Tectonic Setting of Aleutian Volcanism

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The tectonic setting of the Aleutian volcanic arc is relatively straightforward in the context of global plate tectonics theory and, because subaerial exposures are limited to small islands along the central and western parts of the arc, local complexities can be difficult to ferret out. Recently, however, considerable progress has been made through modern geophysical and geological investigations of the arc at all scales. These studies provide a detailed view of the lithosphere's responses to subduction at varying rates and convergence angles along the arc—responses that include variable plate coupling, differences in dip of the subducting slab, block tectonics, and widely differing styles and rates of volcanism.

This chapter first addresses the tectonic setting of Aleutian volcanism with very broad strokes, starting with a brief history of the development of plate tectonics concepts that are essential to the story. Next we describe Aleutian tectonics at plate scale, including along-arc variations in the nature of the overriding North American plate, convergence rate, and convergence angle. Finally, we discuss the arc's recent history of major earthquakes, segmentation, and block tectonics as those issues pertain to the settings of individual Aleutian volcanoes, which are the book's primary focus.

4.1 Subduction Tectonics: Recycling Earth's Surface

So you think *you* have a space problem? Consider this: Earth's surface area, including both land and water, is about 5.1×10^8 km^2 (Weast 1981, p. F-202). Girdling the planet is a 50,000 km-long system of mid-ocean ridges (Fig. 4.1), where new oceanic crust forms more-or-less continuously at an average linear rate of about 100 mm/year (100 km/million years.).[1] Do the math and you realize that about 5 km^2 of new oceanic crust forms each year, which is equivalent to 5 million km^2 of new crust per million years. Potentially, that is a 1 % increase in planetary surface area every million years. Given that plate tectonics began on Earth about 3000 million years ago (Van Kranendonk 2011), you can appreciate the magnitude of the planetary space problem.[2] Most geologists believe that Earth has changed little, if at all, in size since its formation about 4.54 ± 0.05 billion years ago,[3] having maintained a relatively svelte girth of 40,075 km throughout that time.[4] How can new crust be forming at an average rate of 500 ha per year without the planet getting any bigger?

The solution, which only a century ago posed a real conundrum for geologists, is now common knowledge, i.e., a grand recycling scheme called plate tectonics in which

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[1] Average full spreading rates at mid-ocean ridges vary from 2–4 cm/year along slow-spreading segments of the Mid-Atlantic Ridge to ~15 cm/year along parts of the East Pacific Rise. Full spreading rate includes motion of both plates away from the ridge.

(Footnote 1 continued)
Formation of oceanic crust by eruptions of basalt along mid-ocean ridges is episodic over human timescales, but essentially continuous and steady when averaged over periods of several million years.

[2] Radiometric age dating constrains the age of Earth to 4.54 Ga ± ~1 %, i.e., 4540 ± ~50 million years. There is considerably more uncertainty in the date when plate tectonics began, but most experts in the field place it between 2.5 and 4 Ga (Condie and Pease 2008). So, at the present rate of crustal spreading (~5 km^2/year), 12.5–20× 10^9 km^2 of new oceanic crust would have formed since the initiation of plate tectonics. That is 25–40 times Earth's surface area including oceans! On a geologic time scale, subduction tectonics is a remarkably efficient resurfacing agent.

[3] In 1958, Australian geologist S. Warren Carey hypothesized that the breakup of protocontinent Pangaea and subsequent continental drift, as envisioned by Alfred Wegener nearly half a century earlier, was caused by planetary expansion. Carey's expanding Earth hypothesis was rejected in favor of the plate expansion and subduction paradigm of plate tectonics, but his contributions were influential in the debate that shaped modern concepts of global tectonics.

[4] Earth's circumference is 40,075.16 km at the equator and 40,008.00 km at the poles. The difference is a consequence of planetary rotation: Earth's spin causes it to bulge a bit at the equator and flatten at the poles. Points on the equator make the circuit, on average, every 23.9344697 h (the length of a sidereal day), at an average rate of 1674.37 km/h or 465 m/s. Such are the vital signs of a middle-aged planet.

Z. Lu and D. Dzurisin, *InSAR Imaging of Aleutian Volcanoes*,
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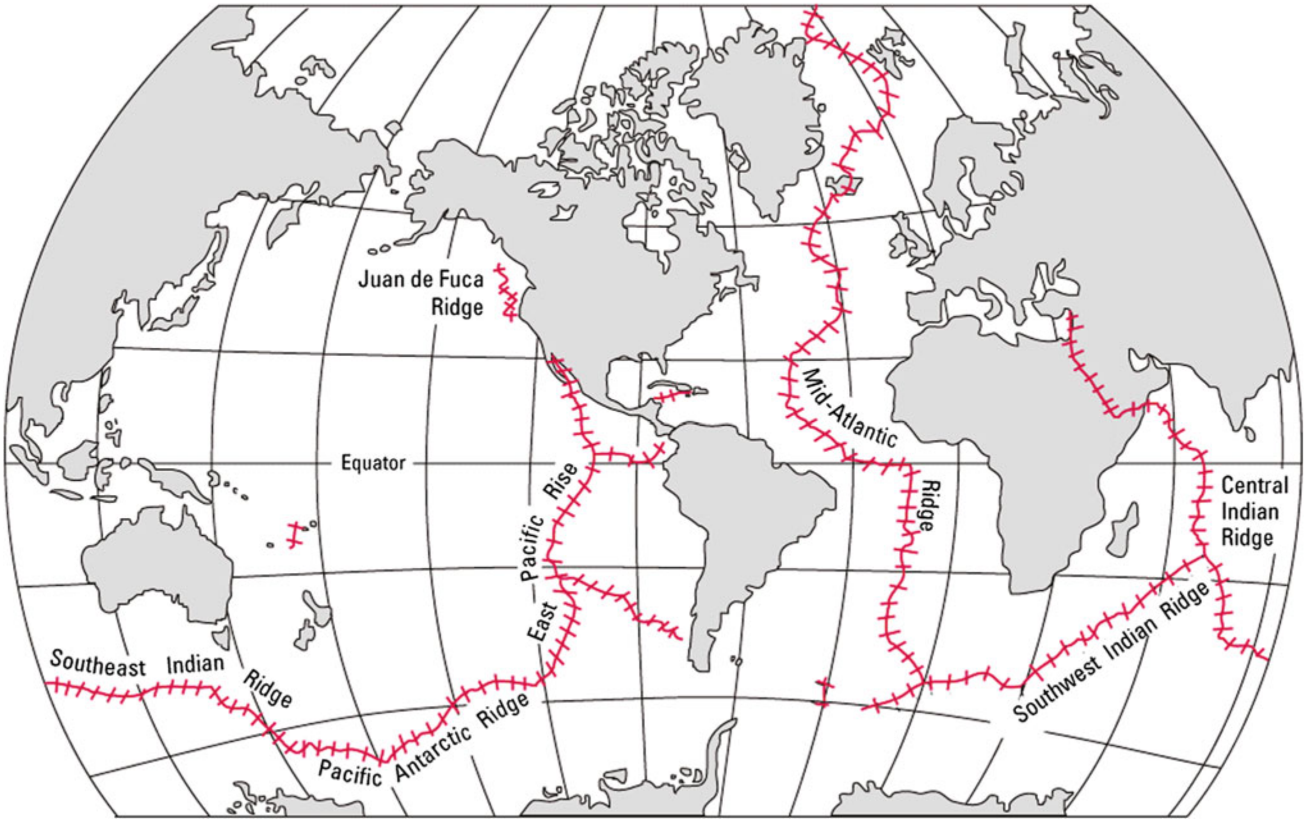

Fig. 4.1 Earth's mid-ocean ridge system, shown in *red*, where oceanic crust forms at an average full spreading rate of about 10 cm/year. Reproduced from Kious and Tilling (1996)

crust is produced at mid-ocean ridges and continental rift zones, and consumed at convergent plate margins. It is a mid-twentieth century idea that has stood the test of time, supported by a vast store of evidence that spans many scientific disciplines. The Aleutian volcanic arc and its associated subduction zone, as we shall see, are textbook examples of a convergent plate margin at which old, cold oceanic crust dives into the mantle to make room for young, hot crust produced at a mid-ocean ridge. First, though, let us review a remarkable period in the history of Earth science that revolutionized thought about our restless planet.

4.1.1 Continental Drift: The Far-Fetched Idea that Sparked an Earth Science Revolution

Arguably the greatest advance in Earth science since publication in 1543 of Nicolaus Copernicus' treatise *On the Motion of the Celestial Spheres* began unobtrusively in a university library some 369 years later. In 1912 at the University of Marburg, Germany, Alfred Wegener came across a scientific paper that listed fossils of identical plants and animals found on opposite sides of the Atlantic Ocean. Orthodox science at the time held that such observations were evidence for ancient land bridges, long since sunken, that once connected far-flung continents. Wegener had a different idea and, in hindsight, a better one. Noting the jigsaw-puzzle pattern of continents separated by vast ocean basins, he proposed that the major land masses once comprised a single protocontinent which he called Pangaea (meaning "all lands") (Fig. 4.2).[5] Over time, he reasoned, Pangaea fragmented and the resulting land masses drifted apart, plowing through the ocean basins or sliding across them and dispersing fossils of plants and animals across the globe. Rather than spanning the gaps between stationary continents with enormous land bridges that vanished into the ocean depths, Wegener put the continents in motion to produce the modern world from a single land mass that he conjured up from the distant past. Which idea seems more

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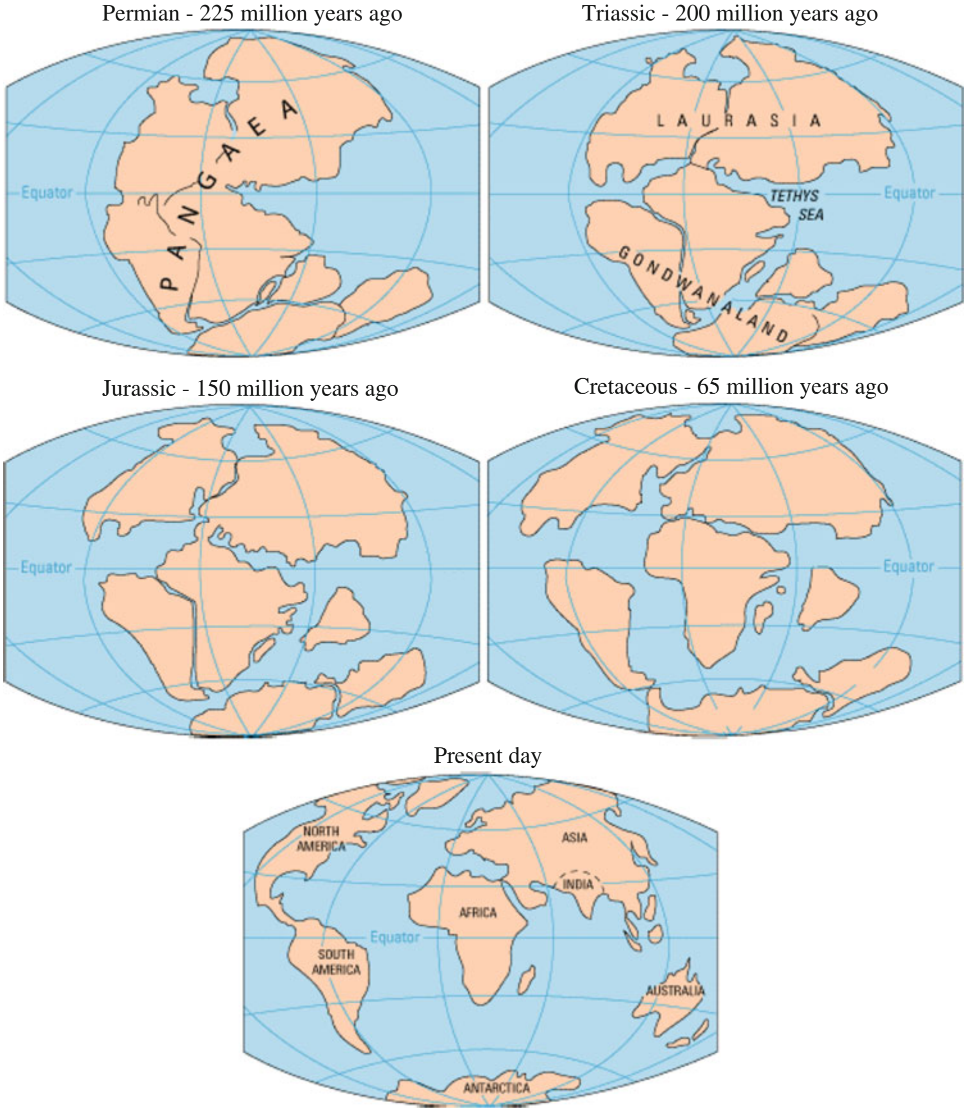
[5] Wegener was not first to notice the puzzle-like pattern of the continents. As early as 1596, Dutch map maker Abraham Ortelius in his work *Thesaurus Geographicus* suggested that the Americas were "torn away from Europe and Africa… by earthquakes and floods" and went on to say: "The vestiges of the rupture reveal themselves, if someone brings forward a map of the world and considers carefully the coasts of the three [continents]" (reproduced from Kious and Tilling 1996). However, it was not until Wegener's work starting in 1912 that the idea received serious scientific attention.


Permian - 225 million years ago

Triassic - 200 million years ago

Jurassic - 150 million years ago

Cretaceous - 65 million years ago

Present day

Fig. 4.2 Snapshots in time illustrating the breakup of protocontinent Pangaea starting 225–200 million years ago and subsequent positions of continental land masses. The jigsaw-puzzle pattern of continents was recognized as early as 1596 by Dutch map maker Abraham Ortelius. Alfred Wegener, in his 1915 treatise *The Origin of Continents and Oceans* (*Die Entstehung der Kontinente und Ozeane*), proposed the theory of continental drift to explain the pattern. Modern plate tectonics theory emerged five decades later with the discovery of lithospheric plates, mid-ocean ridges, and the zebra pattern of magnetic stripes on the ocean floor. Reproduced from Kious and Tilling (1996)

fantastic is debatable even today. Honestly, which side of the debate would *you* have taken as a bright-eyed geology student in the early twentieth century—disappearing transoceanic land bridges or drifting continents? The far-fetched nature of Wegener's hypothesis notwithstanding, it turned out to be partly right. Earth's land masses *have* been moving apart for the past 200–225 million years, taking with them Wegener's matching fossils and many other clues to the history of our dynamic planet (Kious and Tilling 1996).[6]

Human nature being what it is, geologists soon lined up in two camps—one supporting Wegener's hypothesis and

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[6] Modern-day spreading rates vary from less than 20 mm/year at so-called "ultraslow" mid-ocean ridges (e.g., the Gakkel Ridge in the Arctic Ocean between Greenland and Siberia, and the Southwest Indian Ridge between Antarctica and southeast Africa) to more than 150 mm/year across "fast" ridges like the East Pacific Rise near Easter Island in the South Pacific Ocean. The spreading rate across the "slow" Mid-Atlantic Ridge is about 25 mm/year, which equates to 25 km per million years.

the other opposing it. The "mobilists," as they were called, pointed to field evidence in the Alps and elsewhere suggesting that great land masses do, in fact, move. Anti-mobilists ("fixists") parried the contention by arguing that neither Wegener nor anyone else had yet proposed a plausible mechanism for continental drift. Wegener himself proposed that centrifugal force moved the heavy continents toward the equator as the Earth spun. He thought that inertia from centrifugal movement combined with tidal drag could account for continental drift. Some of his detractors had what they thought was a more plausible explanation for the jigsaw pattern of the continents, i.e., they moved apart as Earth expanded during planetary heating cycles. Both ideas seem far-fetched in hindsight, and neither gained widespread acceptance. At the time of Wegener's death in 1930, his ideas continued to generate interest in Japan and throughout the Southern Hemisphere, but in Europe and the United States opposition remained strong—a scientific impasse that persisted for another three decades.

4.1.2 Plate Tectonics and the Decade that Changed Earth Science Forever

While Wegener's continental drift hypothesis languished, more and more evidence emerged to indicate that the continents had indeed been rearranged over geologic time. For example, paleoclimate studies showed that large, geographically dispersed areas were once covered by glaciers, which could not have existed in their present-day locations. Paleomagnetic studies seemed to indicate that Earth's magnetic north pole had wandered all over the globe. If, as theory suggested, the position of the pole was nearly fixed except during magnetic polarity reversals, some of the rocks that record paleo-pole positions were far from their initial locations. There was ample evidence that the polarity of Earth's magnetic field had reversed many times in the past.[7] It also was known that magnetic minerals such as magnetite, which are fairly common in basaltic lava that forms oceanic crust, align with Earth's magnetic field when they cool through the Curie temperature.[8] As the evidence for mobile continents mounted, the search for a driving mechanism intensified.

The next major clues emerged from the wake of World War II when, in the early 1960s, a worldwide network of seismometers installed to monitor nuclear weapons testing led to a remarkable discovery. Many of Earth's volcanoes, earthquakes, and other active geologic features lined up along belts that girdled the planet and defined the edges of great tectonic plates (Dietz 1961; Hess 1962; Wilson 1965; Le Pichon 1968; Morgan 1968) (Figs. 4.3 and 4.4). At about the same time, the U.S. Naval Oceanographic Office published a report summarizing what was known about a curious pattern of magnetic stripes that emerged from marine geophysical surveys starting in the 1950s (Fig. 4.5). Working independently, Vine and Mathews (1963) and Morley and Larochelle (1964; see also Morley 1986) proposed that the magnetic striping was produced by repeated reversals of Earth's magnetic field, which were recorded in the magnetic fabric of oceanic basalts. They envisioned the volcanic rocks of the seafloor as a giant tape recorder, locking in field reversals that occurred, on average, a few times every million years. If their hypothesis was correct, the zebra-stripe pattern on the seafloor should match the timing of magnetic field reversals. Confirmation required an accurate history of reversals, which was lacking at the time.

Enter Allan Cox, Brent Dalrymple, and Richard Doell, who used the potassium-argon radiometric dating technique[9] to reconstruct the history of magnetic reversals for the past several million years (Cox et al. 1963, 1964, 1967).

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[7] During a magnetic reversal, the North pole is transformed into a South pole and the South pole becomes a North pole. The physics of the process is not fully understood, but a computer model developed by Glatzmaier and Roberts (1995) reproduces key elements of Earth's magnetic field, including spontaneous reversals. The model simulates convection and magnetic field generation in a fluid outer core surrounding a solid inner core, using realistic values for the core's dimensions, rotation rate, heat flow, and material properties. Earth's magnetic field has undergone numerous reversals that are recorded in magnetic patterns found in volcanic rocks, especially those recovered from the ocean floors. In the last 10 million years, there have been, on average, 4 or 5 reversals per million years. Over longer time periods, the rate is highly variable—from no reversals in tens of millions of years to more than one reversal in 50,000 years. The last reversal occurred approximately 780,000 years ago (Brunhes–Matuyama Reversal). The symmetric pattern of magnetic stripes emanating from mid-ocean ridges (i.e., ridge-parallel bands of seafloor containing magnetic minerals that record alternating North pole directions) was a critical piece of evidence in the development of plate tectonics.

(Footnote 7 continued)

[8] As a ferromagnetic material such as magnetite cools below the Curie temperature, the magnetic moments within magnetic domains align with Earth's magnetic field, thus recording the polarity of the field. Above the Curie temperature, thermal fluctuations prevent this alignment.

[9] Developed in the 1950s, the potassium-argon dating technique makes use of the fact that certain elements, including potassium, contain unstable parent radioactive isotopes that decay at a steady rate over geologic time to produce daughter isotopes. The rate of decay is expressed in terms of an element's half-life, the time it takes for half of the radioactive isotope of the element to decay. The decay of the radioactive potassium isotope (potassium-40) yields a stable daughter isotope (argon-40), which does not decay further. The age of a rock can be determined by measuring the total amount of potassium in the rock, the amount of the remaining radioactive potassium-40 that has not decayed, and the amount of argon-40. Potassium is found in common rock-forming minerals, and because the potassium-40 isotope has a half-life of 1,310 million years, it can be used to date rocks millions to billions of years old (Kious and Tilling 1996).

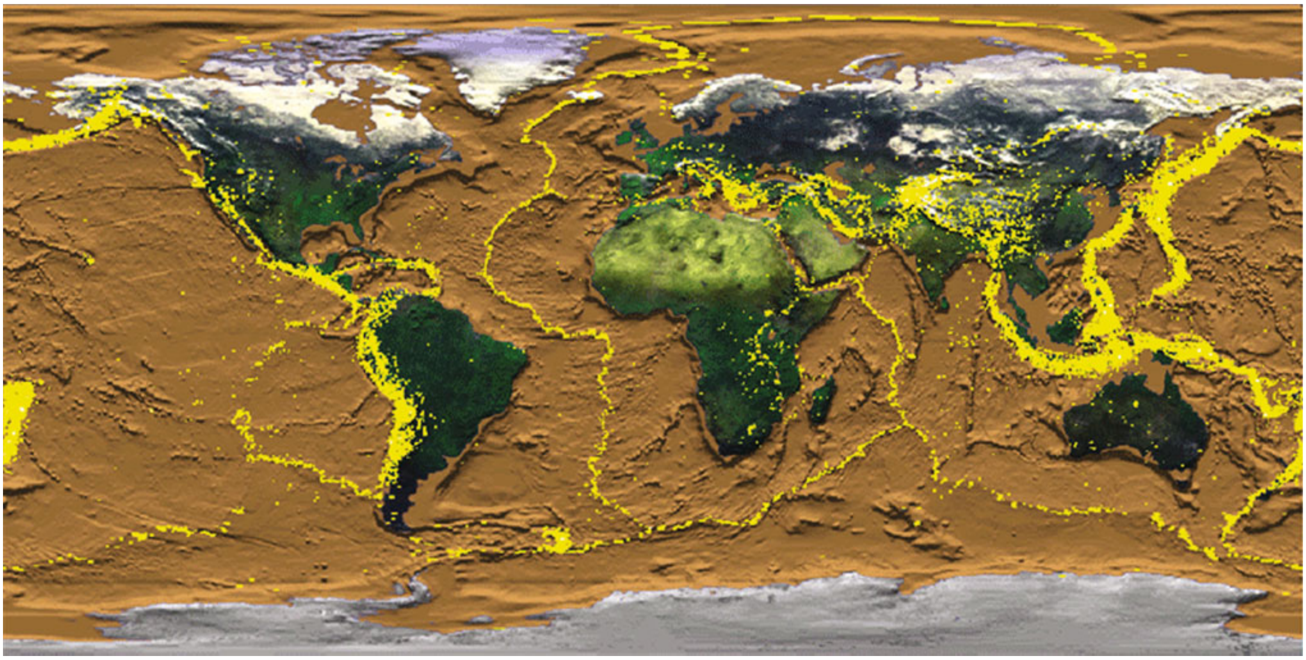

Fig. 4.3 Cumulative global earthquake occurrences (*yellow dots*) from 1960 through 1995, with earthquake magnitude greater than 4.2. Delineation of Earth's lithospheric plates by seismicity was a key piece of evidence in the development of plate tectonics theory during the 1960s. Image produced by NASA/Goddard Space Flight Center, Scientific Visualization Studio

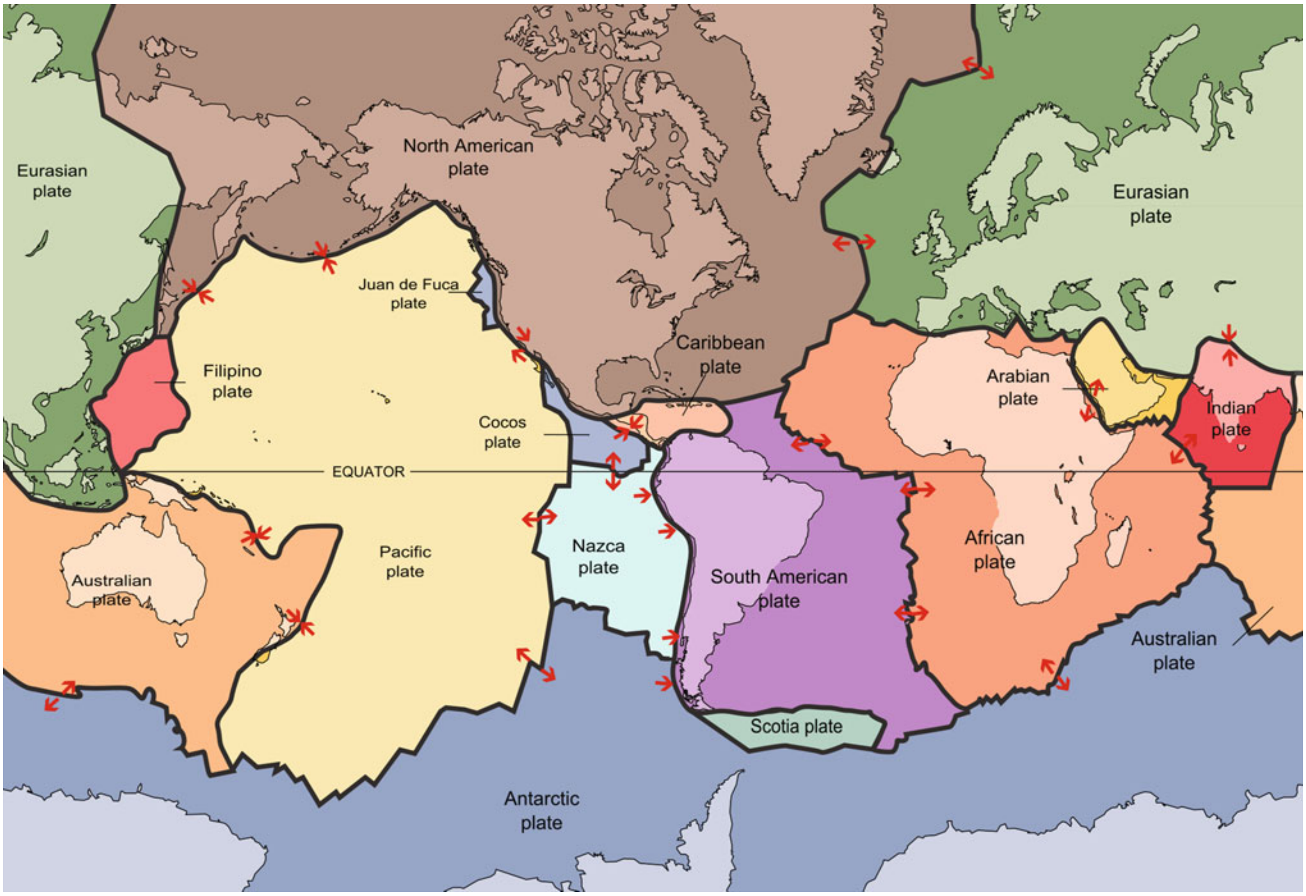

Fig. 4.4 Earth's major lithospheric plates, reproduced from Wikimedia Commons (http://commons.wikimedia.org/wiki/File:Tectonic_plates.png), based on Kious and Tilling (1996). The Aleutian volcanic arc is associated with the collisional boundary between the Pacific plate and the North American plate, where old, cold oceanic lithosphere of the Pacific plate is subducting beneath younger oceanic and continental lithosphere of the North American plate

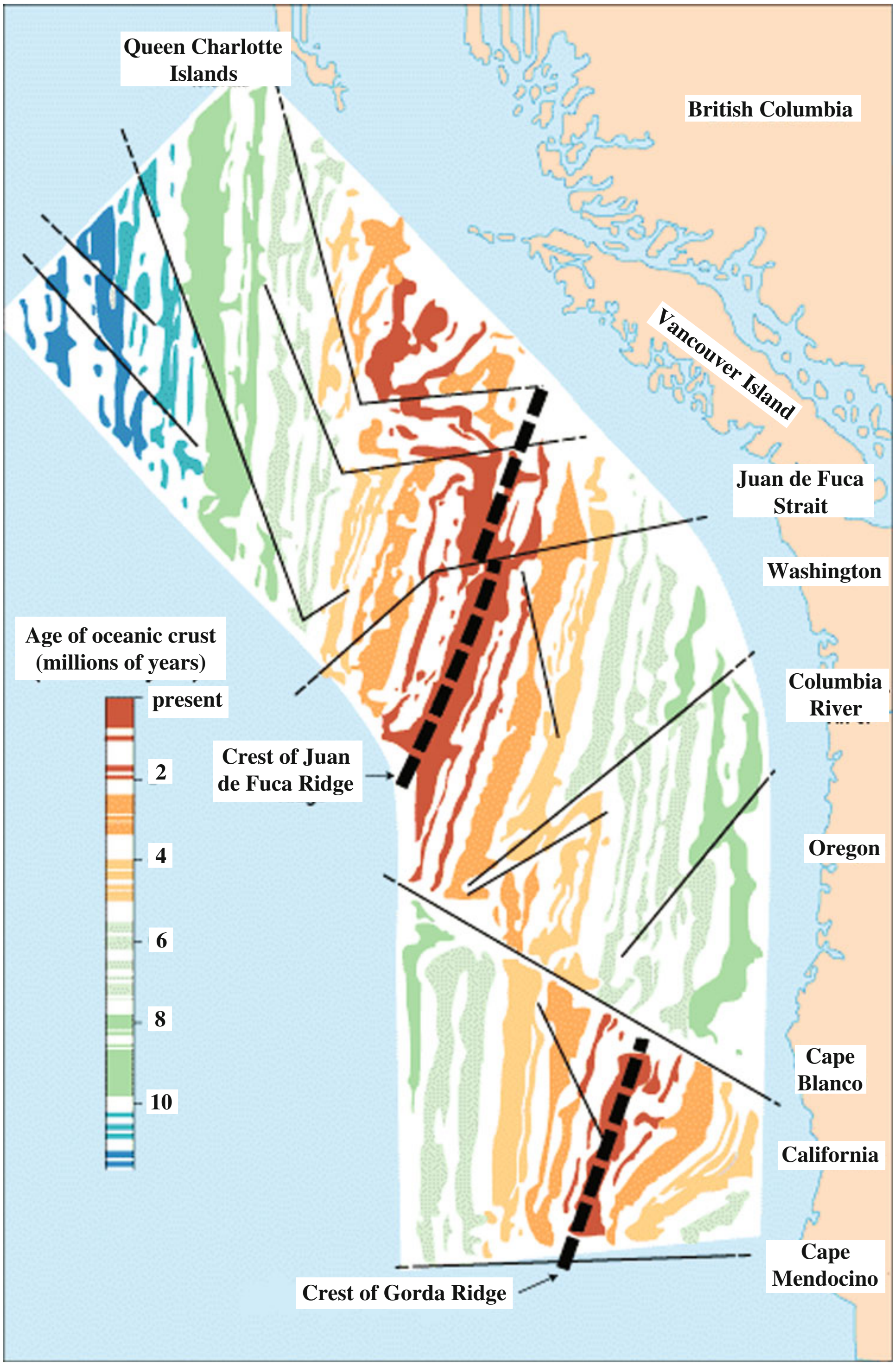

Fig. 4.5 Magnetic striping pattern of seafloor offshore U.S. Pacific Northwest. *Thin black lines* represent transform faults that offset striping and ridge crests. *Sidebar* shows age of oceanic crust in millions of years, which increases with distance from the Juan de Fuca and Gorda ridges. Scale is approximate. Reproduced from Kious and Tilling (1996)

By dating continental volcanic rocks from around the world and measuring the rocks' magnetic orientations, they were able to assign accurate ages to Earth's recent magnetic reversals. Correspondence between the timing of reversals and the pattern of magnetic stripes on the seafloor was unmistakable. The width of a particular stripe indicated how much time had elapsed between successive magnetic reversals while that part of the seafloor was forming, and the alternating pattern of stripes reflected successive polarity flips (Fig. 4.5). Another major piece of the puzzle fell into place in 1968 when, during historic Leg 3 of the Deep Sea Drilling Project, research vessel *Glomar Challenger* drilled 17 holes at 10 different sites along the Mid-Atlantic Ridge between South America and Africa. Dating of the drill core sediments established that they (and underlying oceanic crust) were youngest close to the ridge and progressively older toward both continental margins. Eventually, the correlation between magnetic reversals and magnetic stripes was extended to nearly the entire ocean floor, parts of which are as old as 180 million years.

An astonishing conclusion became inescapable—new oceanic crust was emerging as basaltic lava at mid-ocean ridges and moving laterally away at rates of a few centimeters per year (i.e., tens of kilometers per million years). As the lava cooled, magnetic minerals such as magnetite, which are common in basalt lava, recorded the polarity of Earth's magnetic field. Over time, lava with that distinctive signature was rafted away from the ridge, forming a magnetic "stripe" parallel to the ridge. The process continued for, on average, a few hundred thousand years until the next magnetic reversal, at which time the next stripe, of opposite polarity, began forming. Over a hundred million years or so, the seafloor acquired a magnetic zebra pattern that held the real key to Wegener's puzzle. The continents were not drifting apart by plowing through or sliding across passive ocean basins. Rather, the basins were an integral part of the process, constantly expanding to make room for new oceanic crust.

Imagine the buzz that must have pulsed through the normally staid geological community during the late 1950s and early 1960s, while the plate tectonics revolution was in full swing. One prominent contributor described it this way:

> The critical dividing point in time was the meeting of the American Geophysical Union in the spring of 1967. After the meeting, the idea of plate tectonics began to catch on almost everywhere and with everyone. Those of us working in the field at that time experienced euphoria. Excitement was in the wind. It seemed that every encounter with another scientist resulted in a breathless outpouring of news of the latest developments. We sensed that, through our collective efforts, we were making a major advance in human understanding of the earth, and many of us experienced the thrill of understanding what no one else had ever understood previously. It was a delightful time when important advances in knowledge could be made with very modest effort and the crudest of analyses. We were elated by our accomplishments, but we were also humbled by the awareness that what we had accomplished was partly a consequence of the accident of fate that had put us at the right place at the right time. Nevertheless, the late sixties were a time of excitement and revelation and enthusiasm and unanimity of direction in earth science.
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> Jack E. Oliver, National Academy of Sciences member, speaking at Nobel Conference XXIV at Gustavus Adolphus College, Minneapolis, Minnesota, in October 1988 (Oliver 1990, pp. 3–4).

You can sense the giddiness in Oliver's recollection of the late 1960s even two decades later. At the same conference, Don L. Anderson, another National Academy of Sciences member, delivered his entire address as a poem entitled *From Crust to Core: From Then to Now*. It began (Anderson 1990, p. 112):

> In the beginning
>   Before Geology
>   Prior to geography
>   There was magma oceanography.

He covered the entire topic in 234 lines!

For the first time in human history, scientists in the late 1960s had a unifying theory that not only could put Pangaea back together again, but also explained present-day global patterns of earthquakes and volcanism. Mainly over the course of a single decade (earlier contributions by visionaries including Wegener are duly noted), understanding of our dynamic Earth took a quantum leap forward. But how to make room for vast amounts of oceanic crust known to be emerging inexorably at mid-ocean ridges? Before tackling that conundrum, a brief digression.

The progression from Wegener's continental drift hypothesis to modern plate tectonics concepts is a good example of how science works methodically to arrive at the truth, no matter how remote it might be from popular opinion or perception. Entire continents afloat like driftwood on a churning sea? Ridiculous! Science has a means to deal with such outlandish proposals. To separate one true idea from a multitude of alternate hypotheses, the scientific method requires that all contenders be rigorously tested against the results of carefully documented, reproducible experiments and observations. Those that fail are discarded until only one remains, or until more stringent tests can be devised to eliminate the others. A better idea might emerge to improve our understanding (e.g., plate tectonics derived from continental drift, or Einstein's theory of relativity as a generalization of Newton's laws of motion), but such advances do not invalidate what has come before. The process is seldom tidy or swift (after all, scientists are human, too), but it is relentless in pursuit of truth—and accepting of the outcome, however far-fetched it might seem.

By design, science works at the murky margin between ignorance and understanding. It should come as no surprise, therefore, that research frontiers are commonly fraught with controversy. Vigorous debate among scientists is essential to the process of separating myth from truth, or at least from the closest approximation attainable at the time. Continents

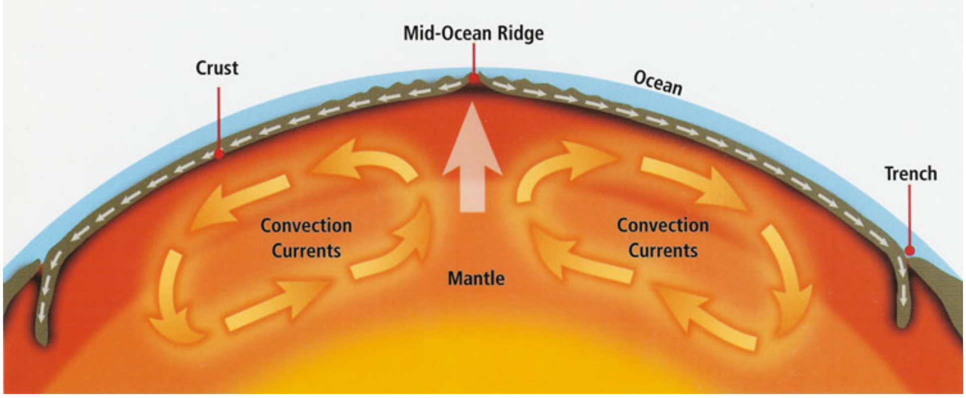

Fig. 4.6 In the early 1960s, plate tectonics pioneers Harry H. Hess and Robert S. Dietz proposed a model driven by mantle convection in which new oceanic crust forms at mid-ocean ridges, moves away, and eventually descends into oceanic trenches

do move, and no amount of bickering, disbelief, or denial will change that fact. Even the most ardent skeptic can measure the widening gulf between South America and Africa, given an open mind and a pair of GPS receivers. Public perception that disagreements among scientists over frontier issues are reason to ignore scientific consensus in other areas is counterproductive, and any attempt to fuel or leverage that perception—as is all too common in some modern media outlets—is dishonest. Disappearing land bridges or continents plowing through ocean basins? Wegener's contemporaries might have disagreed over which was the better idea, but eventually other scientists followed the evidence to a third option—a clearly better one. Plate tectonics might not be the final answer, but it is assuredly a major step forward in our understanding of the Earth system. That, after all, is how science works.

4.1.3 Tectonics on a Sphere: Convergent, Divergent, and Transform Plate Boundaries

Let us get back to that nasty space problem created by the discovery of mid-ocean ridges. Given that Earth is more or less a sphere (we have science to thank for getting *that* right, too) and that new crust is forming continually at mid-ocean ridges, there would seem to be an excess crust problem unless the planet is continually getting bigger (it is not). The problem intrigued Harry H. Hess and Robert S. Dietz, who pioneered the concept of seafloor spreading in the early 1960s (Dietz 1961; Hess 1962). If Earth's crust is expanding along mid-ocean ridges, Hess reasoned, it must be shrinking elsewhere. In the words of another plate tectonics pioneer, J. Tuzo Wilson, "If continents drift…Large areas of crust must be swallowed up in front of an advancing continent and re-created in its wake" (Wilson 1965, p. 344). Hess envisioned a giant recycling machine in which new oceanic crust forms at mid-ocean ridges, moves away, and eventually descends into oceanic trenches (Fig. 4.6). That last bit of insight solves the space problem. Crust is created at ridges (seafloor spreading) and consumed at trenches (subduction). The idea seems simple enough today, but it was a revolutionary insight at the time.

Dietz (1961) picked up on Hess' (1962) seafloor spreading concept, which was first described in a widely circulated report to the Office of Naval Research in 1960, and proposed a mechanism to power the global conveyor belts. According to the Dietz model, mantle convection causes brittle fracture of the lithosphere at mid-ocean ridges.[10] Decompression adiabatic partial melting of mantle rock in the rising limb of a convection cell produces basaltic magma, which intrudes the ridge and in some cases extrudes onto the seafloor. New oceanic crust that forms by this process is rafted away from the ridge by underlying mantle flow, until eventually it is consumed at an oceanic trench. As old oceanic crust is consumed, it is replaced by new crust forming along the ridge. The zero-sum game elucidated by Hess and Dietz neatly explains why Earth does not get bigger as a result of seafloor spreading, why there is so little sediment accumulation on the ocean floor (most of it is too young), and why oceanic rocks are much younger than continental rocks (Kious and Tilling 1996).[11]

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[10] Earth's lithosphere consists of the crust and uppermost mantle, which together behave as a rigid unit that deforms elastically or through brittle failure. The underlying asthenosphere, in contrast, deforms viscously and accommodates strain through plastic deformation. The lithosphere is broken into seven primary tectonic plates (African, Antarctic, Eurasian, Indo-Australian, North American, Pacific, and South American) and many smaller ones, which average about 100 km in thickness.

[11] Early plate tectonics models envisioned the plates riding atop of mantle convection cells like great conveyor belts, a mechanism

Concurrently with the advances pioneered by Hess and Dietz on a global scale, Robert R. Coats studied the geology of the Aleutian Islands and came to a remarkable conclusion. In an often overlooked paper, Coats (1962, p. 92) wrote:

> A reasonable hypothesis for the origin of the volcanic rocks of the Aleutian arc is as follows: Eugeosynclinal sediments and basaltic volcanics were carried down to depths of at least 100 km along a major thrust that dips northward at an angle of roughly 30° beneath the arc and is represented by a zone of earthquake foci. Water and material of granitic composition were sweated out of these materials and were added to a molten fraction of basaltic composition that was interstitial to peridotite of the mantle. This magma rose in the block overlying the thrust zone, probably along tensional fractures or tear faults, and was concentrated at moderate depth in magma chambers. There differentiation of the water-rich magma under constant or increasing partial pressure of oxygen produced the observed variety of volcanic rocks.

Coats correctly interpreted the origin of the Wadati–Benioff seismic zone beneath the Aleutians as resulting from a megathrust, the relation between the location of active volcanoes and the depth to the underthrust crust, and the role of fluids from the down-going slab in magma generation. All this from a few brief visits to several remote islands where the weather is notoriously poor, and at a time when the global context for such insights was just emerging!

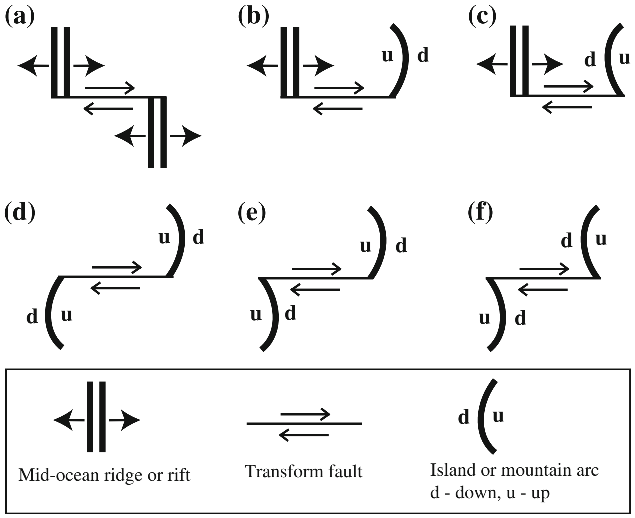

Fig. 4.7 Six possible types of dextral transform faults. **a** ridge to ridge; **b** ridge to concave arc; **c** ridge to convex arc; **d** concave arc to concave arc; **e** concave arc to convex arc; **f** convex arc to convex arc. Reproduced from Wilson (1965)

By the mid-1960s, one more major riddle remained to be solved to complete the plate tectonics revolution, i.e., how to connect three basic types of tectonic boundaries that frame Earth's mobile plates: (1) tensional mid-ocean ridges, where oceanic crust is produced; (2) compressional island arcs and mountain ranges, where plates collide; and (3) horizontal shear zones such as the San Andreas Fault, where plates grind past one another with little or no convergence or divergence. Examples of all three types of elements were easy to recognize in part (e.g., the Mid-Atlantic Ridge, Mariana Islands and Andes mountain range, and San Andreas Fault, respectively), but most appeared to end abruptly in the remote depths of ocean basins. In a milestone publication, Wilson (1965) solved the riddle by proposing that, at a junction between tectonic elements, one type can change into another, akin to a caterpillar changing into a moth! To understand the concept, in your mind's eye connect the ends of two parallel but offset spreading ridges with a shear fault (Fig. 4.7a). Where the fault and a ridge meet, horizontal shear motion along the fault changes abruptly into tension across the ridge. Thus, ridge 1 is "transformed" to ridge 2. Connect one end of a ridge with the corresponding tip of a parallel-trending arc by way of a transform fault, and spreading at the ridge is accommodated by (transformed to) compression in the arc (Fig. 4.7b). And so on for all six possible types of transform faults. Thus are the three basic elements of plate tectonics (ridge, arc, and transform fault) "…connected into a continuous network of mobile belts about the Earth which divide the surface into several large rigid plates" (Wilson 1965, p. 343).

Many important details remained to be worked out, but with Wilson's contribution the essential elements of modern plate tectonics theory were in place. The following summary captures a snapshot of mid-1960s understanding:

- Oceanic crust is produced at tensional mid-ocean ridges and consumed at compressional oceanic trenches.
- Great shear faults called transforms connect ridges and trenches, forming continuous belts that define the edges of rigid lithospheric plates.
- A point where three plates meet is called a triple junction. There are three types of plate margins: ridge (R), trench (T), and transform fault (F). Examples are the Afar Triple Junction, where the Red Sea (R), Gulf of Aden (R), and East African Rift (R) meet in the Afar Triangle; and the Mendocino Triple Junction, where the San Andreas Fault (F), the Mendocino Fault (F), and the trench associated with the Cascadia subduction zone meet off the west coast of North America (T).

(Footnote 11 continued)
referred to as plate drag. However, most scientists now believe that the asthenosphere is not strong enough to drag the plates along by basal friction forces alone. Other mechanisms proposed to account for plate motions include ridge push, slab pull, and trench suction. For a discussion of the ongoing debate over the dominant cause of plate motions, see Conrad and Lithgow-Bertelloni (2002) and references therein.

- Most plate boundaries do not correspond with continental margins, i.e., plates consist of both oceanic and continental lithosphere.
- Plates, ridges, trenches, and transforms are all *mobile* features with respect to a fixed reference frame such as Earth's center of mass. Over geologic time they wander across the globe, driven by mantle convection or the tug of down-going slabs, and they interact in various ways to produce deep oceans and a constantly changing tapestry of continents and other land masses.
- Volcanic arcs are closely associated with oceanic trenches. The latter form where two plates collide and one slides under the other in a process called subduction. Because the collision occurs on a sphere (albeit not a perfectly shaped one), not a plane, the resulting trench is curved, not straight.[12] The Aleutian volcanic arc is associated with the Aleutian megathrust and the Aleutian trench (maximum depth = 7,679 m below sea level), where the Pacific plate is subducting beneath the North American plate.

When a revolutionary idea such as seafloor spreading emerges like a newborn child, brimming with potential but not yet fully formed, the pace of scientific progress can be breathtaking. It is not our intention to recount here the many landmark contributions that, in the brief span of a few decades, shaped present-day understanding of plate tectonics. For that discussion, we refer the interested reader to several excellent books on the subject, including Glen (1982), Menard (1986), Oreskes (1999, 2001), and Uyeda (2002). Nor do we provide even a cursory treatment of modern plate tectonics theory as a whole, which continues to evolve. That material is covered at a technical level by authors such as Bird (1980), Condie (1993), Cox and Hart (1986), and Kearey and Vine (1996); and at the general-interest level by Ballard (1988), Kious and Tilling (1996), and references therein. A tremendous amount of information about plate tectonics is also available on the Worldwide Web. To the recreational reader looking for accurate, non-technical information that's fun to read, we recommend the following web portals:

- http://pubs.usgs.gov/gip/dynamic/dynamic.html (popular overview of plate tectonics concepts)
- http://www.ucmp.berkeley.edu/geology/tectonics.html (fascinating animations of plate motions for the past 750 million years)
- http://earthquake.usgs.gov/learn/topics/topics.php?topicID=30 (extensive links to online plate tectonics resources)

4.2 Tectonics of the North Pacific

The preceding section provides a global context for the following discussion of Aleutian tectonics, which in turn sets the stage for detailed descriptions in Chap. 6 of individual Aleutian volcanoes and how they operate. This section is drawn entirely from the work of others, which we cite with apologies to the original authors for any errors or misrepresentations on our part. In subsequent chapters, we move on to what, for us, is firmer ground by discussing InSAR and what we have learned from our own studies of Aleutian volcanoes. To those interested in reading a landmark paper on the tectonics of the North Pacific written during the emergence of modern plate tectonics theory, we recommend McKenzie and Parker (1967).

4.2.1 Euler Poles and Aleutian Tectonics

Consider the orientations of mid-ocean ridges in the Pacific basin (Fig. 4.1) and the geometry of the Pacific plate (Fig. 4.4). Does it strike you as odd that seafloor spreading along major ridge crests that are oriented more or less north–south (East Pacific Rise, Gorda ridge, Juan de Fuca Ridge) results in northwestward subduction of the Pacific plate along the Aleutian trench to form the Aleutian volcanic arc? If so, do not feel foolish—you are just guilty of thinking like a flatlander while living on a sphere. It is a common mistake. On the other hand, the problem of relative motion of plates on a sphere was solved *almost 300 years ago* by a brilliant Swiss mathematician named Leonhard Euler (1707–1783). So it is OK to feel a little sheepish.

Euler's Fixed Point Theorem states that the movement of a portion of a sphere across the surface of the sphere is uniquely defined by a single angular rotation about a pole of rotation. Consider Earth spinning about its rotation axis. The movement of any point on the surface during any time interval Δt can be uniquely described by the location of the rotation pole and the angle of rotation about that pole. For

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[12] A sphere in compression tends to fail along a small circle, producing arcuate fractures. A small circle is defined as the intersection of a sphere and a plane that does not contain the center of the sphere. Imagine slicing an orange into two unequal pieces; the cut occurs along a small circle of the orange. When lithospheric plates collide, subduction along an arcuate trench or subduction zone is the most likely outcome. This is the case when oceanic crust impinges on continental crust (denser oceanic crust subducts) and when oceanic crust impinges on oceanic crust of another plate (older, denser crust subducts). Examples are subduction of the oceanic Pacific plate beneath the North American continent along the Cascadia subduction zone, and subduction of the Pacific plate beneath younger oceanic crust of the North American plate along the Aleutian trench. The exception is a continental-continental plate collision, in which neither plate subducts. Instead, the plate boundaries are intensely folded and faulted into a great mountain range. An example is the Himalayas, the highest mountain system on Earth, where the Indian plate is colliding with the Eurasian plate.

example, the movement of Arzberg, Germany[13] from 1 h to the next can be described by the location of Earth's rotation pole and the city's rotation angle in an hour's time—for our purposes, 1/24 × 360° = 15°. It follows that, given the locations of the rotation pole and any point on the surface at any time t_0, we can compute the point's location at any past or future time t_1. This is the basis of plate reconstruction, which allows geologists to take Pangaea apart and put it back together again.

But things are not quite that easy. For one thing, each lithospheric plate has its own Euler pole and they are scattered all over the globe. And the concept of *terra firma* turns out to be something of a fraud, because *nothing* on Earth's surface is fixed. Everything is moving with respect to everything else. Plates move, mid-ocean ridges move, subduction zones move, *everything* moves. Even mantle plumes and hotspots, which were thought to be stationary when first envisioned by Wilson (1963) and Morgan (1971, 1972a, b), turn out to be moving at rates of up to a few centimeters per year (Tarduno and Gee 1995; Raymond et al. 2000; Koppers et al. 2001; Tarduno et al. 2003; Tarduno 2007).[14] Earth's center of mass can be considered fixed for most purposes, but we live on the surface more than 6,300 km away. So it was difficult to specify absolute plate motions with respect to a fixed reference frame until the advent of space-based geodetic techniques such as VLBI, GPS, SLR (satellite laser ranging), and DORIS.[15] It would be convenient if there were a simpler way to describe *relative* plate motions—and thanks to Leonhard Euler, there is. A useful corollary of Euler's theorem states that *relative motion of two plates* on a sphere is uniquely defined by an angular separation about an Euler pole of relative motion. So we can speak of the Pacific–North American Euler pole and the velocity of rotation about that pole. Those two parameters uniquely specify relative motion between the plates, thereby avoiding the messy issue of a fixed reference frame. This approach works well for our purposes, because we're less interested in absolute plate motions than in the relative rate of convergence between the Pacific plate and North American plate in the vicinity of the Aleutian trench.

The location of the Pacific–North American Euler pole has been revised several times based on improved plate reconstructions and, more recently, GPS and Very Long Baseline Interferometry (VLBI) measurements of contemporary plate velocities. The exact location isn't important here. It's sufficient to know that relative motion between the Pacific and North American plates is a clockwise rotation about a pole located in the vicinity of Quebec, Canada (Stein and Klosko 2002) (Fig. 4.8). That fact plus the notion that, for points on a rigid plate rotating at a constant angular velocity, linear velocity increases with increasing distance from the rotation pole, makes a number of important relationships immediately clear. For example, right-lateral motion across the San Andreas transform fault is a consequence of: (1) the fault's orientation parallel to the small circle showing relative plate motion,[16] and (2) increasing velocity across the fault with increasing distance from the Euler pole (i.e., the Pacific plate is moving clockwise faster than the North American plate where they meet at the San Andreas transform, resulting in right-lateral movement across the fault). Follow the small circle in Fig. 4.8 clockwise in the direction of relative plate motion and you see that the Pacific–North American boundary changes from extensional in the Gulf of California to compressional at the Aleutian trench, where the two plates collide nearly head-on (i.e., the convergence direction is nearly perpendicular to the trend of the trench).

There are many interesting details to follow, but the first-order question of why the Aleutian volcanic arc exists in the first place has been answered—with a little help from spherical geometry and an eighteenth century Swiss mathematician.

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[13] Arzberg is a quiet, provincial town of about 6,500 inhabitants, situated in the Roslau Valley of the Fichtelgebirge mountain range, only a few miles from the border with the Czech Republic to the east. Discovering the reason for mentioning it here, beyond the need for an arbitrary example, is an exercise left to the reader.

[14] For a fascinating account of the evolution of thought concerning hotspots and plumes, and the controversy that still enlivens debate on the subject, see Anderson and Natland (2005).

[15] The coordinate system for the Global Positioning System (GPS) is centered at Earth's center of mass and includes three orthogonal axes that are defined by convention. The first axis passes through the intersection of the Greenwich meridian and Earth's equatorial plane. The third axis is defined as the average position of Earth's rotation pole for the years 1900–1905. The second axis is orthogonal to the other two. Plate motions measured by GPS are with respect to Earth's center of mass and can be considered absolute for most purposes. The accuracy and stability of the International Terrestrial Reference Frame (ITRF), which is based on a combination of GPS, Very Long Baseline Interferometry (VLBI), satellite laser ranging (SLR), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) observations, are approaching 1 mm and 0.1 mm/year, respectively (National Research Council 2010). Uncertainty in the relative motion between the center of mass of the solid Earth and the center of mass of the Earth system (solid Earth, ice sheets, oceans, and atmosphere) is on the order of 1–2 mm/year (Argus, 2007). Plate velocities are typically 1–2 orders of magnitude greater than these uncertainties, so for this discussion Earth's center of mass can be considered fixed.

[16] A consequence of Euler's Fixed Point Theorem is that the motion of any point on one rigid plate with respect to another (assumed fixed) plate occurs along a small circle centered at the Euler pole of rotation that defines relative motion between the two plates. In Fig. 4.7, for example, the dot-dash line is part of a small circle along which points on the Pacific plate move with respect to the North American plate. In the Gulf of California, there is a small tensional (opening) component to the motion. At the San Andreas Fault the motion is almost purely strike-slip, whereas at the Aleutian trench it is compressional.

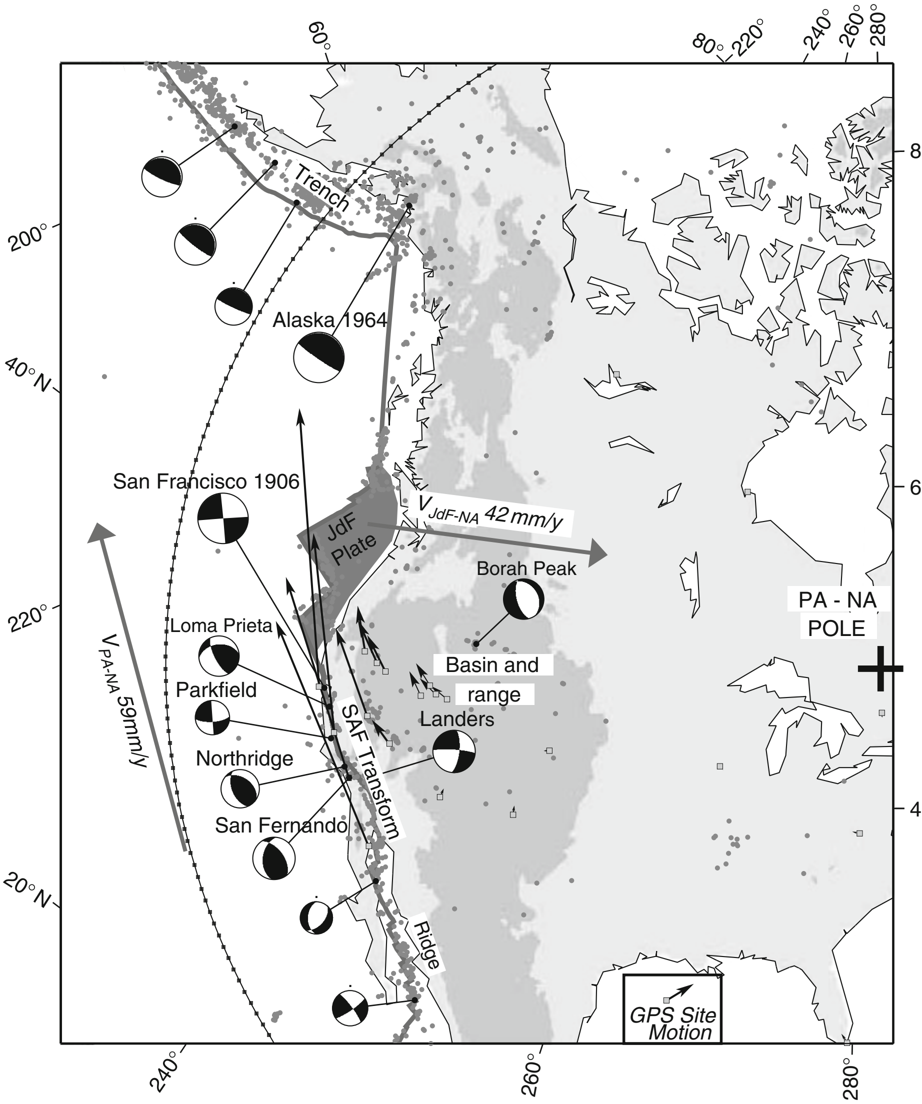

Fig. 4.8 Geometry for a portion of the North America–Pacific plate boundary zone. *Dot-dash line* shows *small circle*, and thus direction of plate motion, about the Pacific–North America Euler pole (+, near right margin). Variation in the boundary type along its length from extension, to transform, to convergence at the Aleutian trench (*upper left*), is shown by focal mechanisms. Diffuse nature of the boundary zone is shown by seismicity (*small dots*), focal mechanisms, topography (1000 m contour shown *shaded*), and vectors showing the motion of GPS and VLBI sites (*small squares*) with respect to stable North America. *PA*, Pacific; *NA*, North America; *SAF*, San Andreas Fault; *JF*, Juan de Fuca. Reproduced from Stein and Klosko (2002)

4.2.2 When Plates Collide: The Three Types of Convergent Plate Interactions

What happens when plates collide is determined by the types (oceanic or continental) and relative ages of lithosphere on either side of the collision zone. When a dense oceanic plate collides with a less dense continental plate, the oceanic plate sinks into the asthenosphere along a subduction zone and a marginal trench forms where the plates meet at the surface (i.e., along the margin of the oceanic plate) (Fig. 4.9). As the oceanic plate and overlying sediment sink into the mantle, pressure increases until, at pressures above ~30 kbar (depth ~100 km), hydrous minerals undergo metamorphism.[17] The process releases

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[17] Sources of water in the downgoing slab include hydrous minerals in hydrothermally altered sediments (clay minerals), basaltic crust (amphiboles), and mantle lithosphere (serpentinites). Hydration of oceanic crust occurs at mid-ocean ridges where high-temperature basalts interact with seawater. Serpentinization of mantle rocks requires deep penetration of seawater, which is facillitated along fracture zones. High-grade metamorphism of hydrous minerals releases bound water that rises into the mantle wedge, lowering its

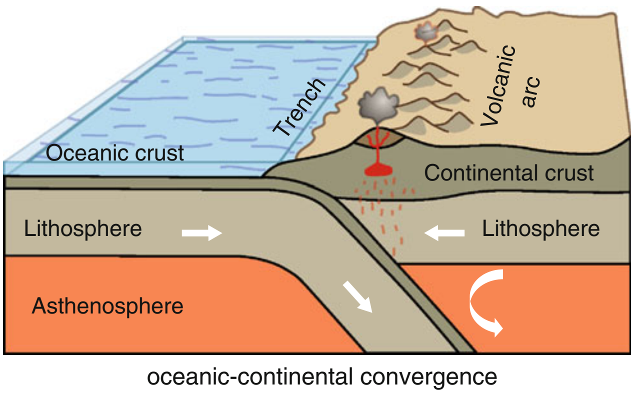

Fig. 4.9 Idealized cross section showing formation of a subduction zone, trench, and volcanic arc resulting from collision between oceanic and continental lithospheric plates. Reproduced from Kious and Tilling (1996)

water, which migrates upward into the overlying wedge of hot mantle and lowers its melting temperature. Resulting partial melting of ultramafic mantle rocks to yield mafic magma is called flux melting.[18] Buoyant ascent of this mafic magma through the crust feeds intrusions and eruptions, and results in formation of a volcanic arc with an intrusive core along the continental plate margin. In this way, subducted sediments play an important role in influencing melting behavior and trace element geochemistry of arc magmas (Plank and Langmuir 1998; Plank 2012). The Andes and Cascade arcs are examples of volcanic arcs that formed as a result of oceanic-continental plate collisions.

When two oceanic plates collide, the older plate subducts because it is colder and slightly denser than the younger plate (Fig. 4.10). A subduction zone, oceanic trench, and volcanic arc form in a manner similar to a continental-oceanic plate collision. In this case, though, a string of volcanoes builds up from the seafloor to form an island arc. The Aleutian Islands, Mariana Islands, and Philippine Islands are examples of island arcs.

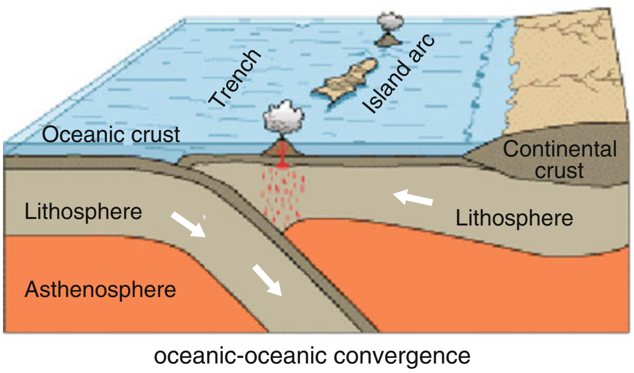

Fig. 4.10 Idealized cross section showing formation of a subduction zone, trench, and island arc resulting from collision between two oceanic lithospheric plates. Reproduced from Kious and Tilling (1996)

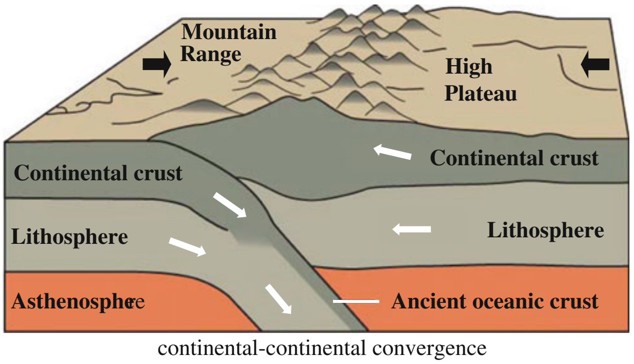

Fig. 4.11 Idealized cross section showing formation of a mountain range and high plateau resulting from collision between two continental lithospheric plates. Modified from: http://www.geogrify.net/GEO1/Lectures/PlateTectonics/#(10)

The third type of plate collision, involving two continental plates, results in a temporary standoff because both plates are relatively light, buoyant, and resist subduction. As a result, continued convergence of the plates causes the crust to buckle and be thrust upward, forming a mountain range (Fig. 4.11). Eventually one plate underthrusts the other, but volcanism is generally absent. The Himalayas, which formed as a result of collision between the Indian and Eurasian plates starting about 50 million years ago, is a spectacular example of the consequences of two continental plates colliding. Today, parts of the range continue to be pushed skyward at rates of nearly 10 mm/year—the highest tectonic uplift rate in the world.

4.3 Tectonics of the Aleutian Volcanic Arc

As described above, the Pacific plate rotates clockwise relative to the North American plate about an Euler pole in southeast Canada, resulting in: (1) convergence in the North

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(Footnote 17 continued)
melting temperature. Partial melting of mantle rock produces mafic magma that rises to sustain the volcanic arc.

[18] Magmas can be broadly categorized on the basis of silica and iron-magnesium (Fe–Mg) contents as ultramafic (picritic), mafic (basaltic), intermediate (andesitic-dacitic), or felsic (rhyolitic). Mafic magmas contain ~50 wt.% SiO_2 and typically <10 wt.% FeO and MgO. Ultramafic magmas contains less than ~45 wt.% SiO_2, generally >18 wt.% MgO, and high FeO. Earth's mantle is composed of ultramafic rocks, and others form as cumulates at the base of mafic magma reservoirs in the crust. Intermediate magmas contain ~60 wt.% SiO_2 and ~3 wt.% Fe–Mg. Felsic magmas contain ~70 wt.% SiO_2 and ~2 wt.% Fe–Mg.

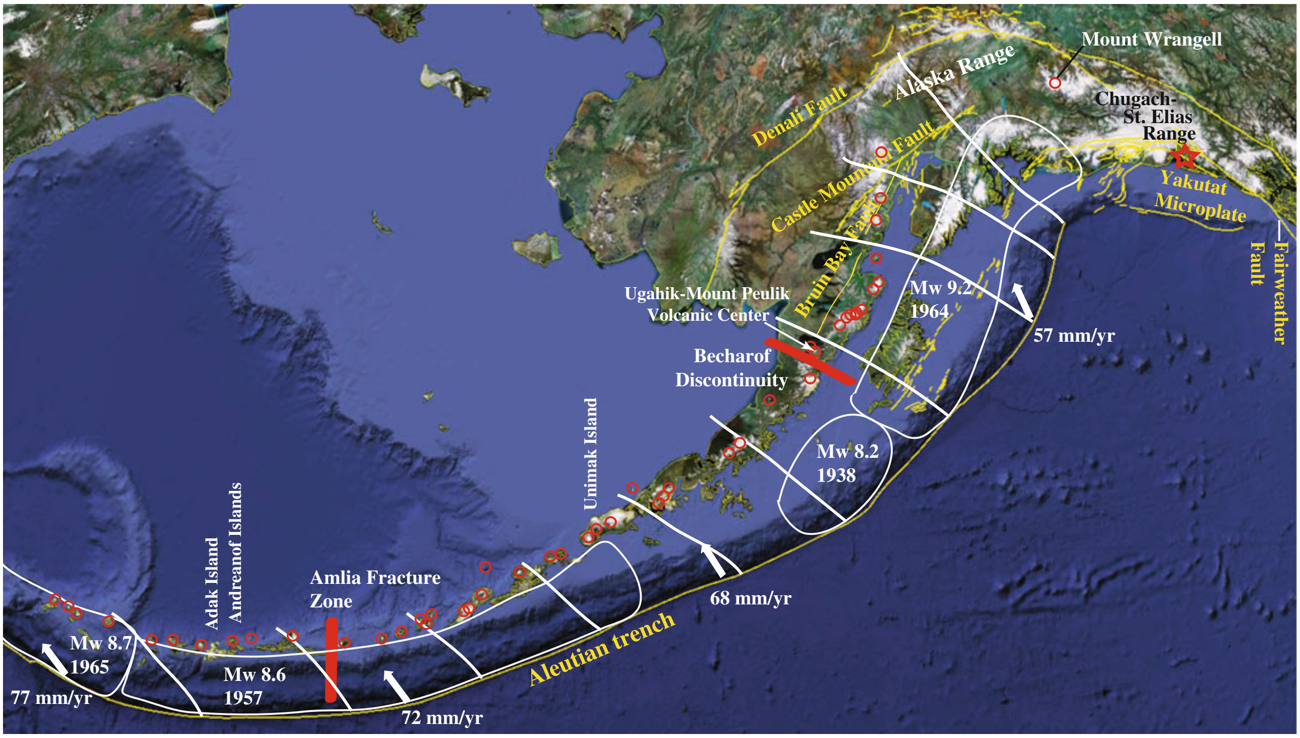

Fig. 4.12 Tectonics and historically active voclaneos of the Aleutian volcanic arc. *Yellow lines* are the Aleutian trench and active faults in Alaska (Koehler et al. 2013). *White polygons* represent approximate extents of rupture zones of historical earthquakes with $M_w > 8.0$; *red star* shows epicenter of 1899 M_w 8.6 earthquake in Yakutat Bay, southeastern Alaska. *White lines* represent directions of greatest compressional stress (Plafker et al. 1994b). *Red circles*, historically active volcanoes

Pacific along the Aleutian trench, (2) subduction of the Pacific plate beneath the North American plate along the Alaska-Aleutian megathrust,[19] and (3) formation of the Aleutian volcanic arc as a consequence of (*a*) metamorphic dewatering of the subducting slab, (*b*) flux melting of the mantle wedge overlying the downgoing slab, and (*c*) buoyant rise of mafic magma to feed eruptions.[20] That is the broad-brush picture of Aleutian tectonics and magmatism, but there are some important details to be addressed in the following three sections. For a comprehensive treatment of contemporary deformation processes in Alaska, see Freymueller et al. (2008).

4.3.1 Variable Nature of the Aleutian Collision Zone

The Aleutian trench and associated volcanic arc extend 3,600 km from the Kamchatka Peninsula in the west to the Gulf of Alaska in the east, including the Aleutian Islands, Alaska Peninsula, Cook Inlet volcanoes, and Wrangell Volcanic Field (Fig. 4.12).[21] The bathymetric expression of

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[19] The Alaska-Aleutian megathrust is a thrust fault that forms the interface between the subducting Pacific Plate and the overriding North American Plate from near Kamchatka in the west to the Gulf of Alaska in the east.

[20] Some authors (e.g., Dickinson 1995) refer to the oceanic portion as the Aleutian trench and to the continental portion as the Alaska trench. Others (e.g., Freymueller et al. 2008) use the term “Alaska-Aleutian trench.” Here we adopt the common usage, Aleutian trench, for the entire length of the convergent boundary.

[21] Aleutian nomenclature is complicated for both geological and geopolitical reasons (the irony of juxtaposing the terms “logical” and “political” in this sentence is noted). The Aleutian trench extends from a triple junction in the west with the Ulakhan Fault and the northern end of the Kuril–Kamchatka Trench, to a junction with the northern end of the Queen Charlotte Fault system in the east—a surface distance of about 3,600 km. Because volcanic arcs form above subduction zones, one might reasonably assume that a trench and its associated arc would be of similar lengths. On the other hand, the Aleutian arc is commonly described as extending from Kiska Island (or nearby Buldir Island) in the west to Mount Spurr in the east—a distance of about 2,500 km. Alaska residents might shrug off the 900 km difference as inconsequential, but there is more to the story. Lying to the west of Kiska and Buldir along a mostly submarine section of the arc are three relatively obscure island groups (from east to west): the Near Islands, Semichi Islands, and Komandorski Islands (a.k.a. Commander Islands). The Near Islands and Semichi Islands are part of Alaska; the Komandorskis are Russian. No eruptions have occurred on any of these islands during Holocene time, which—

the trench ends near the east end of the 1964 *M* 9.2 "Good Friday" earthquake (see Sect. 4.3.2), but convergence between the North American and Pacific plates continues eastward to the Queen Charlotte–Fairweather fault system—a strike-slip transform boundary that accommodates northward motion of the Pacific plate and associated Yakutat terrane, which is in the process of accreting to North America (Bruns 1983; Plafker 1983; Plafker et al. 1994a, b; Chapman et al. 2008). The North American-Pacific plate boundary forms the northern part of the Pacific Ring of Fire, which also includes the Kuril–Japan–Marianas Trench System and the Mindanao Trench to the west, the New Hebrides, Tonga, and Kermadec trenches to the south, and the Middle American and Peru–Chile trenches to the east.

The Aleutian Islands are a classic example of an island arc (Fig. 4.10), in this case formed by subduction of oceanic lithosphere of the Pacific plate beneath oceanic lithosphere of the North American plate. But what about the eastern part of the arc, i.e., the volcanoes of the eastern Aleutian Islands, Alaska Peninsula, and Cook Inlet? These do not fit the definition of an island arc, i.e., an arcuate string of volcanoes built up from the seafloor along an oceanic trench. Instead, volcanoes in the eastern Aleutians are located on or near the continental land mass. The difference lies in the nature of the overriding plate. The upper plate in the western Aleutians consists of old (~120 Ma) *oceanic* lithosphere (Cooper et al. 1976; Worrall 1991), but in the eastern Aleutians it consists of *continental* lithosphere. As a result, subduction in the western Aleutians results in formation of an island arc, while in the eastern Aleutians the result is a continental arc (Figs. 4.9, 4.10). According to Astiz et al. (1988, p. 115): "The [subducting] oceanic plate becomes progressively older to the west along the trench, ranging from 40 to 65 Ma. Seismicity defines the downgoing slab to a maximum depth of 280 km underneath the Aleutian Arc. The dip of the subducting lithosphere shallows progressively to the east from 65° underneath the Aleutian Islands to ~25° beneath the Cook Inlet, where seismicity extends to only 150 km depth." The transition from oceanic trench-island arc to marginal trench-continental arc occurs near the western tip of the Alaska Peninsula and Unimak Island (Fliedner and Klemperer 2000).

The nature of the overriding plate isn't the only thing that changes along the graceful sweep of the Aleutian arc. The convergence rate and convergence angle (obliquity) of the Pacific and North American plates also vary considerably. Relative to a fixed North American plate, the Pacific plate is moving northwest at a rate that increases from 57 mm/year in the eastern part of the arc beneath the Gulf of Alaska, to 72 mm/year in the central part near Unimak Island, to 77 mm/year in the western part near Kiska Island (DeMets et al. 1990, 1994; DeMets 1992) (Fig. 4.12). The convergence angle changes even more. In the central part of the arc near the tip of the Alaska Peninsula and Unimak Island (~160°W longitude), convergence of the plates is nearly perpendicular to the plate boundary (i.e., obliquity is nearly 0° measured clockwise from normal to the plate boundary). Farther West, subduction becomes progressively more oblique until relative plate motion is nearly parallel to the boundary (obliquity about −80°) at the western end of the arc (~180°W longitude) and right-lateral slip dominates (Fig. 4.12). Conversely, in the eastern part of the arc in the vicinity of Kayak Island and the Copper River Delta (~150°W longitude), convergence is such that the obliquity reverses sign to about +40°. The large span in obliquity along the Aleutian trench results in a correspondingly large range in downdip slab velocity, from ~10 mm/year near the west end to ~60 mm/year in the central part and ~40 mm/year near the east end. Farther east in the vicinity of the Wrangell Mountains (~145°W longitude), collision of the Yakutat block with the North American plate results in anomalous thickening of the plate, flat-slab subduction, spectacular uplift of the St. Elias Range, and strike-slip motion along the Fairweather–Queen Charlotte fault system (Plafker 1983; 1987; Plafker, Moore, et al. 1994a, b; Doser et al. 1997; Freymueller et al. 2008).

In addition to smoothly varying changes in geometry and convergence rate along the Aleutian arc, more abrupt differences have been identified and used to distinguish among various arc segments. The segments have been defined based several characteristics including: (1) the extent of rupture during great earthquakes as delineated by aftershock zones (Boyd et al. 1988), (2) inferences from structural geology (Geist et al. 1988; Geist and Scholl 1994; Ryan and Scholl 1993), (3) differing stress orientations from seismic fault plane solutions (Lu and Wyss 1996), and (4) geodetic measurements (Savage 1983; Savage et al. 1986; 1999; Cross and Freymueller 2007; Fournier and Freymueller 2007; Freymueller et al. 2008). Not surprisingly, using different criteria to identify arc segments gives different results in terms of the number of segments identified and their boundaries. These differences are not an important

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(Footnote 21 continued)
combined with their remoteness—might explain why they are not included in the Aleutian arc in common usage. Adding to the nomenclatural complexity is the term "Aleutian Islands" which logically (and geologically) extend from the Komandorskis to Unimak Island, the easternmost island in the chain. East of Unimak Island are the volcanoes of the Alaska Peninsula and Cook Inlet region, i.e., the continental segment of the Aleutian arc that also includes the oceanic segment from Unimak Island westward to Kiska Island (or Buldir Island, or the Near Islands, or the Komandorskis, depending on your point of view). Because we are mostly concerned here with Aleutian volcanoes that have been active during historical time, heretofore we focus our attention from Kiska in the west to Mount Spurr in the east. The rest of the arc, however long, is beyond our scope.

Table 4.1 $M \geq 8.0$ earthquakes in Alaska, 1898–2013

Date	Latitude (N)	Longitude	Depth (km)	M_L	Location/informal name(s)
10 Oct 1899	60.0000	140.0000 W	25.0	8.0	Yakatat Bay
10 Nov 1938	55.4800	158.3700 W	0.0	8.2	East of Shumagin Islands
22 Aug 1949	53.7500	133.2500 W	35.0	8.1	Queen Charlotte Islands earthquake
09 Mar 1957	51.2900	175.6300 W	33.0	8.6	Andreanof Islands earthquake
28 Mar 1964	61.0500	147.4800 W	23.0	9.2	Great Alaskan earthquake Great Alaskan earthquake Portage earthquake
04 Feb 1965	51.2900	178.5500 E	36.0	8.7	Rat Islands earthquake
03 Nov 2002	63.5141	147.4529 W	4.2	7.2	Denali Fault earthquake

Source Alaska Earthquake Information Center (http://www.aeic.alaska.edu/html_docs/db2catalog.html)

problem for us, because our main focus in subsequent chapters is on deformation of individual volcanoes, rather than larger-scale block deformation or rotation. Nonetheless, arc segmentation and local tectonics might play a role in crustal magma transport and storage, which in turn influence such things as magma composition, crustal deformation, and eruptive behavior (see Chap. 7). The following treatment of Aleutian arc segmentation (Sects. 4.3.2 and 4.3.3) is illustrative of the concept. Interested readers can find more detailed information in the research literature, starting with the references cited above.

4.3.2 Alaska: One of the World's Most Seismically Active Areas

One way to define arc segments is by the extent of rupture zones of historical great earthquakes. The Alaska Earthquake Information Center (AEIC) locates about 20,000 earthquakes per year in Alaska, which is more than are located in the other 49 U.S. states combined. Most of these are associated with subduction along the Aleutian trench. A search of the AEIC on-line database (http://www.aeic.alaska.edu/html_docs/db2catalog.html) returned 98 events of Richter $M \geq 7.0$ in Alaska during 1898–2013 (see also USGS 2011; Taber et al. 1991). Of these, seven were of $M \geq 8.0$ and one exceeded M 9 (see below). Four of the largest quakes caused extensive property damage and notable topographic changes. The others were centered in areas with no nearby towns, and therefore went relatively unnoticed (Table 4.1).

Among the largest earthquakes in recorded history is the M_L 9.2 "Good Friday" shock that struck south-central Alaska on March 27, 1964 (March 28, 1964 UTC) (Fig. 4.12). The quake devastated the downtown Anchorage area and triggered a tsunami that destroyed many of the state's coastal towns. Fortuitous timing limited the number of deaths caused by the quake itself, but 122 persons were killed by the ensuing tsunami: 107 in Alaska, 11 in California, and 4 in Oregon. Two hundred kilometers southwest of the epicenter, areas near Kodiak were permanently raised by 9 m. Southeast of Anchorage, areas around the head of Turnagain Arm dropped more than 2 m. In Prince William Sound, Port Valdez suffered a massive underwater landslide, resulting in the deaths of 30 people. Nearby, an 8 m tsunami destroyed the village of Chenega, killing 23 of the 68 people who lived there.

The area near the Andreanof Islands in the central Aleutians sustained a M_L 8.6 earthquake in March 1957 that caused severe damage on Adak and Unimak islands (Fig. 4.12). The rupture, more than 1,000 km long, generated a tsunami that reportedly arrived at Scotch Cap on the coastline of Unimak Island as a wall of water 15 m (50 ft) high. Sand Bay, on the coast of Adak Island, reported 8 m (26 ft) waves. The tsunami continued to Hawaii, where it destroyed two villages and inflicted about $5 million in property damage on Oahu and Kauai islands. Minor damage was also reported in San Diego Bay, California (http://earthquake.usgs.gov/earthquakes/states/events/1957_03_09.php). The earthquake apparently triggered a phreatic eruption at Mount Vsevidof on Umnak Island, which had not been reported active since 1880 (http://avo.alaska.edu/volcanoes/activity.php?volcname=Vsevidof&eruptionid=111&page=basic).

In September 1899, two great earthquakes struck the Yakutat Bay area of southeastern Alaska (Fig. 4.12). A magnitude 8.6 shock on September 10, 1899, was preceded one week earlier by a magnitude 8.2 event. A destructive tsunami 10.6 m in height occurred in Yakutat Bay and tsunamis also were observed at other places along the Alaskan coast. A U.S. Geological Survey (USGS) team surveyed the area in 1905 and reported uplift of the land surface caused by the quake that ranged from 9 m (30 ft) to more than 14 m (47 ft) on the west coast of Disenchantment Bay (http://earthquake.usgs.gov/earthquakes/states/events/1899_09_10.php).

The 2002 M_W (moment magnitude) 7.9 Denali Fault earthquake (local magnitude M_L 7.2) produced 340 km of surface rupture and was the largest strike-slip earthquake in North America in almost 150 years. It began with thrusting on the previously unrecognized Susitna Glacier fault, continued with right-lateral slip on the Denali fault, then stepped right and continued with right-lateral slip on the Totschunda fault (Eberhart-Phillips et al. 2003). Biggs et al. (2009) analyzed GPS and InSAR data for the postseismic 2003–2005 period and concluded that the dominant response of the lithosphere to the stresses imposed by the earthquake occurred in the upper mantle (depths greater than 50 km) during the time period between 1.5 and 2.5 years after the earthquake. They could not distinguish between relaxation of a viscoelastic medium, afterslip on a discrete fault plane, or a combination of both as the primary response mechanism.

4.3.3 Arc Segmentation and Block Tectonics

Early plate tectonics theory notwithstanding, Earth's lithospheric plates are neither perfectly rigid nor uniform. In detail they are broken by fracture zones and are inhomogeneous across many length scales. Especially along subduction zones, major plates consist of many discrete elements (microplates or blocks) that behave differently from one another, making the study of arc volcanism and its relationship to regional tectonics even more complex and fascinating. One means of distinguishing between arc segments is the extent of rupture during large earthquakes, as discussed below.

Rupture zones of very large subduction earthquakes span a significant fraction (hundreds of km) of the entire plate boundary (Fig. 4.12). The occurrence of a great earthquake releases strain along the rupture zone, creating a segment that is less prone to large earthquakes in the near future than are adjoining segments. Subsequent quakes tend to occur along segments that have not ruptured for a long time until, over time, strain along the entire plate boundary is relieved. However, the process is not regular or linear—differences in strain accumulation rate, locking versus creeping behavior, and yet to be understood vagaries of nature tend to randomize any progression of earthquakes along the arc. Freymueller et al. (2008, p. 25) describe the Aleutian case as follows: "The overall picture is that variation in the seismogenic zone is the rule rather than the exception, and any effort to characterize the seismogenic zone in terms of simple variables that vary slowly along strike (e.g., the temperature distribution, plate velocity, or the amount of sediment in the trench) is doomed to failure." With that caution in mind, we discuss plate segmentation as a useful concept to describe large-scale, along-arc variations that occur across identifiable boundaries (e.g., major structural discontinuities or the oceanic-continental crust boundary near Unimak Island) rather than being transitional in nature (e.g., plate convergence angle and rate).

Based on fault plane solutions for about 400 well-recorded earthquakes that occurred in Alaska from 1964 to 1993, Lu and Wyss (1996) identified five boundaries (six segments) along the Aleutian plate boundary at which tectonic stress directions change significantly. They concluded that significant changes in stress orientation occur where the trench intersects major fracture zones in the subducting plate, including the Amlia fracture zone, the Rat and Adak fracture zones to the west, and the Aja fracture zone to the east.[22] Lu and Wyss (1996) suggested that correlation between fracture zones and stress direction changes might indicate decoupling (tearing) within the subducting plate along the fracture zones, across which stress is not transmitted fully. They also noted a lesser, but still fairly strong, correlation between stress discontinuities and asperities or ends of ruptures in great earthquakes. Subsequent studies have shown that these same arc segments behave as discrete tectonic blocks, undergoing relative translation and rotation (Cross and Freymueller 2007), and that they differ in the degree of coupling between the North American and Pacific plates (i.e., locked versus creeping) (Fournier and Freymueller 2007; Freymueller et al. 2008).

The Alaska Earthquake Information Center (AEIC) succinctly describes the tectonic setting of the Aleutians as follows: "The entirety of the Aleutian Islands is composed of complex tectonic collisions, and rectangular blocks contained within shear zones and deforming canyons…" (http://www.aeic.alaska.edu/maps/regional_seismicity_aleutian.html). The complexity extends to the easternmost part of the arc, where northward motion of the Pacific plate and westward motion of the North American plate must be accommodated around the sharp bend in the latter that occurs in the Gulf of Alaska. Referring to this region, Naugler and Wageman (1973, p. 1580) wrote:

> Assuming the rest of Alaska is rigidly attached to the North America plate, a transition of the plate boundary from one of strike-slip displacement (the Queen Charlotte Islands fault system) to one of underthrusting (the Aleutian arc subduction zone) must be occurring within the continental crust of southeastern Alaska. This results in an unstable situation in which subduction of continental crust is required in order that a narrow zone of deformation, typifying most plate boundaries, be maintained throughout the transition. Subduction of continental crust is considered by many to be physically untenable owing to its buoyancy and hyperfusible petrologic make-up (for

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[22] Fracture zones are linear features, often hundreds to thousands of kilometers long, which result from the motion of offset mid-ocean ridge segments. Strike-slip motion along a transform fault offsets the ridge. Fracture zones extend past the active portion of the transform, away from the ridge axis, to an area where both plate segments are moving in the same direction. Strictly speaking, fracture zones are seismically inactive and record evidence of past transform fault activity. In common usage, the term is loosely applied to transform faults aligned with fracture zones.

> example, Dietz and Holden 1970). Thus, to allow for the present differential motion between the Pacific plate and the North America plate, crustal shortening by internal deformation must be occurring to relieve horizontal compressive stresses and complete the plate boundary transition. This zone of compression should lie between the eastern limit of active subduction along the Aleutian trench and the system of transform faults farther east.

The complex transition zone described by Naugler and Wageman (1973) is characterized by collision of the Yakutat block with North America, flat-slab subduction, anomalous thickening of the North American plate by accretion of Yakutat terrane, crustal compression, uplift of the Chugach-St. Elias Range, and strike-slip motion along the Fairweather fault to the east (Fig. 4.12). To what extent might the Yakutat-North America collision influence magmatism in the eastern part of the Aleutian arc? We suspect that the collision's influence extends at least as far southwest as the structurally complex Ugashik-Mount Peulik area, including the cross-arc zone of weakness known as the Becharof discontinuity (see below and Chap. 7).

Decker et al. (2008, p. 85) discussed the tectonic situation in the northeastern part of the Alaska Peninsula (i.e., in the vicinity of the Ugashik-Mount Peulik volcanic center) (Fig. 4.12) in terms of three main tectonic elements: (1) the Ugashik sub-basin, (2) the Ugashik Lakes fault system, and (3) the Becharof discontinuity:

> The Ugashik sub-basin is the northeastern segment of the North Aleutian backarc basin… The Ugashik sub-basin is bounded on the southeast by the Ugashik Lakes fault system, a northeast-trending set of down-to-northwest faults mapped previously from limited outcrop information. The northeast margin of the sub-basin is the Becharof discontinuity, a northwest-trending zone of crustal weakness interpreted from geophysical data, volcanic activity, and modern seismicity. Focal mechanism solutions from the region are consistent with largely strike-slip motion in a present-day stress regime dominated by a nearly north–south-trending, subhorizontal axis of maximum compressive stress.

The picture that emerges from such studies is of two broken and deformed plates interacting in complex fashion to produce the relatively simple form of the Aleutian arc as a whole. The degree to which local tectonic complexities affect the style or products of Aleutian volcanism is a topic of ongoing research. In Chap. 6, which addresses InSAR results for specific volcanoes, we note which are located near major structural features or inferred segment boundaries and cite others' suggestions of possible tectonic influences on volcanism. For purposes of discussion in our final chapter, we adopt a three-segment description of the Aleutian arc (Fig. 4.12) based on observed patterns of seismicity (Buurman et al. 2014), magma composition (Nye 2008), historical eruptions, and inferred depth of magma storage. The western segment stretches from Kiska, the arc's westernmost historically active volcano, to the Amlia fracture zone near the eastern tip of Atka Island. The central segment extends eastward from the Amlia fracture zone to the Becharof discontinuity near the Ugashik-Peulik volcanic center, and the eastern segment stretches from there eastward to Mount Wrangell. We conclude in Chap. 7 that the broken nature of the Pacific and North American plates in the collision zone has played an important role in fashioning the picturesque Aleutian arc we know today.

4.3.4 Early Plutonic and Volcanic History of the Aleutian Arc

The geologic framework of the Aleutian arc was discussed by Vallier et al. (1994) and updated by Jicha et al. (2006) based on radioisotopic dating of volcanic and plutonic rocks. The arc formed about 46 million years. ago and experienced three main pulses of arc-wide magmatism 38–29, 16–11, and 6–0 million years. ago. Jicha et al. (2006) estimated the volume of volcanic and plutonic material along the arc to be 4100–5500 km^3/km, implying an average magma production rate of 89–120 km^3/km/million years. Accounting for material lost to subduction and glacial erosion, the average magma production rate over the past 46 million years. has been 182 km^3/km/million years., a value that ranks the Aleutian arc among the most prolific volcanic arcs on Earth.

4.3.5 Aleutian Tectonics Summary

In this chapter we reviewed the basic tenets of plate tectonics theory and tried to recapture some of the excitement that accompanied its development nearly a half century ago. We applied those concepts to the North Pacific, where collision of the Pacific plate and North American plate has resulted in formation of the spectacular Aleutian trench, subduction zone, and the Aleutian volcanic arc. We touched on a few of the complexities of the collision, including the variable nature of the overriding North American plate, variable convergence rate and convergence angle, arc segmentation and block tectonics, and effects of large earthquakes. Having thus examined the full Aleutian mosaic at arc scale, we now are nearly ready to focus our attention more narrowly on the behavior of individual volcanoes—specifically, what we can learn about their inner structure and workings from InSAR observations of surface deformation. First, though, we address volcano deformation studies in general and what they can tell us about how volcanoes work.

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