A new animation of subduction zone processes developed for the undergraduate and community college audience

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ABSTRACT

Today’s undergraduate students are accustomed to animations as important to their learning. Complex geologic processes such as subduction are well suited to animation. In spite of this opportunity and need, high-quality animations of fundamental Earth processes are uncommon. We have produced a realistic animation of plate creation and destruction processes for the undergraduate audience. First steps focused on building a storyboard, which is a visual outline of scenes to be animated. Then we organized a team of geoscientists and animators to make the animation. Students generated a rough draft animation, which was polished by a professional animator. We also wrote a narrative that was keyed to the animation, with written "call outs" inserted when terms that may be unfamiliar to undergraduates were spoken. Concepts in the animation are explicitly linked to the scientific literature, with references intended to guide interested viewers to sources to learn more. After the animation and narration were completed, we focused on dissemination and assessment. The animation (“Plate Tectonics Basics 1”) was placed on YouTube and the Science Education Resource Center (SERC) portal, and a Japanese version was made. Presentations about the animation were given at the Geological Society of America (GSA) annual meeting and the American Geophysical Union (AGU) Fall meeting. Assessment focused on capturing student understandings before and after watching the animation. Three groups of students were assessed: community college students and lower- and upper-level students at a four-year university. Results of the assessment indicate that students at all levels improved their understanding of subduction zone processes after experiencing the animation, but that upper-level students showed the greatest improvement. More high-quality animations about important plate tectonic processes and additional research into the level of complexity for various student groups are required.

INTRODUCTION

We need improved methods for teaching fundamental plate tectonic processes, including subduction. A range of geoscientific efforts, including National Science Foundation (NSF) research initiatives, MARGINS and GEOPRISMS (http://geoprism.org), have advanced our understanding of subduction zone processes. However, communicating these exciting results to beginning and potential geoscientists—undergraduates and community college students—lags behind our scientific understanding. A wide range of instructional approaches are needed to reach this audience, and it is important to develop better animations of subduction zone processes. Below we describe (1) why geoscience animations are useful; (2) how we generated a high-quality animation about subduction that incorporated scientific advances; (3) how we made the animation available and informed our intended audience of its existence; and (4) how we evaluated its educational impact.

GEOSCIENCE ANIMATIONS AND LEARNING STYLES

People learn in different ways. When asked how best they learn, people talk about preferring one or more of several learning modes: by reading text versus looking at pictures or videos (visual) versus listening to explanations (audio) versus by doing something (kinesthetic learning). Students are best taught using multiple ways of presenting material (Pashler et al., 2008): lectures, readings, exercises, charts and graphs, and animations. It is particularly important to develop materials for visual learners because the tendency of educated people to prefer visual learning is accelerating. According to the Visual Teaching Alliance (http://visualteachingalliance.com), ~65% of the U.S. public are visual learners, but >80% of classroom education is oral or written. More visual materials need to be generated so these can become important components of effective teaching.

Consider a “visualization object” (VO), which is any representation constructed or selected by the instructor to aid understanding—that observers (students, in this case) examine with their eyes. A visualization object could be static or moving. Static VO’s include photographs, paintings, graphs, maps, cross sections, and cartoons; whereas, motion VO’s include computer simulations and animations (Phillips et al., 2010). Visualization objects foster understanding via first formation of an “introspective visualization,” which is a mental image in the mind of the viewer. This leads to development of an “interpretive visualization” in the observer’s mind, which extracts significant aspects from the introspective visualization and helps cognitively integrate new information into the viewer’s evolving understanding of the pertinent system components and processes (Braga et al., 2010). For many natural pro-
cesses, students already have interpretative visualizations, to which additional information from new introspective visualizations is added as students learn. Animations provide a torrent of VOs, only some of which may be incorporated into a student’s mental visualization of the process. There is much we need to learn about how animations might help students integrate complex natural processes, but animations are likely to have great potential for increasing student understanding.

Students now moving through our educational system comprise by far the most visually stimulated generation that we have ever taught. They have high expectations for the quality of educational animations and are mostly disappointed by what the geosciences have to offer, especially when compared with the remarkable animations of space exploration by the National Aeronautics and Space Administration (NASA). The need for high-quality animations is further highlighted by the fact that the most important Earth Science processes reflect complex processes with multiple components and multiple interacting physical, chemical, and biological processes occurring simultaneously. Many of these processes are hidden from direct examination, occurring beneath the sea or in sedimentary basins or deeper in Earth’s crust, mantle, and core. Scientists with expertise in a variety of specialties must collaborate to study these processes. For example, the National Science Foundation–funded GeoPRISMS initiative brings together geoscientists with a wide range of expertise: geochemistry, geophysics, mineralogy, mineral physics, experimental petrology, and geodynamic modeling. In order for these groups of experts to explain the significance of their work to geoscientists in other subdisciplines, community workshops periodically are convened. A good example is the 2015 GeoPRISMS Theoretical and Experimental Institute on Subduction Cycles and Deformation (http://geoprism.org/tei-scd-2015/) and the Subduction: Top-to-Bottom sessions organized for Fall 2016 AGU and Fall 2017 GSA annual meetings. These workshops encourage explanation of results and involve geoscientists at all levels from graduate students and postdocs to senior researchers.

We have been less successful sharing the results of our research with undergraduate students and instructors who know less about subduction zones than do geoscientists at the Ph.D. student level and above. Animations of key geoscientific processes that are firmly based on current science are a good way to reach this audience.

Part of the reason that we have not yet fully met the challenge of better explaining our advancing geoscientific understanding of subduction zones to the undergraduate classroom is that we do not have very good animations of this process. This largely is due to the fact that there are significant hurdles to developing better animations for the undergraduate audience. In the following section, we summarize these challenges and how we worked to overcome them to generate, distribute, and assess an animation of subduction zone processes. This animation is available on YouTube (https://www.youtube.com/watch?v=6wJBOK8xjto) and is included here as Supplemental Item 1. Our hope is that knowing about our experiences will encourage others in this effort and lead to better strategies for generating the fundamental Earth processes animations that we need to improve our teaching.

### HOW WE MADE ‘PLATE TECTONICS BASICS’

Below we briefly describe the steps that we took to make the animation “Plate Tectonics Basics.” We discuss motivations, how the storyboard was put together, how we got the resources to generate the animation, how we generated a rough draft, how we generated a final version, and finally, how we assessed and disseminated the animation.

#### A. Motivation

The first author has studied subduction zones and their products for most of his academic career, beginning with a first visit to the Mariana arc system in 1976. Since then, these studies have continued and evolved, with many research cruises to study the backarc basin, the magmatic arc, the forearc, and the trench. Involvement in NSF programs MARGINS and GeoPRISMS exposed him to the ways that other geoscientists think about subduction zones. The Mariana arc system is an excellent example of a convergent plate margin, and it is not surprising that the generalized sketch of a convergent plate margin and shallow subduction zone shown in Figure 1 is very much like the Mariana convergent plate margin. Beyond these research interests, the first author has taught graduate Tectonics and undergraduate Igneous and Metamorphic Petrology for more than three decades. Both courses require that students understand how subduction zones operate, and the internet has been searched for high-quality animations ever since this was possible, with limited success. It is our opinion that existing animations of subduction zone processes are not very good in terms of scientific content or artistic quality. This interest and disappointment provided the motivation for the project.

#### B. Storyboard

The first step in building a subduction zone animation is to generate a storyboard that captures the critical processes. A storyboard is a graphic organizer in the form of illustrations and images displayed in sequence for the purpose of pre-visualizing a motion picture or animation sequence (Wikipedia). The storyboard was also needed in order to write a proposal to NSF to obtain the research funds needed for this effort. Geoscientists generally lack the technical skill to put together a quality animation (although this may change as technically proficient younger people reach leadership positions); therefore, funds from NSF or other funding agencies are needed. For a proposal to NSF (or any other funding agency), it is not adequate to assert that an animation of subduction zone processes is needed. A plan for how to do this is also required; and a storyboard is that plan. Figure 2 is the storyboard that was generated for the subduction zone animation (details can perhaps be better seen in Figs. 2A–2E). There are several sections, numbered 1–6 in Figure 2; in a general way, these sections track processes from the surface down into the subduction zone.
zone, then back up toward the surface via fluid and melt migration. Section 1 (Fig. 2A) summarizes how the material that drives subduction and feeds the process—oceanic lithosphere, sediments, and younger volcanics—is created and modified. Section 2 (Fig. 2B) summarizes what happens in the shallow subduction zone as the oceanic plate bends and breaks and begins to descend. Section 3 (Fig. 2C) drives home the point that subduction zones inject cold, wet materials into hotter ambient mantle and are responsible for earthquakes that reach much deeper than anywhere else in the Earth. Sections 4 and 5 (Fig. 2D) go deeper into the subduction zone, where oceanic crust is metamorphosed, first to blueschist and then to eclogite, driving water off the subducting slab. Interactions with the overlying asthenosphere are highlighted as well at this stage. Finally, section 6 (Fig. 2E) outlines how melts are generated. One panel explores the controversy about how hydrous fluids and sediment melts are transported, whether by diapirs or by channelized flow upwards through convecting mantle to where melts are generated, near the top of the mantle wedge; it then shows that such melts must traverse the crust, which they may interact with before melts erupt.

Each of the 23 scenes in the storyboard (panels a–w [Figs. 2A–2E]) is firmly based in the results of scientific studies published in the peer-reviewed geoscientific literature, which are summarized in the following paragraphs.

Panel a (Fig. 2A) shows the two main types of plate tectonic boundaries, divergent and convergent, within the context of the upper parts of a subduction zone, location of magmatic arc, forearc, and backarc tectonic realms, as well as the distribution of cold (crust and lithosphere) versus hot (asthenosphere and deeper) realms of the solid Earth; this section draws heavily from Stern (2002). Subducted lithosphere continues to greater depth and may either stagnate above the 670 km discontinuity or pass unimpeded through it (Fukao et al., 2009); these deep parts are not shown in the animation, which focuses on processes in the upper 200–300 km.

Panel b (Fig. 2A) shows the birthplace of lithosphere and oceanic crust at a mid-ocean ridge spreading center (Solomon and Toomey, 1992). It also shows where much water is fixed in the oceanic crust by hydrothermal circulation (Elderfield and Schultz, 1996). Only magmatic spreading is shown in panel b; however, there are also significant segments of especially slow-spreading ridges that are amagmatic. Amagmatic spreading ridges typically expose serpentinitized peridotites exhumed by giant core complexes (Sauter et al., 2004), although even these are associated with localized intrusions and flows (Miranda and Dilek, 2010). Magmatic oceanic crust is ~6–7 km thick. The mantle lithosphere beneath old (>50 Ma) oceanic crust is typically ~100 km thick. Hydrothermal activity at mid-ocean ridges alters oceanic crust to greenschist facies, converting anhydrous igneous minerals into water-rich chlorite and amphibole. This crust is metamorphosed in the subduction zone.

Panel c (Fig. 2A) captures the fact that seafloor will accumulate sediments as a function of time, latitude, water depth, and proximity to continents. It is difficult to generalize about pelagic sedimentation, because there is so much variation due to deposition above and below the carbonate compensation depth, in regions of high versus low surface productivity, beneath cold seas, and seasonal productivity versus tropical seas with little seasonal variation. Pelagic sedimentation rates vary from a few to several microns/year, equivalent to that many meters per m.y. As a segment of the seafloor approaches a continental arc, sediment sources change to more silicate detritus (especially if the filling is filled with sediment such as the Cascadia margin) and sediment rates increase greatly. Observed variability in sedimentary sections above oceanic lithosphere is summarized in Plank and Langmuir (1998).
Subduction Storyboard for Animation

1. What happens before the subduction zone? Ocean Basin Processes

2. First (shallow) subduction zone processes

3. Subduction injects cold material into the mantle and causes hot mantle to flow with it

4. Some detail on the Subduction Zone

5. Cooling Subducted Sediment & Crust

6. The addition of water from the subducted slab lowers the melting temperature of mantle rocks. The volcanic Front (VF) marks the boundary between cold mantle beneath the forearc (too cold to melt, even with water) and mantle further from the trench that is hot enough to melt when water is added.

Figure 2. Storyboard developed for “Plate Tectonics Basics 1.” To view the figure and its sections at full size, please visit http://doi.org/10.1130/GES01360.S2.
Panel d (Fig. 2A) shows how off-ridge (intraplate) volcanoes can further modify the oceanic plate. Unfortunately, a solid review of global off-ridge volcanism, slumping, and volcaniclastics has yet to be written. Regardless, it is well known that off-ridge igneous activity creates volcanic islands and atolls, oceanic plateaus, and seamount chains. These are especially common in the western Pacific south of 30°N. There are also long Cenozoic seamount chains around vigorous hotspots such as Hawaii, Reunion, and the Galapagos. Associated volcanicslastics and slump deposits extend the influence of off-ridge volcanism away from the volcano itself. Erupted materials include both tholeiitic and alkaline basalt compositions. Subduction of alkali materials may result in eruption of enriched arc magmas (Staudigel et al., 2010). Details of panels a–d are shown in Figure 2A.

The three layers of the subducted plate as captured in panels b–d (Fig. 2A) contribute in important but different ways to subduction zone processes. The mantle lithosphere, which makes up ~95% of the subducting plate, provides the density excess that drives both slab subduction and induced convection in the mantle wedge. The oceanic crust supplies most of the water in the subduction zone. The sediments supply most of the trace elements that give arc magmas their distinctive geochemical fingerprint.

Panel e (Fig. 2B) focuses attention on shallow subduction zone processes, on the outer trench high and in the seismogenic zone. The outer trench high is where the oceanic plate begins to respond to forces in the subduction zone. As panel f (Fig. 2B) shows, the plate here is flexed upward by a few hundred meters before descending into the trench and then into the subduction zone (Levitt and Sandwell, 1995). This flexure results in normal faulting of the lithosphere (and associated outer rise earthquakes) as the plate bends downward to descend into the subduction zone (Lefeldt and Grevermeyer, 2008), thus causing extensional faulting and earthquakes capable of producing tsunami. One such tsunami devastated Samoa and northern Tonga in September 2009; it was caused by magnitude 8 extensional faulting on the outer high of the Tonga Trench (Beavan et al., 2010). This deep faulting allows seawater to penetrate deep (>20 km) into the mantle lithosphere of the subducted plate, turning fresh, strong peridotite into hydrous, weak serpentinite (Faccenda et al., 2009). Panel h (Fig. 2B) summarizes the relationship between peridotite and serpentinite, a key concept that lower-level students may not understand. In contrast to strong, dry mantle peridotite, serpentinite is weak and holds a lot of water. Both peridotite and serpentinite are important for the operation of subduction zones (Reynard, 2013).

Panel g (Fig. 2B) summarizes the three different manifestations of “first contact” between the incoming oceanic plate and the overriding plate. If there are thick (>500 m) sediments on the incoming plate, then these are likely to be “bulldozed” off and accreted to the inner trench wall to form an accretionary prism (Clift and Vanucci, 2004), as shown in subpanel A in panel g (Fig. 2B). Some sediments can be partially subducted and accreted to the base of the overriding plate in a process called “subcretion” (Calvert et al., 2003). If there are thin (<500 m) sediments on the incoming plate, then all sediments will be subducted, and the forearc is likely to oversteepen to be tectonically eroded. Oversteepening leads to mass wasting, with the debris delivered to the trench where it is removed by subduction. These linked processes of oversteepening, mass wasting, and subduction removal are called tectonic erosion or subduction erosion (von Huene and Scholl, 1991; subpanel A in panel g (Fig. 2B)). The arrival of seamounts at the trench and their attempted subduction is likely to accelerate tectonic erosion (Ranero and von Huene, 2000). It is also important to note that much water is lost very shallow in the subduction zone, as a result of closing cracks and pores and by diagenetic changes such as conversion of Opal A to Opal C/T (Kastner et al., 1977) and illite to smectite (Huang et al., 1993). These shallow dewatering processes are not shown on the storyboard. Details of panels e–h are shown in Figure 2B.

Panel i (Fig. 2C) summaries the thermal structure of a subduction zone, which is dominated by the injection of cold lithosphere deep into the upper mantle, as has most recently been examined by combined geodynamic and thermal modeling (Syracuse et al., 2010). The characteristic control on slab thermal structure is captured by the “thermal parameter,” which is essentially lithospheric age multiplied by the convergence velocity (Molnar et al., 1979). Injection of cold lithosphere and its slow warming by conduction ensures that the brittle-ductile transition—which is approximated by the 600 °C iso-therm—is pulled far down the subduction zone. This means that earthquakes can occur at far greater depths than is seen elsewhere in the solid Earth, as discussed below.

Panel j (Fig. 2C) presents earthquakes in subduction zones, which define the Wadati-Benioff inclined seismic zone. Subduction zone earthquakes occur as deep as 670 km, much deeper than for any other tectonic setting. These can be subdivided into shallow (<100 km), intermediate (100–300 km), and deep (>300 km) earthquakes. Shallow earthquakes are the most damaging, especially the megathrust earthquakes in the seismogenic zone (panel k [Fig. 2C]). Intermediate depth earthquakes are thought to be associated with prograde metamorphism of oceanic crust (Jung et al., 2004). An interesting feature of intermediate depth earthquakes (not shown on the storyboard) is that they often define two subparallel planes, the upper one related to metamorphic transitions in the upper crust and the lower one reflecting deserpentinization reactions (Peacock, 2001). Water is released by several phase transitions in the oceanic crust and in the serpentinized upper mantle. Released water escapes upwards along the normal faults that originally formed at the outer trench rise (Garth and Rietbrock, 2014). Deep earthquakes are thought to reflect massive phase transformation, from olivine to spinel structure, a reaction that is kinetically retarded in the cold slab (Kirby et al., 1998).

Panel k (Fig. 2C) captures two of the greatest hazards posed by subduction zones—giant megathrust earthquakes and the tsunamis generated by them. Nearly all of the strongest earthquakes (magnitude 8.5 and greater) occur along what is known as the seismogenic zone (Hyndman et al., 1997). The seismogenic zone marks the interface between the two plates, beginning as shallow as 10 km and extending as deep as 50 km. Earthquakes in the seismogenic zone result when there is sudden slip between the two plates. Seismogenic zone earthquakes can be extremely energetic because it is possible to
The effects of the tsunami, which inundated 400 km² of Japan’s coastline, with up to 1.2 m of subsidence along the coast (Ozawa et al., 2011), compounding at the coastline and 50 m of horizontal motion at the trench (Kodaira et al., 2011). Another aspect of fluids in subduction zones that is not captured by the panels is that a water-melt critical point occurs at ~2–3 GPa (Zheng and Hermann, 2014), and this is likely to affect the chemical elements that are transferred from the downgoing plate into the mantle wedge.

Panel q (Fig. 2D) highlights the effects of subduction on the mantle wedge. The mantle wedge varies in temperature. At shallow depths (<80 km deep), the water flux serpentinizes the cool forearc mantle (Hyndman and Peacock, 2005); this mantle is weak and buoyant and mostly is not dragged down with the sinking plate. At depths greater than ~80 km, the downgoing slab begins to interact with much warmer asthenospheric mantle (Wada and Wang, 2009). Sinking lithosphere drags the adjacent asthenosphere of the overlying mantle wedge downward with it, inducing mantle convection (Kelemen et al., 2003). The top of the subducted plate—sediments and mélangé carried down with the plate—is strongly heated by the convecting asthenosphere, sometimes causing sediments and mélangé to melt (Plank, 2005), although supercritical fluids may also be important. Panel r (Fig. 2D) emphasizes that with increasing temperature, serpentine will dehydrate to reform peridotite. Details of panels m–r are shown in Figure 2D.

Panel s (Fig. 2E) summarizes how magmas form above subduction zones. The “volcanic front” on the surface approximates the surface projection of the vertical boundary between cold mantle beneath the forearc (too cold to melt, even with water) and mantle farther from the trench that is hot enough to melt if hydrous fluids are added. Panel t (Fig. 2E) shows that the volcanic front has a strong geometric relationship with the downgoing slab, it lies 70–170 km above it, with a mean distance above the subducted slab of 105 km (Syracuse and Abers, 2006).

Panel u (Fig. 2E) explores the controversy of how fluids and melts generated below the subduction interface rise through the downward convecting mantle to the zone of melt generation. We do not know how these fluids and melts manage to rise and reach the region near the top of the mantle where melting occurs. It could happen by fluids flowing up vertical channels through the mantle wedge (Cagnioncle et al., 2007) or by diapirs of low-density serpentinite and other materials rising like balloons from the base of the mantle wedge (Hall and Kincaid, 2001). However it is accomplished, addition of water to shallow asthenosphere causes melting and forms basaltic melt, which rises to the surface and erupts.

Panels v and w (Fig. 2E) make the final point that the mantle melts to make basalt but that many arc volcanoes erupt more felsic lavas. Modification of mantle-derived magmas in the crust is an important part of any arc magmatic system and may occur as a result of fractional crystallization or by remelting the crust. The combination of high water contents from subducted materials

Stern et al. | Subduction zone animation
and silica-rich magmas as a result of crustal interactions results in the most explosive eruptions of our planet (Stern et al., 2016). Details of panels s-w are shown in Figure 2E.

The expert subductologist will immediately note that much detail and nuance are omitted for the sake of simplicity and brevity. For example, there is no mention of slab windows or slab melting, oblique convergence, behavior of sediments in subduction zones, or backarc basins, or subduction initiation, to mention only a few of the omissions. The target audience of lower-level undergraduates and community college students should be kept in mind. Teaching and inspiring this audience requires clarity and simplicity; the desired product was an animation that lasts 5–10 min and minimizes terminology in favor of building student appreciation of processes. With this goal in mind, it was not possible for the final animation to cover all of the topics in the storyboard, much less explore other complications and nuances. Regardless, the storyboard and the above documentation provide a firm scientific basis for the animation. In addition, the storyboard can be easily modified for other purposes.

C. Building the Animation

After the storyboard was put together, we began work on the animation. This required matching the scientific expertise and motivation needed to identify the geoscientific processes to be explained and to craft the storyboard with the technical expertise needed to bring the animation to life. The traditional professor-postdoc-grad student-undergraduate student “vertical structure” of modern science does not lend itself to developing such teams within Geoscience departments; the team must be developed outside the traditions of our science. To that end, two talented undergraduate students were recruited from majors in the School of Arts, Technology, and Emerging Communications (ATEC) at UTD (http://www.utdallas.edu/atec). Geoscientists Stern and Lieu met weekly through April 2015 with the two undergraduates to create a draft animation and, at the same time, develop the accompanying narration.

We began creating the animation by breaking it down into smaller, more manageable steps. The UTD ATEC animation students provided a fast way to explore different animation vignettes that we could iteratively study, critique, and improve. We assigned small animation problems weekly for undergraduates, A. Manthey and A. Ward, and reviewed them together. Their solutions usually differed somewhat. We ultimately used Manthey’s hand-drawn, color-keyed illustrations for the animation. For this reason we are limited to using fluid flow effect (as in water) with “blobs” of solid was optimal. It should be noted that this process (mantle flow) is not directly observable; therefore, depicting it must be partially accomplished artistically. Of course, geoscientific understanding should not be violated (for example, showing rigid lithosphere moving over low-viscosity fluid asthenosphere); but the animation should not be bound by adhering to formal mathematical modeling because our aim is to convey fundamental concepts to undergraduates. Windler developed an algorithm that produces streams of translucent, rotating-in-place blobs, confined to travel in a pre-defined path (e.g., oceanic crust bending into the deep mantle) to produce the desired effect. Application of color overlays was also found to better differentiate the various layers (crust and upper and lower mantle) and is used throughout the animation.

It became very clear early in this process that it would not be possible to animate the entire storyboard. There are 23 panels, and if each took 5 min on average to explain, the animation would last almost 2 h. The storyboard does lend itself to being expanded upon and produced as a documentary-length video, perhaps alternating between animations and field visits (e.g., Catalina schist, Andean and submarine arc volcanoes, Oman ophiolite, Sierra Nevada batholith, etc.); however, such an effort would require investments of time, money, and expertise that are far beyond what we could successfully undertake. We instead aimed to produce a 5–10 min animation, requiring further culling of the topics covered. We consider this length to be optimal in terms of matching our ability and resources to students’ attention spans. We also recognized the need to add introductory material in the form of basic information about plate tectonics, including a short description of the types of plate boundaries. We also needed to explain lithosphere and asthenosphere as well as where and how lithosphere is created. It also was useful to show a real place on Earth where lithosphere was created and destroyed; we chose the Pacific–South American margin. The animation we developed lasts 8 min and 43 seconds and is included as Supplemental Item 1 (see footnote 1). It is accompanied by a narration of 1001 words (Supplemental Item 2).

The animation begins by looking down at Earth from space, with clouds, oceans, and continents of this region (Fig. 3A). The clouds and water are
Figure 3. Screenshots of important elements of "Plate Tectonics Basics 1" animation. See text for further explanation.
removed, and we look down at Earth’s solid surface, with the Nazca plate in the center of the scene (Fig. 3B). Next, the plate boundaries in this region are shown. First, divergent plate boundaries are highlighted, along with relative plate motions. The location of the subduction zone and the trench is shown (Fig. 3C). After important surface features are shown, a rectangular slice is cut out of the Earth and lifted to display a cross section down to ~600 km depth, emphasizing both compositional (crust and mantle) and rheological (lithosphere and asthenosphere) layers (Fig. 3D). The perspective moves farther back to show the entire system, then zooms back into the mid-ocean ridge section to show how plate separation leads to asthenospheric upwelling and decompression melting (Fig. 3E). The concept of two-phase flow is explained (Fig. 3F), and the resultant magmas form the basaltic oceanic crust. How these processes relate to seafloor spreading is explained (Fig. 3G), as is the relationship between lithosphere and the plate of plate tectonics (Fig. 3H). The hydration of oceanic crust at the ridge axis is briefly mentioned, including a short video clip of a deep-sea hydrothermal vent (Fig. 3I).

The perspective then follows the section to the convergent plate boundary, and the upper 250 km of its manifestation at depth—the subduction zone—is shown (Fig. 3J). Shallow earthquakes of the seismogenic zone are animated (Fig. 3K), as is the relationship of the sinking lithosphere at greater depth to the asthenospheric counterflow it induces (Fig. 3L). Water released from the subducted oceanic crust is illustrated, and at greater depths, sediment melts (Fig. 3M). The region of melt generation near the top of the circulating asthenosphere is shown, and the concept of flux melting is explained (Fig. 3N). The perspective then zooms in to show igneous processes in the continental crust and how surface volcanoes relate to the igneous processes at depth (Fig. 3O). Mafic magma produced by melting in the mantle wedge is shown pooling at the base of the crust, which causes melting of the crust to produce granite magma; magma chambers (Fig. 3P) and diapirs (Fig. 3Q) rising through the crust to form plutons are also animated. The animation then segues to a sped-up video of Yosemite Valley in California, which spectacularly exposes granitic plutons that have been exposed by glacial erosion (Fig. 3R). It closes by moving farther away from the Earth slice and lifting the slice out so that convection in the mantle down to the core is shown (Fig. 3S). The slice is put back into the Earth, and the oceans and atmosphere are shown again. Final comments about the possibility of plate tectonics on other planets are made, and then the credits are shown (Fig. 3T).

### DISSEMINATION

A key part of building a geoscience animation is to let the intended audience know that it exists and how to access it. We are making our animation available through textbook publishers, the Science Education Resource Center (SERC) and the internet via YouTube. The animation will be used as a supplement for McGraw-Hill textbooks in oceanography, physical geology, Earth science, geography, historical geology, natural hazards, and natural resources; this publisher is considering using snippets of the animation to illustrate particular processes. Other textbook authors and publishers are welcome to use it. The animation and assessment materials are also available on the SERC “On the Cutting Edge” Teaching Geophysics in the 21st Century (http://serc.carleton.edu/NAGTWorkshops/geophysics/activities/121556.html).

The animation in Supplemental Item 1 (see footnote 1) is also posted on YouTube and can be viewed at https://www.youtube.com/watch?v=6wJB0k9jxjo. YouTube provides an easy way to track views of the animation (via “statistics”) and also viewer feedback; but still there must be an effort to “spread the word” about the animation. Presentations about the animation were given at the GSA annual meeting (Stern et al., 2015a) and the Fall AGU meeting (Stern et al., 2015b). How these and other talks affected community knowledge of the animation is reflected in the statistics of views on YouTube as of January 2017 (Fig. 4). Figure 4 shows that dissemination was more successful at GSA than at AGU, most likely because of a blog entry during the GSA meeting by Justin Samuel (https://geosociety.wordpress.com/2015/11/03/new-animation-of-subduction-zone-processes-developed-for-the-undergraduate-and-2yc-audience/). There were several bloggers covering the Fall AGU meeting, but we were not able to attract any to blog about the animation. Clearly, a strategy for dissemination is important to the success of any animation effort.

A Japanese-language version was released in April 2016 (https://www.youtube.com/watch?v=frrz-4dwGc). As of mid-January 2017, the site had been viewed 4525 times.

### ASSESSMENT

Geoscientific processes are well suited for capturing students’ mental representations via sketching (Jee et al., 2014), and sketching is an efficient and authentic means of assessment (Johnson and Reynolds, 2005). Within the context of visualization discussed in the introduction, student sketches capture their interpretive visualizations at the time of sketching. The following simple assessment exercise was designed for students viewing “Plate Tectonics Basics 1,” and the results are shown in Table 1 and Figures 5 and 6. The animation is most useful as part of normal classroom presentation of plate tectonics. After the students have read about plate tectonics and the topic has been presented in lecture, ~30 min of class time should be set aside for “Plate Tectonics Basics 1,” and the results are shown in Table 1 and Figures 5 and 6. The animation is most useful as part of normal classroom presentation of plate tectonics. After the students have read about plate tectonics and the topic has been presented in lecture, ~30 min of class time should be set aside for “Plate Tectonics Basics 1” viewing and assessment. Before the class watches and listens to the animation, students are asked to make one sketch at each of divergent (mid-ocean ridge) and convergent (subduction zone) plate boundaries, using pencils on the gridted and scaled template shown in Figure 5. These “pre-viewing” sketches should be done on the upper spaces on the template. Pre-viewing sketches also usefully assess student understanding of normal classroom presentation of plate tectonics. Five minutes should be allowed for each sketch. The class then watches and listens to the animation and sketches the two sections a second time, again taking 5 min each.
Student sketches are scored according to a four-point scale for divergent plate margins (left-hand sketches) and a six-point scale for convergent plate margins and subduction zones (right-hand sketches); thus, there are a total of ten points for the pairs of pre- and post-viewing sketches. Points are allocated for all sketches by assigning one point for each of four key conceptualizations (fractional points can be given where appropriate).

1. For both divergent margin and convergent margin sketches:
   a. Scale and proportionality: Does the student show features as they should appear in terms of their relative size and location? Does the student show the Earth’s solid surface near 0 km?
   b. Crust and lithosphere: Does the student clearly distinguish between crust and mantle lithosphere? Is lithosphere shown thinning toward the spreading axis?
   c. Lithosphere and asthenosphere: Does the student distinguish between mantle lithosphere and asthenosphere?
   d. Mantle flow and melting: Does the student accurately depict overall flow of lithosphere and asthenosphere? Does the student show where magmas are generated?

2. Two additional points are scored for convergent margin and/or subduction zone (right-hand sketches) only:
   a. Fluids and sediment melts from subduction zone: Does the student show fluids released from subducted slab rising into overlying mantle?
   b. Magma-crust interactions: Does the student show magma interacting with crust beneath volcano?

For each category above, fractional points can be scored as well.

Student sketches show significant differences in detail and accuracy, as captured by representative “before and after” sketches shown in Figure 6. In general, higher-level students show more accurate and detailed sketches than do lower-level students, in both before and after sketches. This indicates that students’ development of interpretive visualization improves as their undergraduate education progresses.

Sketches are collected and are folded so that the “before” and “after” sketches are scored independently, thus minimizing the influence between the pairs of sketches. We are interested in how these scores change from sketches done before viewing to those done after viewing; this difference (change score)
Draw cross-sections for divergent and convergent plate margins down to 200 km depth
5 minutes for each sketch (10 minutes before viewing, 10 minutes after viewing)

Before viewing animation
"Plate Tectonics Basics 1"

After viewing animation
"Plate Tectonics Basics 1"

Figure 5. Template for student sketches. Students should sketch convergent and divergent margins before and after watching and listening to animation.
Before viewing                         After viewing

Figure 6. Representative “before and after” sketches for three groups of classes with different knowledge bases. Note that only the convergent margin sketches are shown because of space limitations. UTD—University of Texas at Dallas.
captures any short-term gain in understanding. Even with the above scoring rubric, assignment of points is somewhat objective, and it is useful to determine how the change scores of independent graders compare. Figures 7A and 7B show “change scores” determined by independent graders for the same sketches done by a single introductory geology class at Collin College, a Dallas area community college. The two graders generated different means (1.1 versus 2.2) but with overlapping standard deviations. We conclude that mean assessment “change scores” are independently reproducible to about ±1 for a given class.

We examined how short-term understanding of key plate tectonic processes improved in students of different levels of students. One cohort consisted of 21 community college (Richland College) students in a lower-level introductory geology class (including non-majors and advanced high school students); this cohort is comparable to the Collin College cohort summarized in Figures 7A and 7B. Another cohort consisted of 27 UT Dallas lower-level geology majors in three different introductory Earth Science classes. The most advanced group consisted of 15 UT Dallas upper-level geology majors in a petrology class. Figures 7C–7E summarizes “change scores” for these student cohorts. The positive numbers listed in column “mean change” in Table 1 and shown in Figure 7 demonstrate that all three student groups understood more about divergent plate margins and subduction zones after watching and listening to the animation. Community college students improved on average by ~1.5 points, whereas lower-level students at a four-year university improved by 2.6 points. Upper-level geology majors benefited the most, improving by 3.1 points.

![Figure 7](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/13/3/628/2542630/628.pdf)

Figure 7. Change in student sketch before and after viewing and listening to animation. Note that most students at all levels had better understanding of fundamental plate tectonic processes after viewing animation but that upper-level students showed the largest gains in understanding. Panels A and B compare results for two independent graders of the same sketches done by a community college introductory geology class, showing differences between “change scores,” but with indistinguishable means, within uncertainty. Panels C, D, and E summarize “change scores” for a community college introductory college class (C), a four-year university introductory geology class (D), and an upper-level geology major class (E). s.d. — standard deviation; UTD — University of Texas at Dallas.
**DISCUSSION**

In this section, we consider lessons learned, focusing on what we learned about producing the animation, disseminating it, and assessing its impact on student learning.

Generating a more realistic animation of what is oceanic lithosphere and how a subduction zone works requires focused effort, especially about what to show and what to leave out. We learned a lot from this process, and we also gained insights into why there are not more high-quality animations of fundamental Earth processes. Animations should be developed by research scientists working with animators, and it is difficult to enlist geoscientists to this effort. Constructing a high-quality animation requires a level of effort that may be greater than normally expected for “Broader Impacts" activities associated with a NSF-Geosciences proposal and therefore is not routinely done by researchers. Large integrated science organizations such as NASA recognize the importance of animations and have resources to do these “in house," but NSF's process is more fragmented because it is proposal driven. Given the current funding environment, it is not clear how to increase the production of high-quality animations of fundamental Earth processes. Community-driven initiatives such as GeoPRISMS could develop an animation component as part of initiative office activities, but that would require more resources.

In spite of structural obstacles to generating more and better geoscience animations, it is clear that there is much promise in this effort to improve teaching of fundamental Earth Science processes. Storyboards that are referenced to the peer-reviewed literature are essential for linking to science and provide a way to solicit community feedback before any work begins on the animation itself. However, new ways to share storyboards with the research community and solicit feedback need to be developed, as well as ways to encourage such feedback. This seems like an appropriate task for the managing offices of community-driven initiatives.

We also have learned a lot about the importance of a good dissemination plan. We focused on textbook publishers, SERC, and talks at national meetings (optimally coordinated with blogging); also writing papers for the peer-reviewed scientific literature (like this one) is an important dissemination tool.

We gained new insights into student comprehension of subduction zones from our assessment. Our animation was designed for undergraduates, but there is a huge range in understanding between the weak and often erroneous conceptualizations of beginning students and the more detailed understandings of advanced students. It is thus not surprising that “before” scores of upper-level students are higher than those of lower-level and community college students, as is seen in the first column in Table 1. Advanced students learn about plate tectonics and subduction in multiple classes and should have better informed introspective and interpretive visualizations of these processes than beginning students, who have just started to form such mental visualizations. We were more surprised that the improvement in student comprehension (as measured by “mean change" in Table 1 and as shown by representative sketches in Fig. 5) increased with student level. We take this to indicate that undergraduates with the strongest backgrounds benefitted most from viewing and listening to the animation. This may reflect the fact that upper-level students can better assimilate the detail that is provided by the animation but that lower-level and community college students are overwhelmed by it. For upper-level undergraduates, the animation seems to have stimulated a new and improved introspective and interpretive visualization, allowing adjustment of previously assimilated knowledge.

In scoring the sketches, we noted that details about melt generation beneath spreading ridge and above subduction zones and melt-crust interaction beneath arc volcanoes were often overlooked by the students, in both pre-viewing and post-viewing sketches. The reason for this may illuminate important aspects of how students learn. For example, after watching and listening to the animation, many students correctly adjusted their depictions of absolute and relative thicknesses of crust, lithosphere, and asthenosphere. Also, their geometric depiction of subducting and overriding plates showed marked improvement. Is this a result of the nearly four minutes of the animation time spent focused on these aspects? This is a long time spent on essentially one process, especially when compared to contemporary culture's propensity for fast-cutting edits of visual media (movies, TV, etc.). Is a single, long-held shot necessary to allow the student time to absorb such information-dense animation and narration? Compare this improvement with the much shorter (~1 min long) sequence of flux melting and the interaction of melt in the continental crust, for which we saw markedly lower improvement scores. This sequence may need to be significantly lengthened to better show the myriad processes animated clearly and the multi-step processes broken down into its components and animated.

Another conclusion from sketch assessments is that students seem to have a conceptualization hurdle to overcome when they are depicting mantle melting beneath ridges and above subduction zones. Some seem to have a strongly embedded misconception that the mantle is molten, perhaps due to the incorrect portrayals of the mantle in popular culture. Students may hesitate to sketch a new concept that contradicts their preconceived visualization of Earth's interior. In producing the animation, there was a conscious effort to portray the mantle as a solid but one that can deform and flow. Perhaps more emphasis should be placed on making that more obvious in the animation and the narration.

An important outcome of the assessment was that length and complexity are significant obstacles to understanding, especially for lower-level students. This result is in tension with comments from scientists who criticize the many points about subduction that were not mentioned—for example, the role of sediments or how magmas evolve and move in the crust. Animations of important geoscientific processes should be aware of these tensions. One way to partially reconcile these tensions is to first develop a more detailed animation and then simplify this for lower level students.

The results of the assessment exercise provide much food for thought regarding future animation projects. For example, what is the best length for an animation? How many “call-outs" are optimal? It may be that the animation...
would be most useful for the lower-level audience if it was shortened and simplified to better communicate key concepts to them. Future animation projects might want to consider two versions: a full version for upper-level students and a shorter, simpler version for lower-level and community college students.

**CONCLUSIONS**

High-quality animations of important geoscientific processes provide a useful way to teach undergraduates. There are not enough such animations at present, and more are needed. There is a significant learning curve for making geoscientific animations that are scientifically sound, aesthetically pleasing, and that present material at the appropriate level for students. All such animations should be explicitly linked to the scientific literature, with references intended to guide interested viewers to where they can learn more. A publication in a peer-reviewed journal such as this one is optimal. All such animations should be broadly disseminated, including by giving presentations at meetings such as AGU and GSA, blogging, and reaching out to textbook publishers.

Significant obstacles make it difficult to generate such animations, including both “upstream” and “downstream” aspects of the process. Upstream aspects include which fundamental Earth processes should be animated, how to ensure the involvement of scientists with deep understanding of the processes to be animated, building interdisciplinary animation teams, and how animations are best aimed at different groups of undergraduates (lower-level non-majors versus upper-level majors). Downstream aspects include how best to use animations in the classroom and in textbooks and how to assess the ways in which watching and listening to animations affect undergraduate learning. Funding agencies should find ways to build the interdisciplinary teams needed to encourage the generation and assessment of additional high-quality geoscience animations.

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**REFERENCES CITED**


