi et al., 2002). Internal deformation of plates, features associated with arc migration, and microplate motions are not generally incorporated in the ridge-anomaly framework, but are displayed in many regions of the geodetic framework.

A no-net-rotation framework necessarily minimizes relative motions of plate boundaries, so if subduction provides the major drive, any systematic relationships will be obscured by this framework. A subduction drive of plate motions cannot be rationalized from the hodge-podge of boundary motions and stabilities in the no-net-rotation framework.

Antarctica Fixed Frame

If subduction does indeed control motions of both overriding and subducting plates, then there should be a bulk-Earth framework in which hinges mostly roll back and in which rates and orientations of plate rotations make general sense in relation to those hinges. Plates should move toward subduction systems, and plates minimally bounded by such systems should be relatively fixed. An Antarctica-fixed.framework approximately fits these criteria because, alone among major plates, the Antarctic plate is bounded almost entirely by spreading ridges migrating relatively away from the continent at its center (Fig. 2). The ridges vary much in orientations, spreading rates, and distances from the continent. whereas both hotspot and no-net-rotation frameworks assign substantial motion to the Antarctic plate. Both hotspot and no-net-rotation frameworks assign substantial motion to the Antarctic plate, and little support for a subduction drive can be found within either of those frames.

Most global plate motions make sense, in terms of a subduction drive, in an Antarctica-fixed framework (Fig. 18). Most subduction hinges roll back in this framework. Plates move toward hinges, ridges form between plates moving toward different hinges, and, as expected of top-driven motion, ridges migrate to tap fresh asthenosphere. The westward migration of the East Pacific Rise in this framework accords with the asymmetry shown by abundant geophysical data from its south-tropical sector (analysis and references in Hamilton, 2002). Carbotte et al. (2004) and Katz et al. (2004) recognized systematic variations in ridge morphology and magmatism, including petrology, with migration directions of fast-spreading ridges, but thought the correlations poor because they assumed a fixed-hotspot frame, whereas their correlations are good in the Antarctica-fixed frame.

Senses and amounts of rotations of most plates in the Antarctica-fixed frame accord with subduction as their primary drive. Africa rotates slowly counterclockwise toward subduction systems in the northeast, and Arabia rotates faster, pulling away from Africa, into the Makran system, whereas in hotspot and no-net-rotation frameworks Africa moves rapidly eastward with no likely means of propulsion. Internally stable and subduction-free northern Eurasia also is almost stationary in the Antarctic reference frame, not moving rapidly eastward as in hotspot and no-net-rotation frameworks. East Asian regions, squeezed in front of advancing India, migrate eastward toward the free edges of Pacific subduction systems. Velocity of the Indian-Australian plate increases eastward as subduction increases to the north. The Americas move westward, at twice the rate of migration of the MidAtlantic Ridge from Europe and Africa, toward bounding subduction systems and, for the non-subducting margin of part of North America, toward the obliquely retreating Pacific plate. The west-coast arcs of South America, of North America from Oregon into British Columbia, and the Aleutian arc are advancing as hinges roll back in front of them. In the southwest Pacific, the New Hebrides and Tonga hinges are migrating apart, and both are rolling back in the Antarctica-fixed frame even though Tonga and the Pacific are converging at uniquely high velocity. In Indonesia and western Melanesia, the hinges that bound small plates—Wetar, North Sulawesi, Halmahera, Sangihe, New Guinea, and Manus—appear to be rolling back in the Antarctic frame insofar as data are available (Kreemer et al., 2000; Walpersdorf et al., 1998).

Plate motions have a net westward drift in the Antarctic reference frame. That Earth's rotation is a factor in plate motions is likely because Euler poles (which are independent of framework) of relative motions between large plates are mostly at high latitudes and relative plate motions are faster at low latitudes than high. Paleomagnetic data are of low resolution compared to kinematic constraints from seafloor spreading and satellite geodesy, and provide no limit on net eastward or westward motion, but they are adequate to preclude major true polar wander whereby the entire lithosphere has large net motion through the pole of rotation.

Complications

Although motions of large plates and many small ones accord with subduction drive in the Antarctic frame, a number of arc systems have short-term GPS motions, mostly slow, that are retrograde in that frame. Some of these motions may record transient locking of slabs and overriding plates, and net long-term motions, which include large coseismic slip and associated creep (cf. Melbourne et al., 2002), may commonly be forward in the Antarctic frame. Slow shortening thickens the crust and produces a lithostatic head that results in abrupt coseismic thrusting opposite to the shortening vector. Parts of the Pacific side of Japan have westward vectors, in the Antarctic frame, of interseismic short-term GPS motion but, as noted previously, Pacific lithosphere is plated down in the transition zone far westward from Japan, and the Japan Sea side indeed is moving eastward, as required by the relationship of the islands to nearby east-moving mainland Asia and the nonsubducting Sea of Japan. Another candidate for such a seismic-locking explanation may be south-central Alaska, which has at least short-term northward motion absorbed in interior shortening, although the oceanic Aleutian island arc is moving southward toward a rolling-back hinge, in the Antarctic frame. Short-term vectors of south-facing Java are mostly northeastward at 1-2 cm/yr (Kreemer et al., 2000), although here also long-term southward and southwestward migration seems likely when large coseismic slips are factored in (cf. Subarya et al., 2006).

Other examples indicate that if the general concepts developed here are valid, that lithosphere and subjacent mantle motions much less tidy than the two-dimensional ones of Figure 17 are required in complex arc systems. Explanations likely include mantle flow around the ends of subducting slabs, and beneath slabs that are limited to the upper few hundred kilometers of the mantle. West-facing Middle America has a slow eastward GPS motion relative to fixed Antarctica; subduction of young Pacific lithosphere there extends only to shallow depth and mantle underflow may be indicated. The components of the east-facing Caribbean arc have a slow westward motion in the Antarctic frame, and mantle underflow and endflow might both be involved.

Relationships are complex in the arc systems from Japan to Indonesia. The Philippine Sea plate, which is outlined by arcs on both sides, is rotating clockwise (independent of framework) relative to Asia and the Pacific about an Euler pole near central Japan. This rotation transfers major convergence between the Pacific and Asia from the east side of the Philippine Sea complex in the north to the west side in the south. Along northern Japan, Pacific-Asia convergence is at the Japan trench. Offshore from central Japan, this trench swings south (Bonin Trench), then bows eastward into the Pacific (Mariana Trench), then dribbles out southward in small festoons (inactive Yap and Palau Trenches) and scissors into a slowly spreading ridge. On the west side of the Philippine Sea thus outlined, compensatory convergence increases southward, from near zero along Honshu, thence along the Nankai and Ryukyu Trenches and, beyond them, to a maximum in the southern Philippines and northern Indonesia. On the west side of the Philippine Sea plate, GPS vectors in the Antarctic frame are eastward in the east-facing Ryukyu arc, and westward in west-facing Luzon, but the southern Philippines, which face east over the Philippine Trench, also have at least short-term westward vectors (e.g., Walpersdorf et al., 1998). (The Philippines tectonically resemble New Zealand in propeller rotation, although motion is counterclockwise rather than clockwise, with the transition from westward to eastward subduction similarly marked by longitudinal strike-slip faulting.) The east-facing Bonin and Mariana arcs, bounding the Philippine Sea plate on the east, have northwestward GPS velocity vectors to ~6 cm/yr (e.g., Kato et al., 2003), opposite to rollback sense, in the Antarctic frame. South of the Philippines are the miniplate complexities of northern Indonesia.

So many major features fit the general scheme of subduction control in an Antarctica-fixed framework that I assume that the complications just noted can also be fit into it. My specific rationalizations are not substantive enough to warrant further exposition here.

AFTERWORD

A top-down subduction drive, an approximate Antarctic reference frame of “absolute” motion, and closure of plate circulation above 660 km discontinuity provide a simple explanation for plate motions and interactions. This drive, frame, and closure also are compatible with much additional information, only a little of which was noted here. Extrapolation of the theme predicts that continental collisions and continuing convergence, including that of India with Asia, also are driven by subduction, but reliable and detailed tomographic data with which to test this notion and evaluate geometries are not yet available. Most subducted slabs for which good tomography is available are plated down on the 660-km discontinuity, and so even if some slabs do sink through that discontinuity the mechanism postulated here should be generally applicable.

My explanations can be broadly correct only if assumptions now widely accepted in geodynamics, geophysics, and geochemistry are false. Those assumptions derive from conjectures, originated in the 1950s and 1960s, regarding the detailed composition, slow evolution, and bottom-up behavior of the Earth. These assumptions predate a huge body of contrary information and yet are now dogma in much of the geoscience community.

The conventional view of Earth’s secular evolution is of progressive fractionation. Elsewhere (Hamilton, in review) I develop the opposite concept: Earth was highly fractionated very early in its history, and its subsequent evolution, consequent on changes enabled by cooling, has involved progressive enrichment of the upper mantle by downward recycling of crustal materials back into it. Plate tectonics provides the current major mode of that recycling, but time-varying processes of delamination may have dominated most of Earth’s evolution.

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repeatedly studied Ray's elegantly written work and incorporated his concepts in my own research (as, here in my discussion of accretionary wedges), and Ray and his wife Mina are now my good friends.

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ILLUSTRATIONS

Figure 1. Schematic diagram (from Simkin et al., 1989) that incorporates many popular misconceptions about plate tectonics, such as oceanic lithosphere that spreads away from a fixed ridge, tips sharply downward at a fixed trench, and slides down a slot in the mantle, where an overriding plate is crumpled against the hinge; and the ridge and trench are parallel components of a cylindrical system. These features do not occur on the Earth. (The current version of this figure, in Tilling et al. [2006], retains similar never-happens geometry but does not show the crumpling required by that hypothetical geometry; some accompanying materials are now realistic.)

Figure 2. Age of oceanic crust. The broad features of plate interactions displayed here (e.g., rapid spreading of the shrinking Pacific, slow spreading of the enlarging Atlantic, intersections of ridges and trenches) cannot be explained by current models of geodynamics as driven by bottom-heated convection. Isochrons correspond to identified magnetic anomalies. Map prepared by David Sandwell from data of Müller et al., 1997.

Figure 3. Cross section of convergent margin between continental and oceanic plates. The trench is the broad dihedral angle between the tops of the gently inclined subducting oceanic plate and the top of the accretionary wedge of, mostly, scraped-off trench sediments. The presence of a forearc basin indicates that the thin leading edge of the overriding plate was not crumpled during the period recorded by basin sedimentation.

This section is scaled to fit modern Sumatra and Cretaceous California, which are dimensionally similar except that the former is currently active and the latter is variably eroded to expose deeper features. After Hamilton, 1995; there is no vertical exaggeration.

Figure 4. Physiographic map of the active Sumatra-Java-Banda arc system. The trench is the outermost conspicuous arcuate feature, and the magmatic arc (highlands on Sumatra and Java, and islands around the Banda Arc) the innermost. The magmatic arc of Sumatra and Java is superimposed on a geanticline produced by magmatic underplating and injection of the crust. A continuous forearc ridge and a forearc basin lie concentrically between trench and magmatic arc. The slope from ridge to trench is the surface of the accretionary wedge, which is in front of the overriding plate; the basin is on the thin leading edge of the overriding plate. The arc expanded eastward from Java during Neogene time to form the eastern U-shaped Banda part of the system, the east end was inaugurated long after the west part, and the trench is above continental crust in the east, on the continental shelf of Australia and New Guinea. See Hamilton (1979, 1988) for tectonic synthesis. Area extends from 95°to 135° East, and from 0° to 15° South. Short-wavelength bathymetry is derived from gravity determined from satellite altimetry, long-wavelength bathymetry is from ship-sounding tracks, and land topography is from EROS Data Center (Earth Resources Observation and Science, U.S. Geological Survey). Map compiled and provided by David Sandwell.

Figure 5. Single-channel reflection profile, with great vertical exaggeration, across the Sumatra forearc and trench. Northeast (left) end of line is 50 km from the coast of south Sumatra at 5° South. Trench is 6 km deep and has very thin turbidites (layered) above oceanic pelagic sediments (transparent). Oceanic crust continues with gentle dip beneath the accretionary wedge but is not resolved on this image; compare with Figure 6. Outer rise is due to waveform depression of elastic crust by weight of accretionary wedge. Vertical exaggeration is 25 or 30 to 1, and actual slope of top of accretionary wedge is a few degrees. Profile was provided by Maurice Ewing, Lamont-Doherty Earth Observatory of Columbia University.

Figure 6. Depth-converted seismic-reflection and velocity profiles across Nankai Trench and toe of accretionary wedge, offshore Shikoku, Japan. Top of oceanic crust (at ~6.3 km depth on left, 5.8 km on right) dips gently beneath the wedge of sheared-off sediments that presses it down. Imbricated sheets of higher-velocity basal-wedge materials illustrate thrusting as wedge is thickened by plate drag but thinned by gravitational outflow. Profiles provided by Gregory F. Moore; processing and velocity mapping described by Costa Pisani et al. (2005).

Figure 7. Physiographic map of part of the Middle American trench. Subaerial digital topography and submarine sidescan sonar are shown in exaggerated shaded relief, illuminated from the north; actual slope of accretionary wedge is very gentle (cf. Fig. 6). The toe of the wedge is imbricated by trench-parallel thrust faults, and the subducting oceanic plate is broken by trench-parallel normal faults as it rolls through the gentle outer rise and into the trench. Area is 330 km wide. Discontinuous forearc basins underlie the continental shelf. Figure provided by César Ranero (cf. Ranero et al., 2003, their Fig. 1).

Figure 8. Physiographic map of southwest Japan. Discontinuous forearc basins are separated by ridges. Arrow shows direction of relative convergence, 44 mm/yr, of continental and oceanic plates and does not imply absolute motions. Slightly modified from Wells et al. (2003, their Fig. 2C); figure provided by Ray Wells.

Figure 9. Cross section of convergent margin across central Oregon. Fore-arc basin is filled by little-deformed Eocene through Quaternary strata. Dotted contours show P-wave velocities, in km/sec. After Wells et al. (2003, their Fig. 19B); figure provided by Ray Wells. No vertical exaggeration (VE).

Figure 10. Marked seismic-reflection west-east profile across the northern Peru Trench to a forearc basin on the leading edge of the overriding South American plate. Lines added on left show top of oceanic crust, which can be traced under the small accretionary wedge; an intracrustal reflector; and, at about 9 seconds on the left edge, probably the Mohorovičić discontinuity. Reprinted from Moberly et al. (1982, their Fig. 6), and reproduced by permission of Ralph Moberly and the Geological Society of London.

Figure 11. West-east reflection profile and stratigraphic analysis of the forearc ridge and basin of northernmost Chile. Reprinted from Moberly et al. (1982, their Fig. 9), who recognized that the landward migration of depocenters indicates progressive elevation of the leading edge of the overriding South American plate as accretionary-wedge material was stuffed beneath it, and yet that the thin leading edge itself is not crumpled. Reproduced by permission of Ralph Moberly and the Geological Society of London.

Figure 12. Global Positioning System (satellite geodesy) velocity field of Aegean and Turkish region

relative to internally-stable northwest Eurasia. Velocities in the overriding plate increase along curving trajectories toward a south-facing subduction system. The trench is not shown but trends near SW and SE corners of map area, is convex southward, and is ~250 km south of Crete, the long island at bottom center. The overriding plate is being extended toward the retreating hinge (not shortened and crumpled against a fixed hinge), the free edge, as it is extruded between the converging Arabian and European plates. High-strain zones of strike-slip and extension, not marked here, outline miniplates of lesser internal deformation (Nyst and Thatcher, 2004). Other unmarked arc features: forearc ridge (the crest of the active accretionary wedge) is ~100 km offshore from Peloponnisos (large peninsula of southern Greece, left center), 150 km south of Crete, and 100 km south of Turkish coast at far right; the magmatic arc is convex southward, and is 150 km north of Crete at closest. Slightly modified from figure provided by Wayne Thatcher; cf. Nyst and Thatcher (2004, their Fig. 2).

Figure 13. Map of global seismicity. Earthquakes, magnitude >5.1, were plotted from the database of Engdahl et al. (1998) by David Sandwell, who provided the figure.

Figure 14. WNW-ESE tomographic section across the subduction system of central Honshu, showing P-wave velocity anomalies of crust and upper mantle. Black bar along surface represents Honshu, and trench is just beyond right end of profile. White circles are earthquakes within 40 km of profile. The computer program solved independently for anomalies bounded by marked positions of the Mohorovičić discontinuity, a hypothetical mid-crustal discontinuity, and the top of the subducting slab. After Zhao (2004, his Fig. 21), who provided the figure.

Figure 15. Tomographic profile through northeast China and central Japan of P-wave velocity anomalies. Triangles at top mark intraplate Changbai volcano in China, and the magmatic arc of Japan. White circles are earthquakes recorded within 100 km of profile. 410 km and 660 km discontinuities are marked. After Zhao (2004, his Fig. 18), who provided the figure.

Figure 16. Global map of P-wave velocity variations at a depth of 550 km, in the mantle transition zone. Broad tracts of high velocities, marking oceanic lithosphere plated down on the 660 km discontinuity, apparently are delineated in East Asia, western Pacific, Australasia, and western North America. Triangles mark some hypothetical "hotspots." Figure provided by Dapeng Zhao; this model is slightly different than that published by Zhao (2004, his Fig. 5).

Figure 17. Subduction drive of plate tectonics. A subducting slab, sinking broadside as its upper hinge rolls back, pushes all sub-lithosphere upper mantle back under incoming plate and forces rapid seafloor spreading. The sunken slab is plated down, behind an advancing lower hinge, on the 660 km discontinuity, and is overpassed as the overriding plate is sucked forward by the retreating slab. The sunken slab is thus transferred to a slow-spreading ocean behind the continent. Circulation is confined to the upper mantle. After Hamilton (2003).

Figure 18. Plate motions relative to a fixed Antarctic plate. Motions of plates and their boundaries in this framework generally accord with subduction, enabled by cooling from the top of oceanic asthenosphere, as the primary drive of plate motions. All ridges migrate to tap fresh asthenosphere. Neither internal deformation of plates nor backarc spreading is incorporated in these vectors. Illustration provided by L.H. Estey via http://jules.unavco.org/VoyagerJr/Earth.

Figure 1

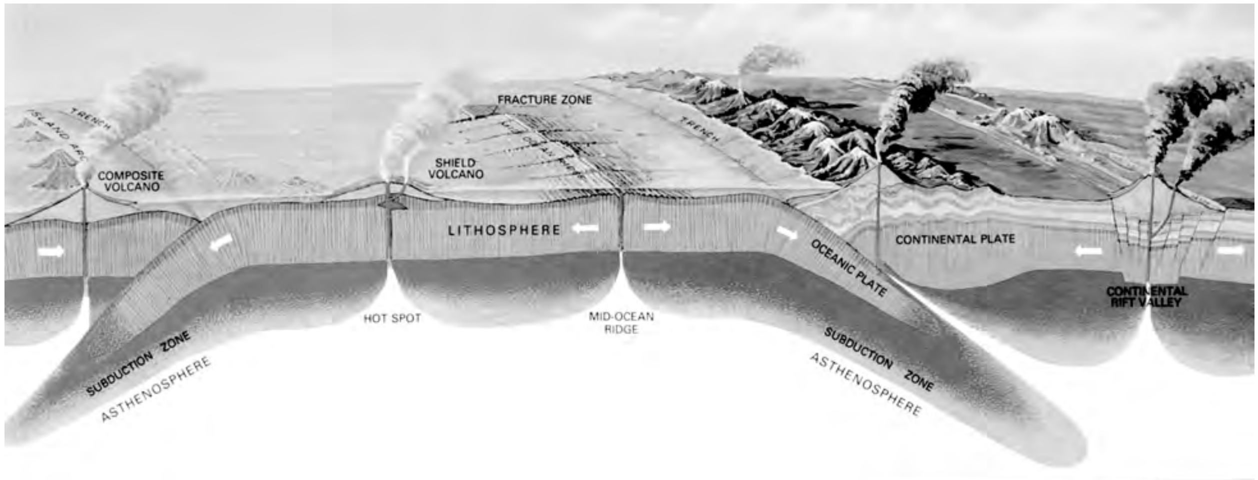


Figure 2

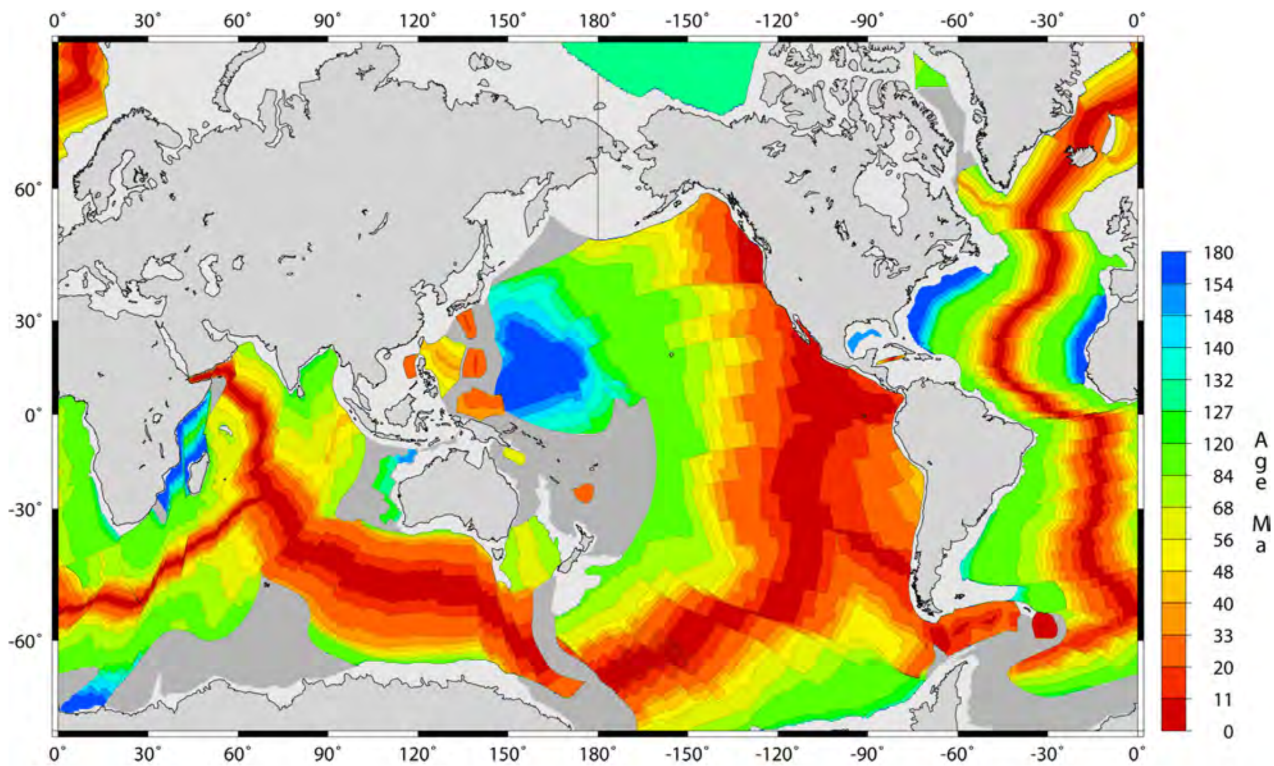
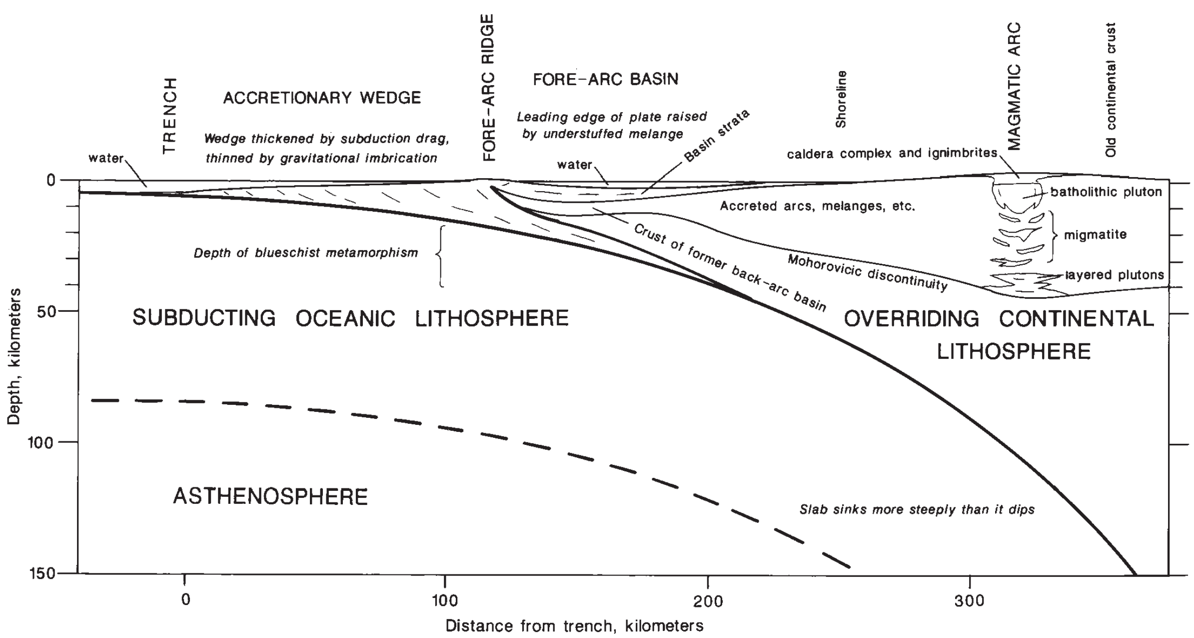


Figure 3



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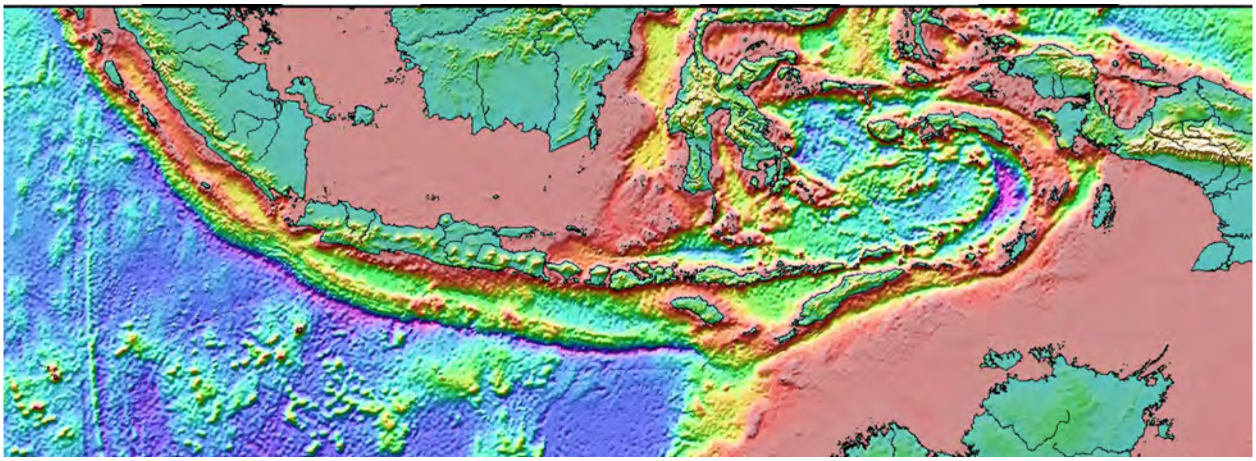


Figure 5

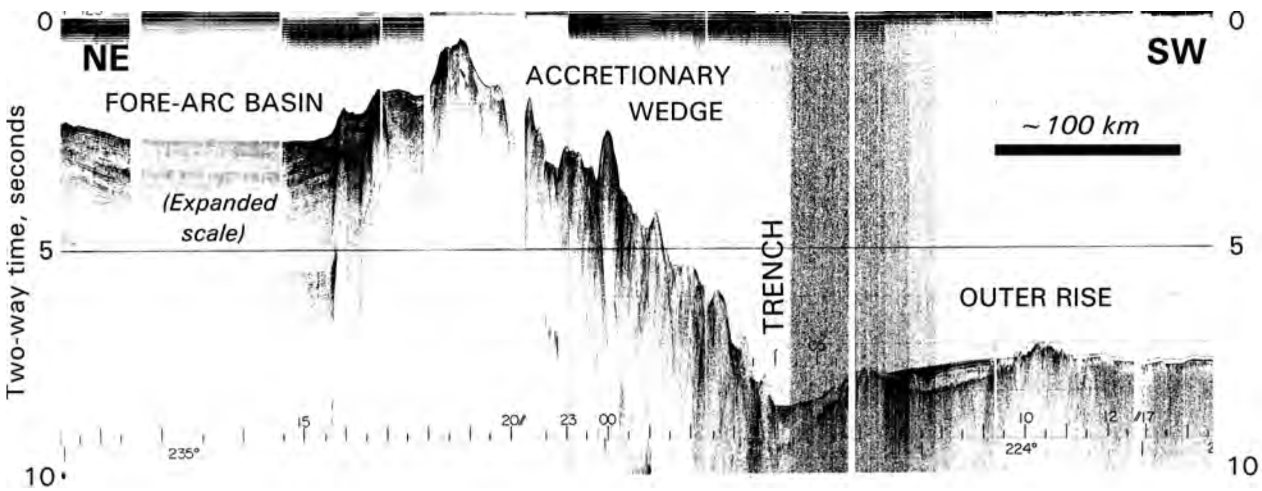


Figure 6

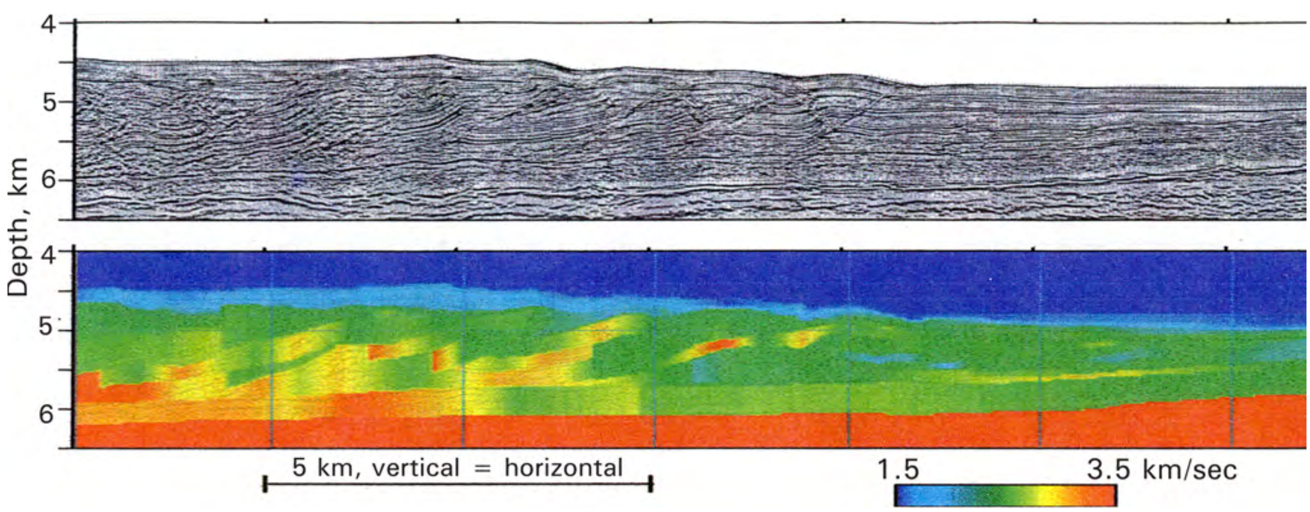


Figure 7

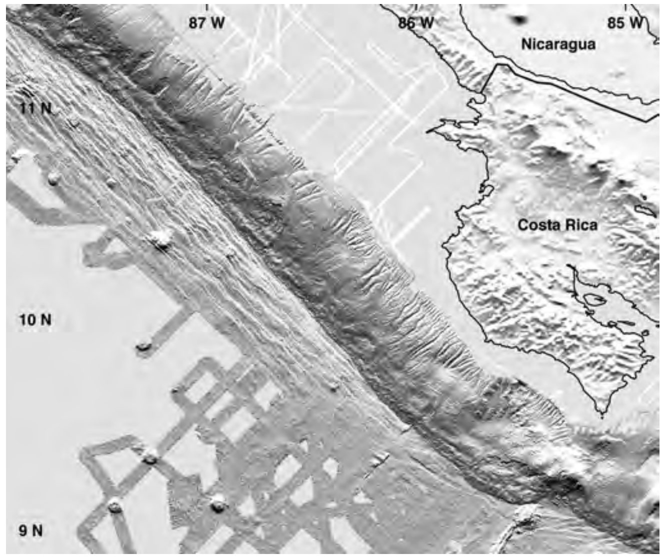


Figure 8

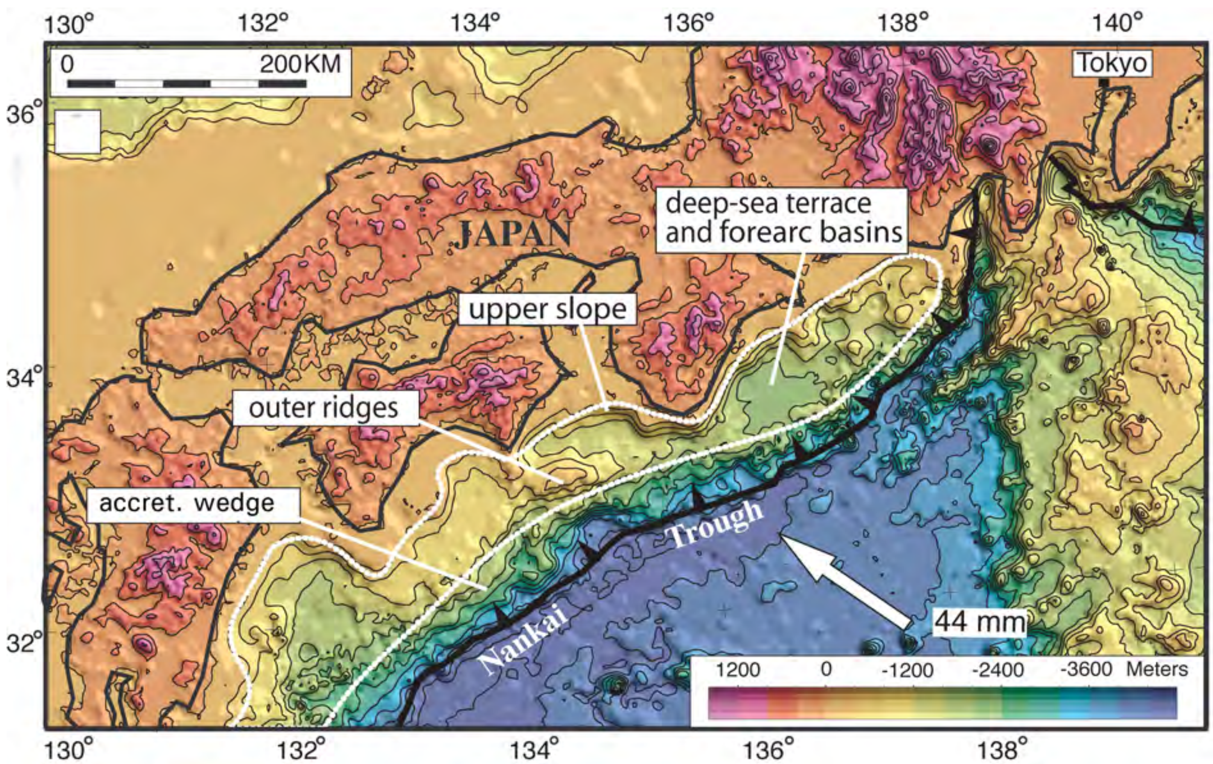


Figure 9

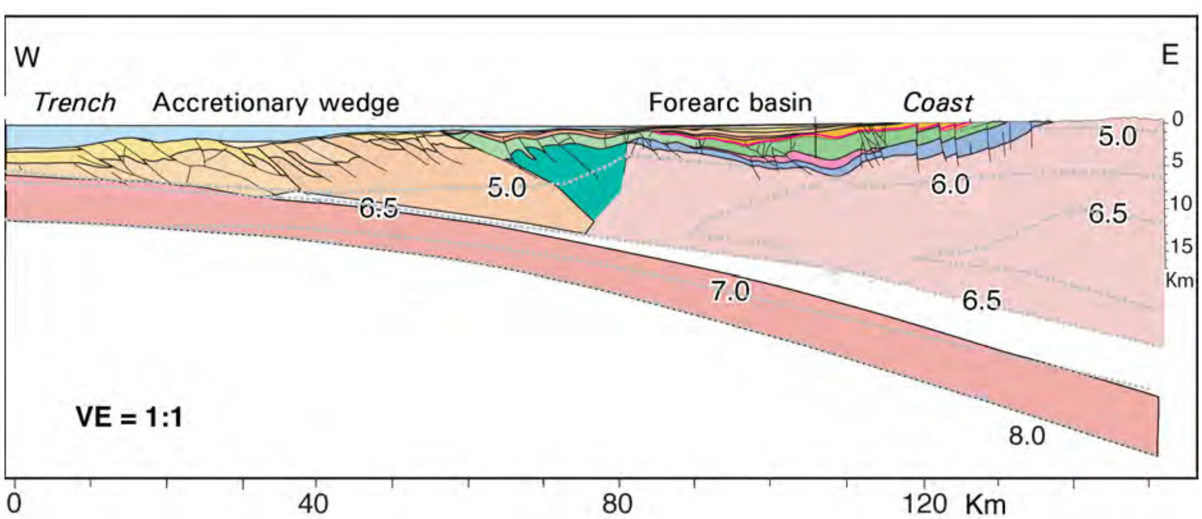


Figure 10

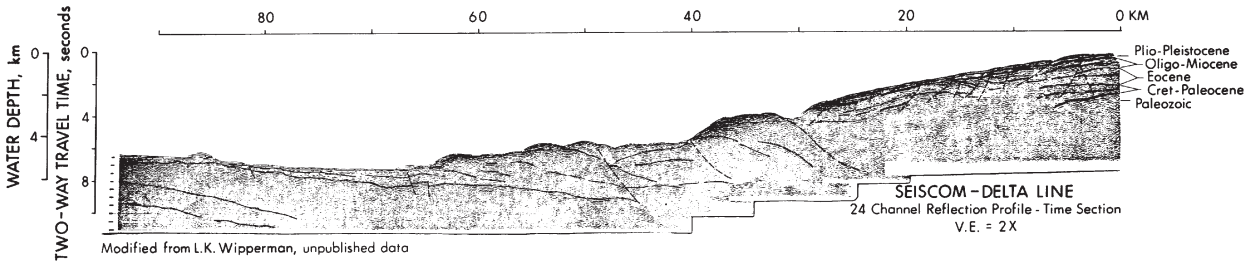


Figure 11

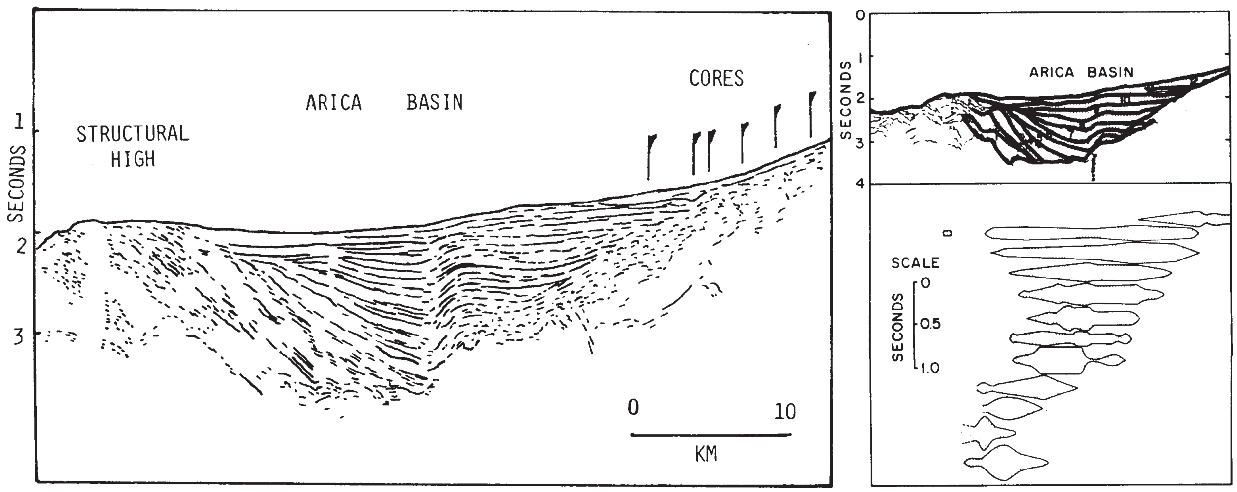


Figure 12

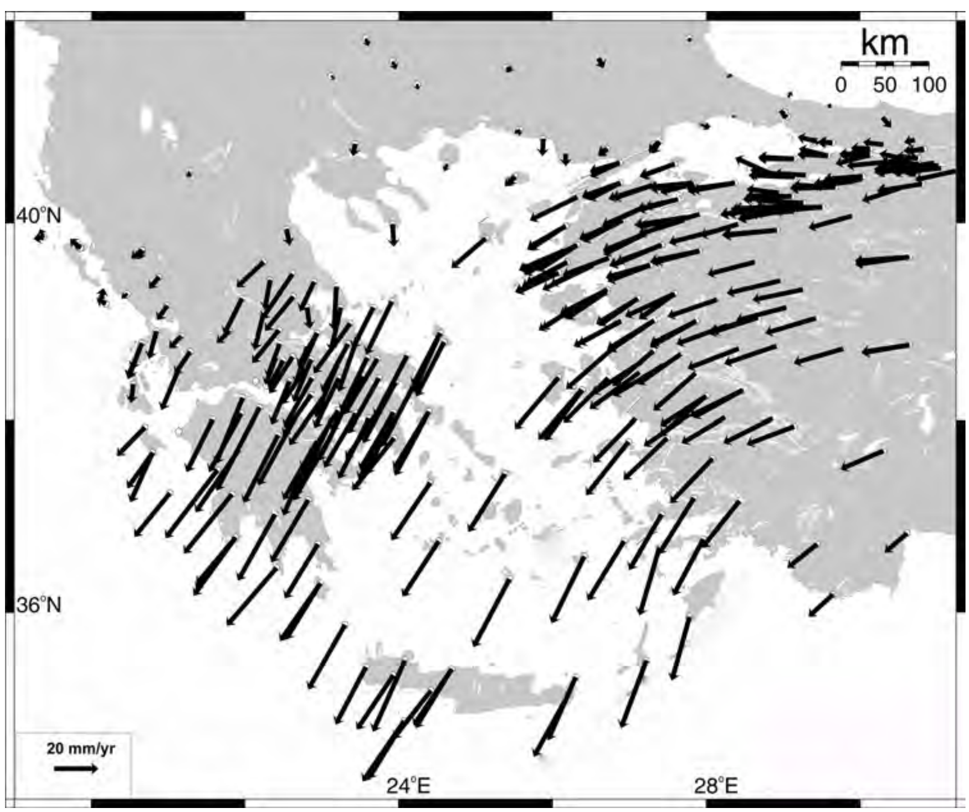
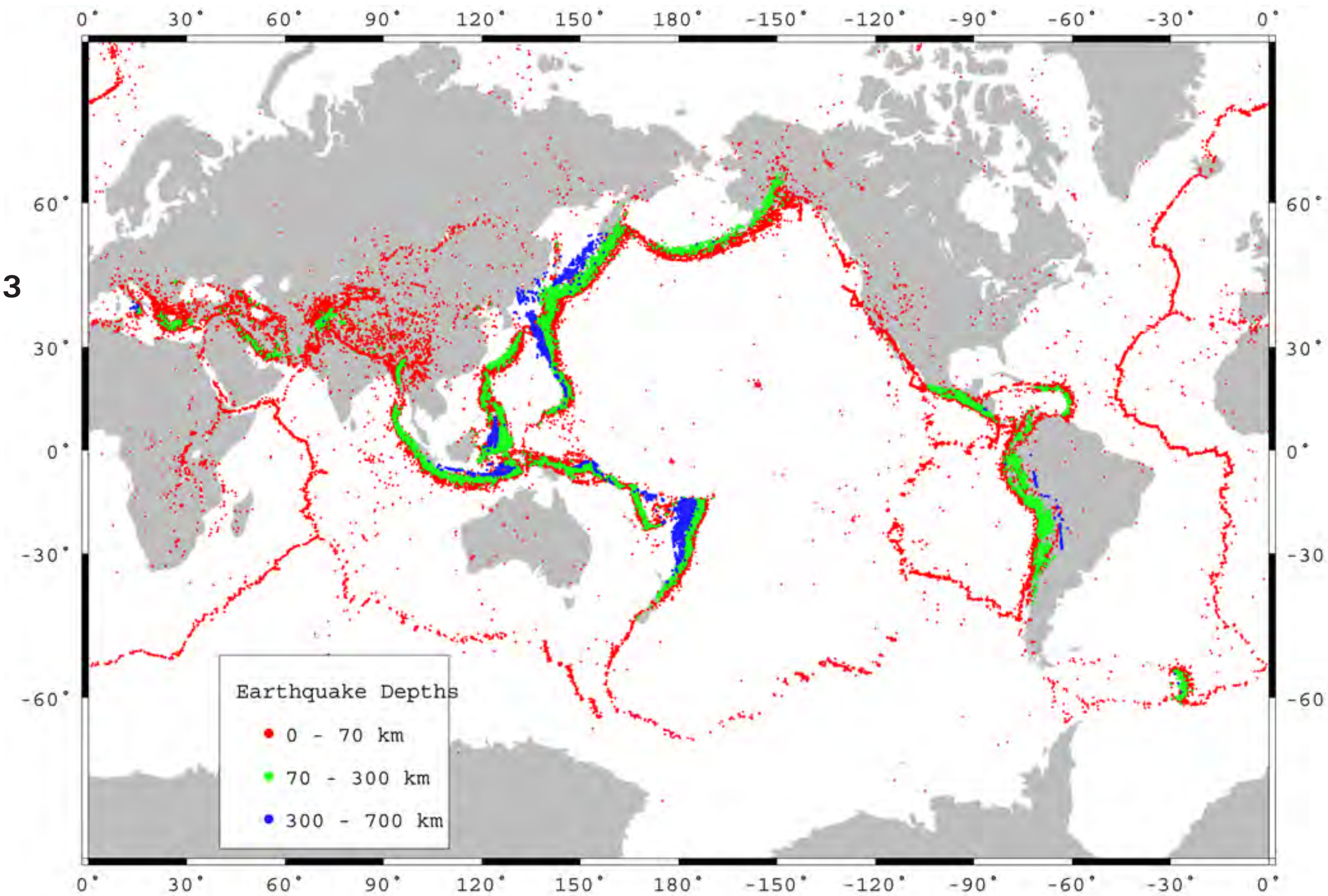


Figure 13



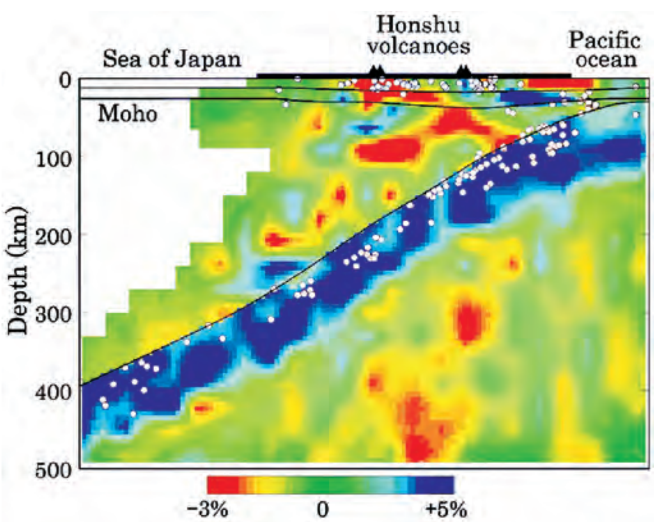


Figure 14

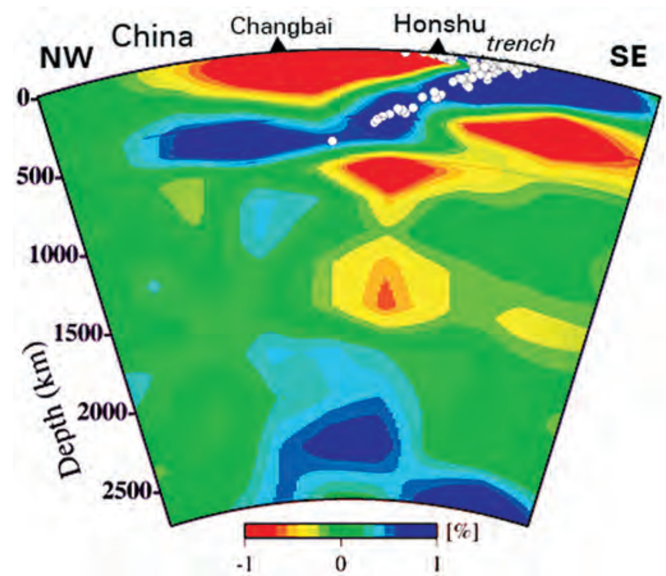


Figure 15

Figure 16

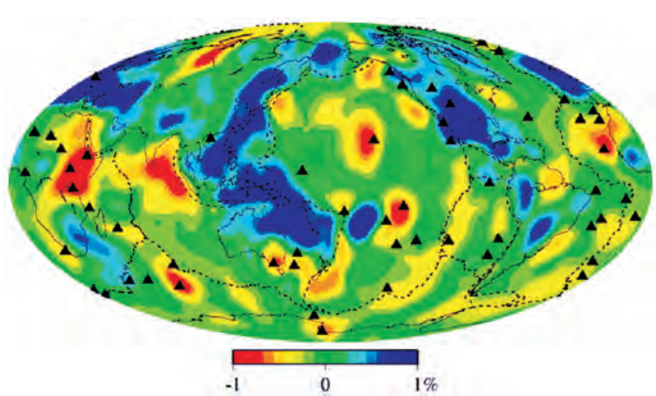


Figure 17

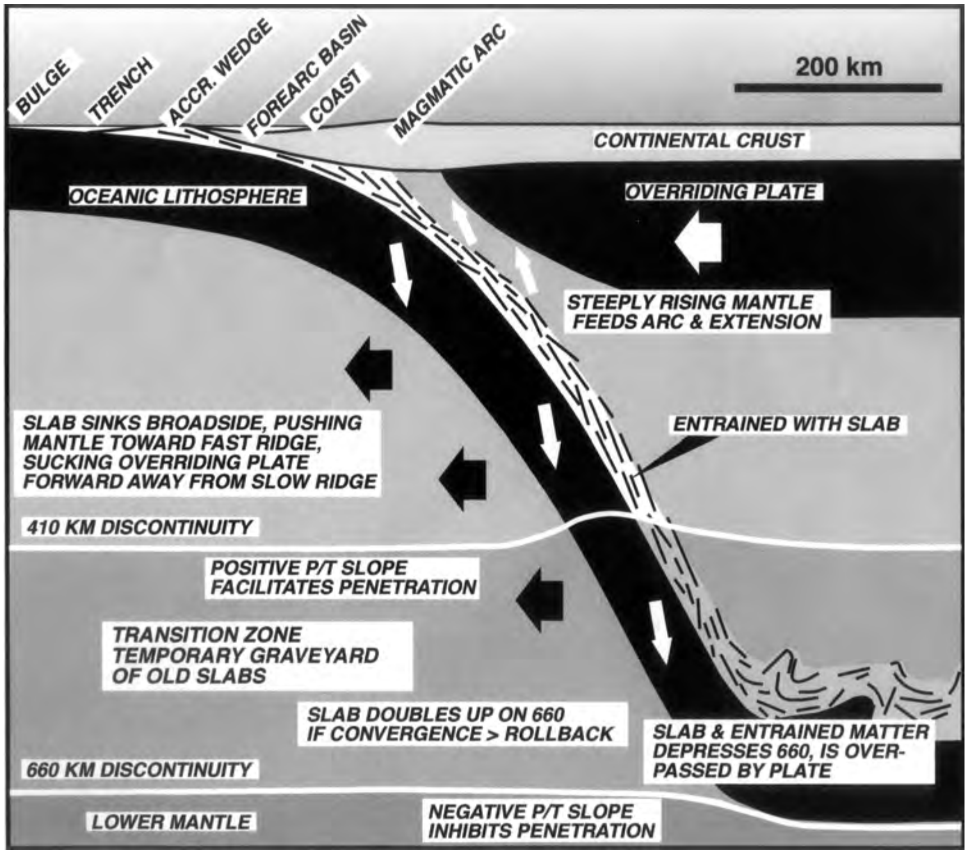


Figure 18