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A Subduction Primer for Instructors of Introductory-Geology Courses and Authors of Introductory-Geology Textbooks

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ABSTRACT

We need to find better ways to explain subduction to students in introductory-geology classes. Students' grasp of plate tectonics and earth-system science depends on a basic understanding of this fundamental and unique earth process. Most subduction-zone models currently presented in introductory-geology texts are obsolete and inconsistent with modern understanding of the subduction process. A better model, which emphasizes the importance of lithospheric density and melting of the overlying mantle, is outlined here. Old lithosphere is relatively cold and thick and is denser than underlying asthenospheric mantle, whereas young lithosphere is warm and thin and is less dense than asthenosphere. Because of the density differences, old lithosphere subducts easily whereas young lithosphere does not, and subduction zones involving young lithosphere behave differently than those subducting old lithosphere. Conductive heating of the lithosphere in the subduction zone is slow compared to subduction rates, with the result that subduction zones define broad regions of unusually low temperature in the mantle. Subducting lithosphere drags the overlying mantle as it sinks, inducing convection in the sub-arc mantle. Melting of the subducted plate occurs only if very young crust is subducted. In the normal case, arc volcanism happens because water is sweated out of the subducted plate and rises into the overlying, convecting, warm mantle, where the addition of water greatly lowers the temperature of mantle melting.

Keywords: Education – geoscience; geology – teaching and curriculum; plate tectonics.

INTRODUCTION

The earth is a uniquely dynamic planet, with continuing interactions among planetary interior, hydrosphere, and atmosphere that occur in the context of moving lithospheric plates. Subduction is an essential part of this interaction because it provides the only means of recycling surface materials back into the deep mantle at the same time that it allows for the generation of new continental crust. For this reason, it is important that teachers and students understand how subduction zones work. From the perspective of mastering geoscience fundamentals, subduction is important not only because the process is essential for plate tectonics, but also because the processes and products of subduction are important to a wide range of human endeavors. Teaching well about subduction is also important from a heuristic perspective. Learning about subduction leads the student naturally to ask important questions about physics and chemistry, lines of inquiry that can motivate the student to care more about these fundamental sciences. Furthermore, genuine appreciation of subduction-zone processes can stimulate the student's curiosity and sense of wonder, improving the classroom environment for both student and teacher.

In spite of its importance, most introductory textbooks present the subduction process poorly. A simplified version of the "textbook paradigm" identifies the following three essential but erroneous themes: 1) mantle convection drags the plates, forcing them down subduction zones; 2) the mantle beneath the arc does not convect, and frictional heating of the subducting plate occurs as it grinds against this mantle. Frictional heating leads to 3) the generation of island-arc magmas by melting of the subducted crust. This model is attractive to instructors and students because it is plausible and simple, and has been clearly and consistently presented in introductory textbooks for the past two or three decades. Nevertheless, the textbook model does not reflect what we know about the forces driving the plates, the strength of the asthenosphere, coupling between subducted plate and the mantle beneath the arc, how the subducted plate is heated, and how arc magmas are generated. This essay is intended to provide a concise overview of our present understanding of how subduction zones operate; it is aimed at instructors of introductory-geology courses and authors of textbooks for such courses. Most of the following presentation comes from my efforts over the years to understand the scientific literature concerning subduction in the course of my own research in this field. The presentation purposely minimizes references in the text; a reference list is offered to help the interested reader delve deeper.

CHARACTERIZATION OF SUBDUCTION ZONES

Subduction zones are revealed by inclined zones of earthquakes which approximate the geometry of the subducted plate. These seismic zones are also known as "Wadati-Benioff Zones" after the geophysicists who first noted them. Deep-sea trenches define the boundary between two plates at a convergent plate boundary and mark where the subducting plate begins its descent beneath the overriding plate. Trenches are typically associated with a parallel line of arc volcanoes built about 130 km above the seismic zone; trenches and arc volcanoes are the two most

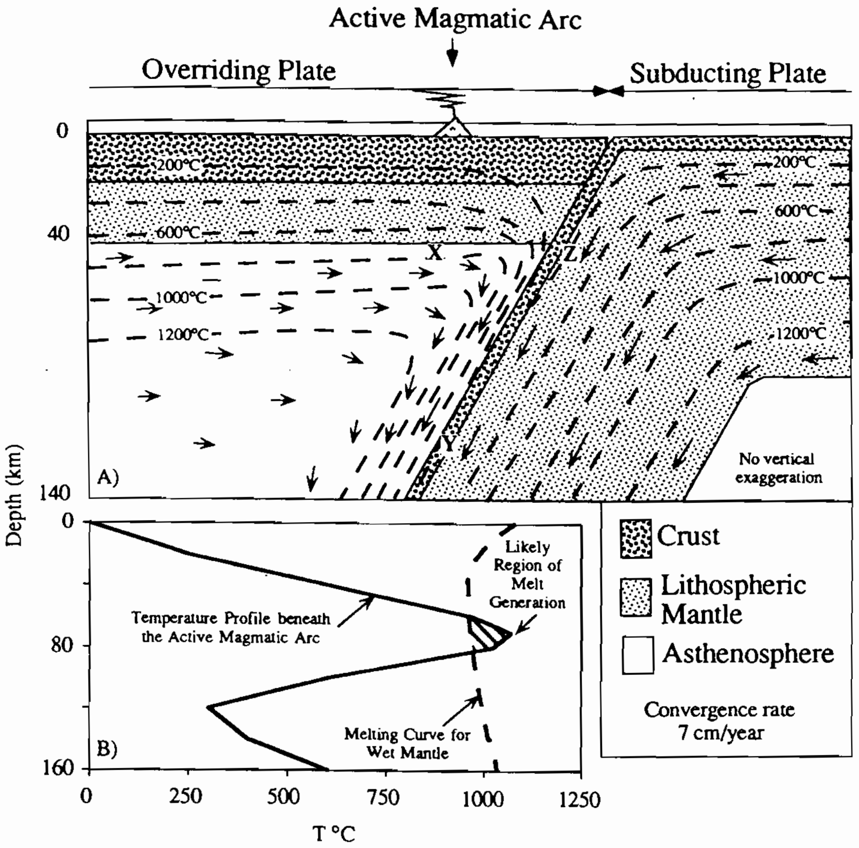

Figure 1. (A) Material movement (arrows) and temperature structure (dashed lines) of a simplified convergent margin, modified after finite element models of Davies and Stevenson (1992). Note that three physical components are shown: crust, mantle lithosphere, and asthenosphere. Crust and associated mantle lithosphere comprise the plate of plate tectonics, while asthenosphere is weak, warm, convecting mantle. Note that the crust and mantle lithosphere of the subducting plate move at a constant velocity, dragging the asthenosphere beneath the overriding plate with it. Note also that the isotherms remain approximately parallel with the original seafloor, even deep into the subduction zone. The mantle wedge, outlined by points X, Y, and Z, approximate the location of detail shown in Figure 5. (B) Temperature profile beneath the arc volcanoes (thick line) and melting curve for wet mantle (dashed line). Note that the temperature reaches a maximum at about 70 km depth, then decreases as the subducted lithosphere is approached, reaching a minimum at a depth of about 120 km. The temperature is high enough for mantle melting about 40 km above the subducted plate.

spectacular surface manifestations of subduction. These parallel features are associated with strong variations in the gravity field. The trench is associated with a strongly negative gravity anomaly, because the lithosphere is pulled down and the void is filled by water. A positive gravity anomaly lies near the line of arc volcanoes, due to the high-density subducted lithosphere in the subduction zone beneath the arc. The geologic – that is, crustal – entity that extends from the trench to the line of volcanoes is the "arc system." An arc system may include an accretionary prism (sediments scraped off the subducting plate), forearc crust, and the volcanic arc itself. The effects of subduction may be expressed farther from the trench than the volcanic arc, where back-arc sea-floor spreading or thrust faulting may occur, depending on conditions. The arc system, the underlying mantle "wedge," and the subducted plate make up the convergent plate margin.

Convergent margins are great earth "factories," where materials recycled from the surface are heated, squeezed, distilled, mixed with the surrounding mantle, and melted into new materials. Continental crust is the principal product, and it is turned out at a global rate of about one cubic kilometer per year. In addition to providing the ground beneath our feet, ancient convergent margins have produced most of the world's orebodies, and associated sedimentary basins contain important deposits of oil and gas. Earth's convergent-margin factories use and release tremendous amounts of energy, much of it catastrophically as earthquakes, tsunamis, and violent volcanic eruptions. There is continuous competition between subduction and sea-floor spreading. Sometimes and in some places spreading outpaces subduction, and the ocean basin widens; this is now the case for the Atlantic Ocean. Otherwise subduction outstrips spreading, closing the ocean basin and leading inevitably to collision between arcs or continents. Mountain ranges such as the Alps or Himalayas are the spectacular result of stopping the subduction factory.

Physics of Subduction

Davies and Stevenson (1992) carried out numerical experiments that provide the most recent and comprehensive treatment of subduction-zone processes, especially interactions among moving plates, mantle, fluids and melts. Theirs is a much more comprehensive treatment than needs to be presented to introductory students, but the reasoning is accessible and the principal conclusions are important. Figure 1 is adapted from their results, and it shows the most important aspects of subduction.

If students are to grasp subduction fundamentals, they must first understand the difference between lithosphere (strong and cool; the plate of plate tectonics) and asthenosphere (weak and warm; the substrate over which the plates move) on the one hand, and between crust and mantle parts of the lithosphere on the other. This is because the driving force for subduction (and for plate motion in general) resides mostly in the excess density of mantle lithosphere, but the to-be-recycled components reside mostly in the crust. Another way to put this is that to understand subduction's

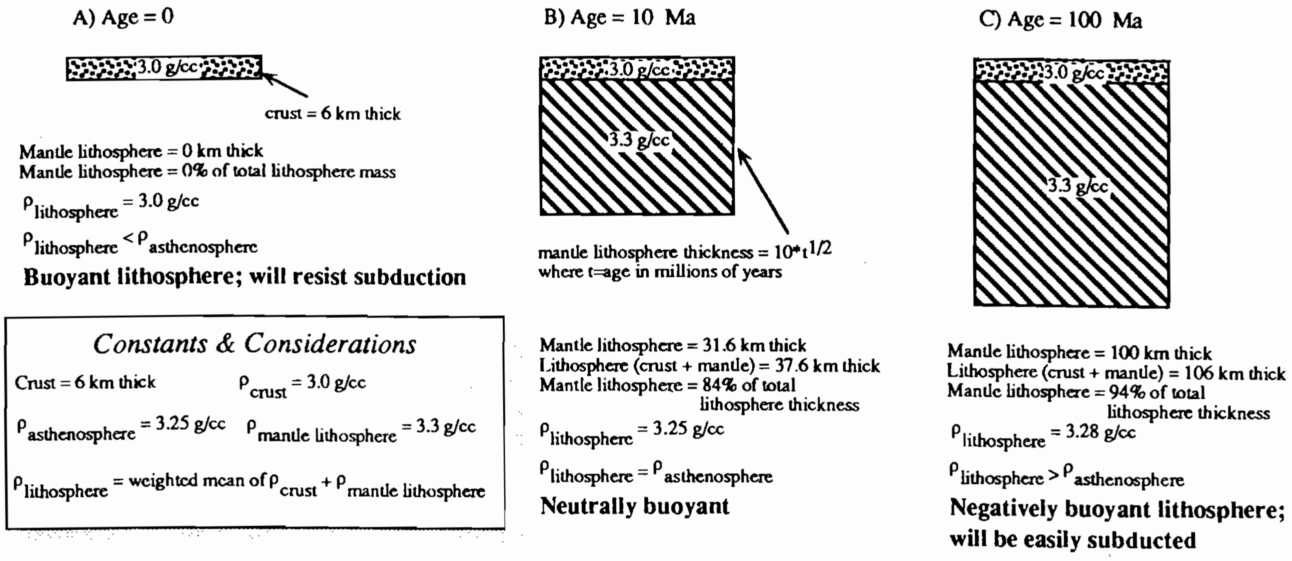

Figure 2. Diagramatic representation of how lithospheric thickness and density (ρ) increase with age. See text for further discussion.

physics we must focus on the mantle lithosphere, but to understand its chemistry we must focus on the crust and sediments.

Subduction is driven by the excess density of the lithosphere relative to the underlying asthenosphere, and this excess density first appears and increases continuously as plates age. Mantle lithosphere cools by conduction and thus thickens with age, in proportion to the square root of age as shown by the following equation.

Thickness (in km) = 10 x(age in 10^6 years)$^{1/2}$. (1)

This expression indicates that the thickness of oceanic lithosphere varies directly and simply with its age. While the thickness of the oceanic crust is constant at about 6 km and the thickness of sediments may vary from a few hundred to a few thousand meters, the great bulk of the subducted plate consists of mantle lithosphere.

It is essential to note that subduction results from the relatively greater density of the subducted plate relative to the underlying asthenosphere, and the greater the age of the subducted lithosphere, the greater its bulk density. This can be readily demonstrated to students by assuming densities for the crust, mantle lithosphere, and asthenosphere of $\rho_c = 3.0$ g/cc, $\rho_l = 3.3$ g/cc, and $\rho_a = 3.25$ g/cc, and the thickness of mantle lithosphere as a function of age discussed in the preceding paragraph. The precise numbers are not critical, but it is generally accepted in the scientific community that the crust is about 10% less dense than the mantle and that lithospheric mantle is 1 to 2% denser than asthenospheric mantle. Figure 2 shows how the lithosphere increases in density as it ages and the mantle portion thickens. It is important to recall that the thickness and density of oceanic crust do not change whereas the thickness of mantle lithosphere is constantly increasing as it ages and cools. Lithosphere is thin when it forms and consists of all or a very high proportion of oceanic crust, which is much less dense than the mantle (Figure 2A). As the lithosphere ages, it thickens and increases in density rapidly, so that after about 10 million years its density is similar to that of asthenospheric mantle (Figure 2B). After this time, lithosphere is denser than asthenosphere and will sink back into the mantle at the first opportunity. By the time the lithosphere is 100 million years old, it will have a bulk density of 3.28 g/cc (Figure 2C). Although this is only about 1% denser than the underlying asthenospheric mantle, any excess density of the lithosphere relative to the asthenosphere will allow sinking. The fact that old plates are easily subducted is best seen along the convergent margins of the Western Pacific, where Jurassic and Cretaceous sea-floor – some of the oldest in any ocean today – returns to the mantle. Evidence that this sinking is gravitationally favored – that is, denser lithosphere is exchanging places with more buoyant asthenosphere – can be found in the observation that such arcs have fewer earthquakes, steep subduction zones, and back-arc extension.

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Subducted lithosphere can be identified at depths greater than the deepest earthquakes. A new geophysical technique called seismic tomography allows three-dimensional mapping of relatively fast and slow regions in the mantle. Seismically slow regions are inferred to be hotter or even partially melted zones. Fast regions are interpreted to be relatively cold, revealing the down-dip extent of subducted lithosphere.

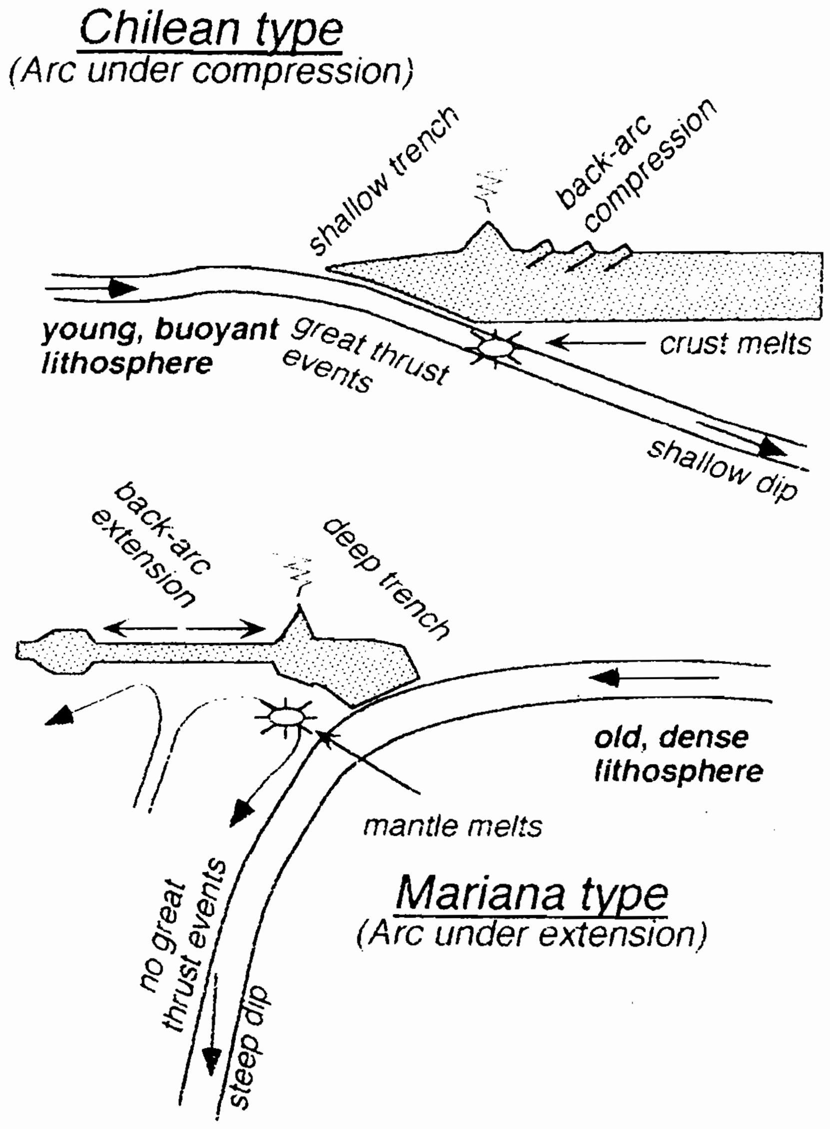

Figure 3. Endmember types of subduction zones, modified after Uyeda and Kanamori (1979). Chilean-type subduction zones subduct young, buoyant lithosphere, which resists subduction and results in a shallowly dipping seismic zone, shallow trench, great thrust earthquakes, and back-arc folding and thrust faulting. Young, warm crust may melt. Mariana-type subduction zones involve old, dense lithosphere, which readily sinks. Mariana-type subduction zones are characterized by a steeply dipping seismic zone, deep trench, absence of great thrust faults, and back-arc extension.

Some subducted lithospheres can be traced to depths of up to 1200 km, such as that beneath the Mariana arc. Other subducted lithospheres such as that beneath Japan do not appear to penetrate the 670-km discontinuity.

It should be appreciated that the motion of the plate in a subduction zone is not strictly down dip, that is, parallel to the seismic zone. Hamilton (1988, p. 1507) warns about "...the false assumption that a subducting plate rolls over a hinge and slides down a slot that is fixed in the mantle...." There is a significant vertical vector of sinking, so that subducting slabs sink more steeply than the dip of the Wadati-Benioff zone, and trenches retreat, or "roll back." Perhaps the best proof of this is the fact that the Pacific Ocean basin is becoming smaller; this would not be possible if trench rollback did not occur.

In contrast to the case of old sea-floor, young sea-floor is buoyant. As shown in Figure 2, until the lithosphere is older than about 10 million years it will be less dense than the underlying asthenosphere and will resist subduction. An example of this occurs in the subduction of Eastern Pacific sea-floor beneath South America, where violent earthquakes, flat subduction zones, and back-arc thrusting indicate that young lithosphere is resisting being returned to the mantle. Figure 3 shows the relationship between the age of subducted lithosphere and the style of the subduction zone, with "Chilean type" subduction zones involving young, buoyant lithosphere and "Mariana type" subduction zones involving old, dense lithosphere. It is important to point out that whereas the "Chilean type" subduction zone is reminiscent of the textbook paradigm, such a subduction zone is neither stable nor typical. Subduction of young lithosphere soon ends by intersection of spreading ridge and trench, which typically converts the convergent margin into a transform margin. In contrast, sliding and sinking of old lithosphere beneath "Mariana type" subduction zones is energetically stable and likely to continue indefinitely.

The Thermal Structure of Subduction Zones

Earth scientists still argue about definitions of lithosphere and asthenosphere, but all that introductory students need understand is that lithosphere is the outer portion of the earth that is heated and cooled by conduction whereas heat is transported through the asthenosphere by convection. This definition holds not only while the lithosphere is cooling and thickening on the sea-floor but also while it is being heated during subduction. Conduction is a very inefficient way to transmit heat, so subducted materials are heated to the temperature of the surrounding mantle only after tens to hundreds of millions of years. In the situation shown in Figure 1A, the subducted plate has a velocity of 7cm/year – typical for subduction zones – and will reach a depth directly beneath the line of

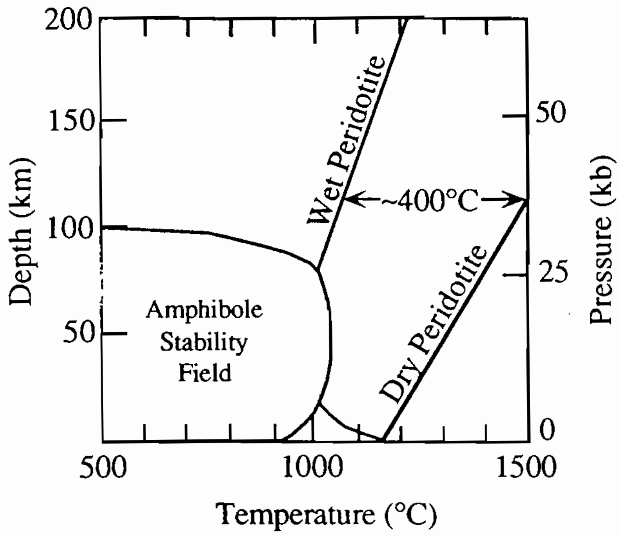

Figure 4: Simplified phase diagram for peridotite, modified after Wyllie (1979). Temperature is marked on the horizontal axis, while the vertical axis is marked both in depth and pressure (assuming pressure over this depth range in the earth rises at about 1 kilobar (1 kb) every 3 km). Curves labeled "Dry Peridotite" and "Wet Peridotite" indicate the minimum temperature when melting begins for anhydrous peridotite and peridotite that is saturated with water. Note that at depths of about 100 km, wet peridotite begins to melt at temperatures as much as 400°C cooler than dry peridotite. The shaded field labeled "Amphibole stability field" indicates the pressure and temperature range over which amphibole peridotite is stable. Amphiboles break down and release water at pressures greater than about 30 kb or temperatures greater than 1050°C.

arc volcanoes after only about 2 million years (note: 1mm/year = 1km/million years). This is far too little time for the subducted lithosphere to heat to the temperature of the ambient mantle, and most modern thermal models indicate that subducted lithosphere generally does not melt. Melting of subducted crust may occur when very young – and therefore hot – sea-floor is subducted (Defant and Drummond, 1990), but this is unusual. The unfortunate tendency of introductory-geology texts to show the subducted crust being melted beneath the arc volcano is a lamentable misrepresentation of our scienc"s understanding of this fundamental and distinctive earth process.

While the cold, subducted plate is slowly warmed by the ambient mantle, the mantle is also cooled. The result is that subduction zones involving an old descending plate are by far the coldest parts of Earth's interior. Support for this statement is found in the great depth of seismicity in subduction zones and by the results of seismic tomography discussed in the preceding section. The student may already have learned that earthquake foci are restricted to the outer, cold, and therefore brittle parts of the planet. In most tectonic settings, earthquake foci are found to depths of no more than 10 km, but in subduction zones foci extend to almost 700 km. This statement should puzzle the introductory student because subduction zones are associated with volcanoes. Two of the thoughtful student's logic trains can be expected to collide: 1) arc volcanoes require lava, which means that something must be hot enough to melt; however, 2) deep earthquakes and thermal considerations indicate that subduction zones are cold. How is melting possible? The teacher needs to be prepared to help the student understand and resolve this paradox, and *most introductory texts do not even recognize the problem, much less answer it.*

The key to understanding the puzzle can be found in Figure 1. The only thing that is set in motion in this model is the subducting plate, but this drags the asthenosphere below the overriding plate with it. It is essential that the student learn that mantle immediately adjacent to the descending plate is dragged with the plate deeper into the earth. Sinking material must be replaced by asthenospheric mantle from greater depth or distance from the trench. This results in "induced convection" beneath the arc, so named because it is caused by motion of the subducting plate. An important result of induced convection is that the asthenosphere beneath the overriding plate is not progressively chilled with time, as would be expected from simple conduction, but has a normal mantle temperature. The continuous replenishment of normal asthenospheric mantle beneath the arc is an essential part of understanding how island-arc magmatic systems are maintained without showing significant changes in magma composition or volume with time.

Generation of Arc Magmas

If the subducted plate doesn't melt, what does? The key can be gleaned from a simplified phase diagram for peridotite (Figure 4). The mantle, both asthenospheric and lithospheric, is composed of peridotite. As shown in Figure 1B, the maximum temperature directly beneath arc volcanoes occurs at a depth of about 80 km, or about 25 kbar. At this pressure, *wet* peridotite begins to melt at a much lower temperature (as much as 400°C lower) than *dry* peridotite. We know that arc magmas are much richer in water than magmas from any other tectonic setting, and that this water is ultimately derived from the subducted plate. If water can be delivered to the region of maximum temperature beneath arc volcanoes (the region labeled "Likely Region of Melt Generation" in Figure 1B), then melting will occur. How is water delivered from the subducting plate to this meltable mantle? Inspection of Figure 1A shows that at its closest the 1200°C isotherm is about 30 km from the subducted plate, and both the subducted plate and the adjacent mantle are moving downward and away from the "Likely Region of Melt Generation." Thus, the question of how arc magmas are generated depends on understanding how water gets from the subducted plate to the region of meltable mantle.

This part of the story is complex, as revealed by inspection of Figure 5 which shows detail in the mantle wedge (area X-Y-Z of Figure 1A). Subducted sediments and oceanic crust carry water into the subduction zone,

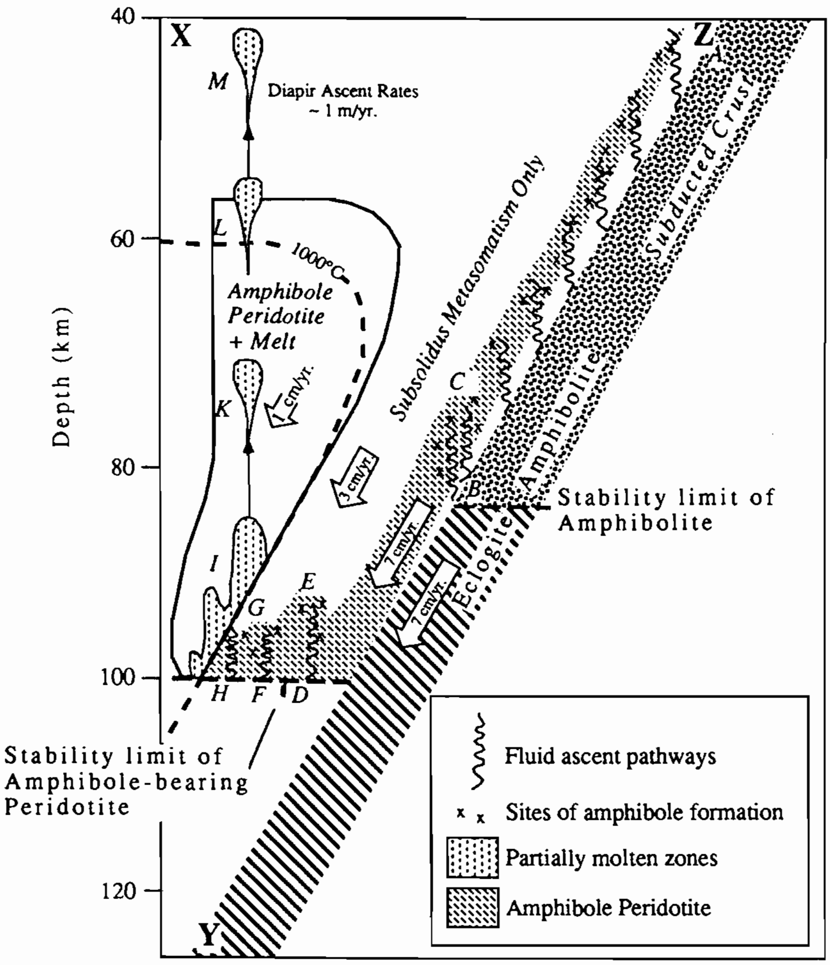

Figure 5. Detail of the mantle wedge (region of detail outlined as X, Y, and Z in Figure 1A). See text for further discussion.

and this water is continuously released as subduction proceeds. The release is initially due to squeezing shut of cracks and pore spaces, but mineral reactions become more important in controlling water release as pressures increase. Amphiboles are especially important for carrying water to great depths because they are stable over a wide temperature range to depths of about 100 km (Figure 4). Figure 5 shows water being continuously released from the subducted crust, and the water rises into the overlying mantle where it forms amphibole peridotite. Induced convection results in this mantle being dragged downwards with the subducted slab. Amphibolite (metamorphosed basalt) is stable to only about 80 km depth (B on Figure 5), where the amphibolite breaks down to form eclogite. This breakdown releases a large amount of water which rises into the mantle to form amphibole peridotite (C). This is carried down to the maximum depth of stability for amphibole peridotite, about 100 km, where it breaks down to anhydrous peridotite and water (D). Released water rises vertically; note that this carries the water away from the subducted slab and towards the likely region of melting. At some point the rising water reacts with the mantle to form amphibole peridotite again (E). This will be carried with the descending mantle until the amphibole peridotite stability limit is exceeded and water is again released (F). Amphibole peridotite forms again (G) and breaks down again (H). In this zig-zag fashion the water is carried laterally away from the subducted slab and into warmer parts of the mantle wedge.

The area inside the solid line in Figure 5 corresponds to that part of the mantle that will partially melt if sufficient water is provided, similar to the "Likely Region of Melt Generation" in Figure 1B. Above point H, the mantle is sufficiently hot that water added to it leads to partial melting (I). The mantle is still moving downward, so in order for melt to rise to the surface and erupt it must separate from the residual mantle. This may happen either by fracturing of the mantle, which allows melt to travel rapidly through channels (not shown in Figure 5), or by forming partially molten diapirs (K). Because these contain perhaps 10% melt, they are less dense than the surrounding mantle and can rise through it, at a rate of perhaps 1m/year (L). If they rise sufficiently fast, diapirs will change temperature only slightly, and the decrease in presure they experience during ascent may lead to further melting, so the diapir may be 30% melted when it arrives at the base of the lithosphere. At this point the magma separates from the unmelted part of the diapir and feeds the eruption of an arc volcano.

APPLICATIONS OF THE MODEL TO CONVERGENT MARGINS

It may be instructive to apply the outline of how subduction zones operate to a real subduction zone. As shown in Figure 3, there are two subduction-zone endmembers which are defined by the age of the subducting lithosphere. The Chilean-type is inherently unstable, not only because subduction of progressively younger lithosphere becomes increasingly difficult, but because at some point the ridge and trench will meet and the convergent margin will become a transform margin, as was the case for western North America during mid-Tertiary time. In contrast, Mariana-type subduction zones are stable because denser lithosphere sinks beneath less dense asthenosphere, and in this sense are the more "normal" type of subduction zone.

Figure 6 shows the Mariana convergent margin in true scale, with all of the important elements of the subduction-zone model presented here. This is a tectonic cartoon in

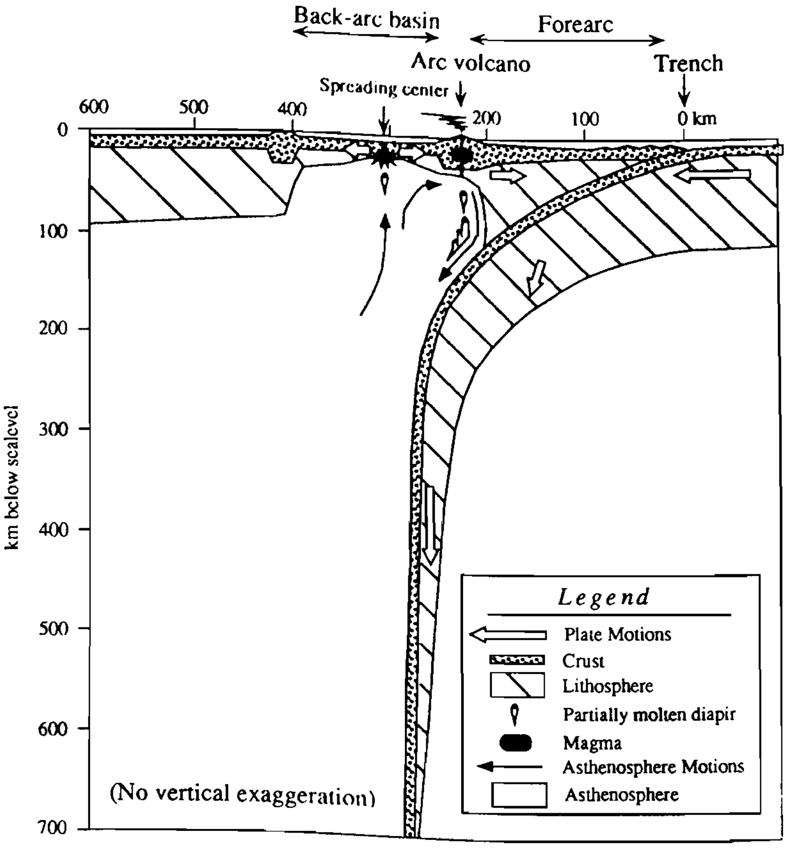

Figure 6. True-scale cross section of the Mariana convergent margin and subduction zone. This approximates an E-W section at about 18°N.

many respects. For example, whereas we know the thickness of the crust, we know very little about the thickness of the lithosphere. The very thick lithosphere beneath the forearc is consistent with observed low heat flow, and the nearly vertical boundary between asthenosphere and lithosphere beneath the arc is consistent with thermal models as well as with the requirement that melting occur where water from the subducted crust interacts with convecting asthenosphere. Similarly, we know that seismicity defines a subduction-zone geometry like that shown here, and that seismicity ends at about 700 km. The different behavior of the crust and mantle lithosphere in the subduction zone reflects the fact that the crust is a chemical entity whereas the mantle lithosphere is thermally defined. The plate slowly heats up as it is subducted, and the part that is mantle lithosphere thins whereas the crust portion does not. Note also that there is a back-arc-basin spreading center behind the line of arc volcanoes. This demonstrates that the entire arc system is being pulled apart as the slab sinks and the trench retreats, or "rolls back." The magmatic systems associated with the back-arc-basin spreading center and arc volcanoes are associated with different mantle flow regimes. Arc magmas must ascend through downwelling mantle, either as diapirs or as channelized flow, while back-arc-basin diapirs ascend with upwelling mantle.

In addition to showing differences between the textbook paradigm and the general model presented in this essay, the section shown in Figure 6 also differs from those shown in most introductory texts in displaying the essential elements of a convergent plate boundary in their true proportions.

IMPLICATIONS FOR STUDENTS' UNDERSTANDING OF PLATE TECTONICS

The ramifications of continuing to teach the textbook paradigm as opposed to the more modern model presented here extend beyond the issue of teaching introductory students how subduction zones work, particularly for continuing geology students. These students are likely to develop very different perspectives about what makes plates move depending on which model they intellectually assimilate. Students learning the textbook paradigm will sense that mantle convection drives the plates and conclude that this is sufficiently strong to force the plates down subduction zones even as they grind against each other to the point of melting. They are likely to conclude that the asthenosphere is strongly coupled to the lithosphere and that plate motions are determined by asthenospheric convection. In contrast, students learning the modern model will realize that the plates move because they are pulled by the weight of the lithosphere in subduction zones, much as the wet edge of a towel hanging over the edge of the bathtub can pull the towel down. They are likely to conclude that the asthenosphere is weakly coupled to the lithosphere and that plate motions are determined by the excess density of the lithosphere. Students learning the textbook paradigm will equate plate motion with excess interior heat of the earth, and conclude that plate tectonics must have been more vigorous in the Precambrian, when the earth was hotter. Students learning the modern model will appreciate that the plates move because the outer part of the earth has cooled enough to sink and wonder when the earth cooled sufficiently that plate tectonics could begin. Students learning the textbook paradigm may be baffled why a hot planet like Venus (in most physical respects, Earth's twin) does not have plate tectonics, while those learning the modern model will easily grasp that the hot Venusian exterior makes plate tectonics impossible. Most importantly, students who learn the modern model and go on to major in geology and on to graduate school will not have to be re-educated about the most important aspects of subduction.

CONCLUSIONS

Hopefully, this essay will stimulate further discussion about how best to first teach about subduction zones. We need to stimulate dialogue on this topic among research scientists, instructors of introductory-geology classes, and authors of introductory-geology textbooks. Many instructors and authors may be understandably reluctant to abandon the textbook paradigm, which has advantages of simplicity, consistency, and history, and they are only likely to do this if they can be convinced that the textbook paradigm is wrong. The model presented here may suffer from being more complicated than the textbook paradigm, and surely has errors of omission and commission. It surely also is a better depiction of our present understanding of the subduction process than the textbook paradigm, and it will improve with future tellings of the tale.

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REFERENCES

Alvarez, W., 1982, Geological evidence for the geographical pattern of mantle return flow and the driving mechanism of plate tectonics: Journal of Geophysical Research, v. 87, p. 6697-6710.

Anderson, D.L., 1995, Lithosphere, asthenosphere, and perisphere: Reviews of Geophysics, v. 33, p. 125-149.

Carlson, R.L., Hilde, T.W.C., and Uyeda, S., 1983, The driving mechanism of plate tectonics: Relation to age of the lithosphere at trenches.

Davies, G.F., 1992, On the emergence of plate tectonics: Geology, v. 20, p. 963-966.

Davies, G.F., and Richards, M.A., 1992, Mantle convection: Journal of Geology, v. 100, p. 151-206.

Davies, J.H., and Stevenson, D.J., 1992, Physical model of source region of subduction volcanics: Journal of Geophysical Research, v. 97, p. 2037-2070.

Defant, M.J., and Drummond, M.S., 1990, Derivation of some modern arc magmas by melting of young subducted lithosphere: Nature, v. 347, p. 662-665.

Forsyth, D., and Uyeda, S., 1979, On the relative importance of the driving forces of plate motion: Geophysical Journal of the Royal Astronomical Society, v. 43, p. 163-200.

Garfunkel, Z., Anderson, C.A., and Schubert, G., 1986, Mantle circulation and the lateral migration of subducted slabs: Journal of Geophysical Research, v. 91, p. 7205-7223.

Green II, H.W., and Houston, H., 1995, The mechanics of deep earthquakes: Annual Review of Earth and Planetary Sciences, v. 23, p. 169-213.

Hamilton, W., 1988, Plate tectonics and island arcs: Geological Society of America Bulletin, v. 100, p. 1503-1527.

Jarrard, R.D., 1986. Relations among subduction parameters: Reviews of Geophysics, v. 24, p. 217-284.

Lay, T. 1994, The fate of descending slabs: Annual Review of Earth and Planetary Sciences, v. 22, p. 33-61.

Lee, J., Stern, R.J., and Bloomer, S.H., 1995, Forty million years of magmatic evolution in the Mariana arc: The tephra glass record: Journal of Geophysical Research, v. 100, p. 17,671-17,687.

Molnar, P., and Atwater, T., 1978, Interarc spreading and Cordilleran tectonics as alternates related to the age of subducted oceanic lithosphere: Earth and Planetary Science Letters, v. 41, p. 330-340.

Peacock, S.M., 1990, Fluid processes in subduction zones: Science, v. 248, p. 329-337.

Plank, T., and Langmuir, C.H., 1988, An evaluation of the global variations in the major element chemistry of arc basalts: Earth and Planetary Science Letters, v. 90, p. 349-370.

Reymer, A., and Schubert, G., 1984, Phanerozoic addition rates to the continental crust and crustal growth: Tectonics, v. 3, p. 63-77.

Spiegelman, M., and McKenzie, D., 1987, Simple 2-D models for melt extraction at mid-ocean ridges and island arcs: Earth and Planetary Science Letters, v. 83, p. 137-152.

Stern, R.J., and Bloomer, S.H., 1992, Subduction zone infancy: Examples from the Eocene Izu-Bonin-Mariana and Jurassic California arcs: Geological Society of America Bulletin, v. 104, p. 1621-1636.

Tarney, J., and Jones, C.E., 1994, Trace element geochemistry of orogenic igneous rocks and crustal growth models: Journal of the Geological Society, London, v. 151, p. 855-868.

Uyeda, S., and Kanamori, H., 1979, Back-arc opening and the mode of subduction: Journal of Geophysical Research, v. 84, p. 1049-1061.

von Huene, R., and Scholl, D.W., 1993, The return of sialic material to the mantle indicated by terrigeneous material subducted at convergent margins: Tectonophysics, v. 219, p. 163-175.

Wyllie, P.J., 1979, Magmas and volatile components: American Mineralogist, v. 64, p. 469-500.

Zhao, D., Hasegawa, A., and Kanamori, H., 1994, Deep structure of Japan subduction zone as derived from local, regional, and teleseismic events: Journal of Geophysical Research, v. 99, p. 22,313-22,329.

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