

THE EARTH SCIENTIST



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FREE INSIDE
Earthquakes...Like Ripples
on Water? full-color
educational poster

IRIS

Large liquefaction features resulting from strong earthquake-shaking in the New Madrid seismic zone. Exposed through trenching, the wall and floor of the excavation reveal a portion of a sand blow and related sand dikes. The degree of soil development above and within the sand blow suggest that the earthquake that formed this feature occurred prior to the 1811-1812 New Madrid earthquakes. Photo by Marititia Tuttle.

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FROM THE PRESIDENT

The Next Tilly

by Ardis Herrold, *NESTA President 2010 – 2012*

This issue of the Earth Scientist is being sponsored by IRIS - Incorporated Research Institutions for Seismology. We are most grateful for their excellent contributions and support. It is because of the leadership efforts and financial contributions of groups like IRIS that we are able to keep membership dues so affordable. Thank you, IRIS!

As the folks at IRIS know, an earthquake gets everyone's attention. A former student of mine had just moved to Santiago, Chile to begin a new job a few weeks before the magnitude 8.8 earthquake of February 27, 2010. Here's an excerpt from Derek's blog:

"I woke up to a siren going off. I felt something was amiss but didn't know what was going on. Then my bed starting shaking and I thought that was a bad sign. Then it stopped shaking and a second later the entire hotel started rumbling and shaking. It was like an airplane hitting really bad turbulence, but remove the plane and replace it with a 17 story concrete and steel building. I was so nervous that I got up and looked out the window. I wish I hadn't... all the buildings around me (15 to 25 stories) were lit up by arcing electrical lines. In the brief flashes of light I could see all the buildings swaying like crazy, like palm trees in a hurricane. It was the craziest and scariest thing I have ever seen. I was sure they would start collapsing one by one, but they just continued to sway. I got back on the floor and rode it out there."

Natural hazard prediction and mitigation efforts are only one of the key reasons why we need to educate the public and encourage students to pursue careers in the Earth Sciences. Many of us remember the story of ten year old Tilly Smith from England, who had studied tsunamis just two weeks before visiting Phuket, Thailand on holiday in December, 2005. She recognized the signs of the approaching tsunami and because of her warning the lives of more than 100 people were spared.

Just two weeks ago I had a conversation with a district administrator who expressed that Earth Science can be eliminated from the high school curriculum because it is not a major content area covered on the state eleventh grade test (eventhough in reality, the test has Earth Science content parity with Biology and Physical Science). I am certain this was comment familiar to many readers of *The Earth Scientist*.

Many of us are familiar with another quotation: "If it can't be grown, it's mined." Going one step farther, it *won't* grow if the soil or climate conditions are unfavorable, or if there is not enough fresh water for irrigation. Our mission as Earth science teachers is to educate our students about the entire Earth and space system, with its many intricate cycles and complex variants. Not the least of these complexities is the challenge of providing pertinent information to those in positions of policy-making. I encourage you all to persevere, if just for the sake of the next Tilly in your classroom.

FROM THE EXECUTIVE DIRECTOR

Dear NESTA Members,

NESTA has a very full schedule of events planned for the Spring NSTA National Conference in San Francisco, 9-13 March 2011. Please see our full page announcement elsewhere in the issue for details on our events at the conference. I'd like to thank the following individuals and organizations for their support for our activities at the Spring conference:

- The Incorporated Research Institutions for Seismology (IRIS), UNAVCO and SCEC for their assistance with helping to put together a wonderful set of speakers for our Earth and Space Science Resource Day Breakfast on March 12th as well as our three Advances in Earth and Space Science lectures later that day.
- Dr. David Schwartz of the USGS in Menlo Park for agreeing to lead our Field Trip on Wednesday, March 9, entitled “A Tour of Subsidence, Jurassic Cherts, Active Faults, and an Antiform!”
- The American Geophysical Union for their continuing support of our advertisement in the NSTA program, through which we also promote the AGU Lecture, on Friday, March 11 at 2 pm, by Dr. Todd Hoeksema, who will be speaking on “Our Eye on the Sun – the Latest from SDO – the Solar Dynamics Observatory”.
- The American Geological Institute for their contributions in support of the Friends of Earth Science Reception on Friday evening, and remind you all that the AGI Edward C. Roy, Jr. Award For Excellence in K-8 Earth Science Teaching will be awarded at this event on Friday evening – don’t miss it!
- Carolina Biological, for their continuing support of NESTA for refreshments at our Rock and Mineral Raffle, as well as for consistently contributing wonderful specimens to the raffle.

Without the support of these organizations and of many other volunteers, NESTA would not be able to put together such a packed program, with so many exciting events for teachers. Thanks to all of you for your efforts!

Best Regards,

Dr. Roberta Johnson
Executive Director, NESTA

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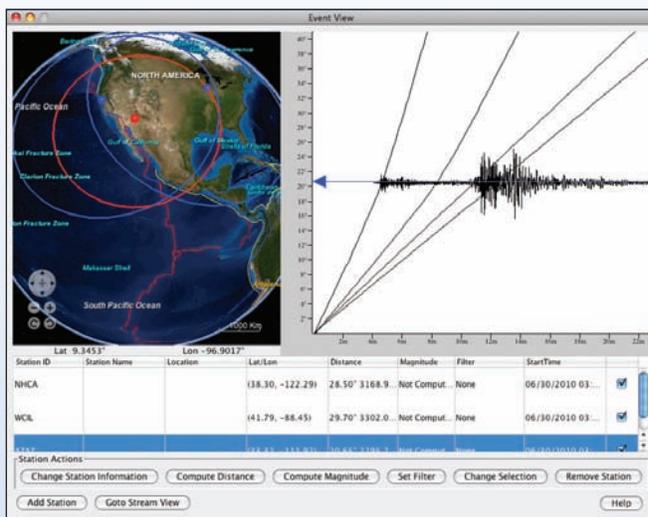
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The Incorporated Research Institutions for Seismology (IRIS) Consortium is pleased to partner with the National Earth Science Teachers Association (NESTA) to develop this special seismology focused issue of *The Earth Scientist*. The theme for this issue is *Modernizing Your Seismology Education*. Here you will find a collection of five invited articles that showcase the complexity and wealth of new teaching opportunities that exist within seismology education.

While the place of seismology education in the earth science classroom is well established as an avenue to address many Nation Science Education Standards, instruction is too frequently limited to a dated view of seismology. Common activities include a variation on the classic 1960's-era earthquake location exercise, plotting of global seismicity on a map to define Earth's tectonic plates, and/or the use of a nomogram to determine the Richter magnitude for a local earthquake. While these exercises are not ineffectual, they do suffer from a number of issues that makes them less than desirable. For example, seismologists have rarely used the S-P method of earthquake location since the late 1960's, and Richter magnitudes have largely been replaced by moment magnitudes. If seismic data are included as part of these activities for student analysis, they often look hand-drawn or inauthentic, which inappropriately glosses-over the inherent complexities of the Earth's interior. Further, these activities focus on narrow aspects of seismic data (e.g. magnitude and event location) instead of helping students conceptualize seismic phenomena within a larger plate tectonic framework or addressing some of the major misconceptions students have about Earth.

To fill the gaps left by commercially available instructional resources the IRIS E&O program is committed to developing and disseminating teaching materials and teacher-ready products. Such products are designed to impact a spectrum of learners from students in grades 5 to 16, to educators and the general public. These translate into powerful learning experiences that transpire in a variety of educational settings ranging from the excitement and awe of an interactive museum exhibit hall¹, to a major public lecture², or the dynamic classroom of a teacher that has participated in one of IRIS's professional development workshops³. Several such products are featured within this *Modernizing Your Seismology Education* issue of *The Earth Scientist*. Common across all five articles and the poster insert is the connection to new research that has yet to make it into commercially available textbooks or curricula.

This issue features a two article sequence that introduces the geological phenomena of Episodic Tremor and Slip, one of the greatest seismological discoveries in the past decade, and describes how this phenomenon can be conveyed to students using models and kinesthetic learning. Another article explores how the USArray, a currently deployed dense network of seismometers, and resulting data can be leveraged to generate new visualizations to enhance the conceptualization of seismic waves in the classroom. The fourth article explores the ever-growing literature base of students' alternative conceptions of geoscience topics and suggests strategies to use this to inform your curriculum, instruction and assessment. The final article introduces both new science on intraplate seismic zones and a physical model that can be used to explore this information with students. This piece is timely as we reach the bicentennial of the 1811-1812 New Madrid earthquakes.

If you are reading this you have probably already opened and examined the poster we have included for you! Like the previously mentioned article on seismic waves, this poster also uses USArray

1 http://www.iris.edu/hq/programs/education_and_outreach/museum_displays

2 http://www.iris.edu/hq/programs/education_and_outreach/distinguished_lectureship

3 http://www.iris.edu/hq/programs/education_and_outreach/professional_development

data to create a visual analogy that is a great catalyst for student-generated questions, inquiry, and learning. Short descriptions of IRIS teacher-ready products such as Teachable Moment slide sets available the day after major earthquakes, or portals to access seismological data such as the IRIS Earthquake Browser are interspersed throughout the issue to attract your interest. We hope these, plus our collection of classroom activities, the Seismographs in Schools program, and real-time displays of global seismicity (all available via www.iris.edu) further equips you to try something new in your unit on seismology.

We would love to hear from you so please don't hesitate to contact any of the authors. Or, if you are attending the NSTA meeting, please be sure to stop to talk with us at either the IRIS booth (#607) or at one of the NESTA's geoscience Share-A-Thons!

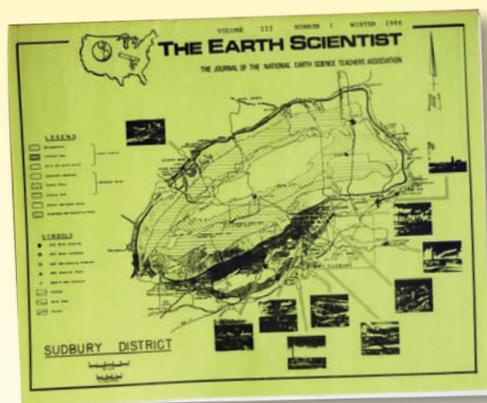
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TES Editor, Tom Ervin

Twenty-five years ago in TES

Twenty-five years ago, TES was in its third year of publication. In 1986, the Volume 3, issue 1 cover featured a map of the Sudbury District on the North Shore of Lake Huron. This was followed by an article featuring the Geology of that unique district. There was an article on Jovian and Saturnian Moons, featuring the “newest photos from Voyager 2”, and



making special note of the “newly discovered volcanic plumes, spewing forth on the surface of Io”. Another article discussed Teaching Earth Science (through Postage Stamps). First Class postage in 1986 was a whopping 20 cents. Another article informed us about the current eruptions of Nevada Del

Ruiz, a volcano in western Columbia. One article was devoted to a discussion of the 4,007 pieces of “space junk” in orbit around the earth. And finally, there was a review of the “Thomas Alva Edison Kits, again available for use in your Earth Science Classroom”.

The Earth Scientist

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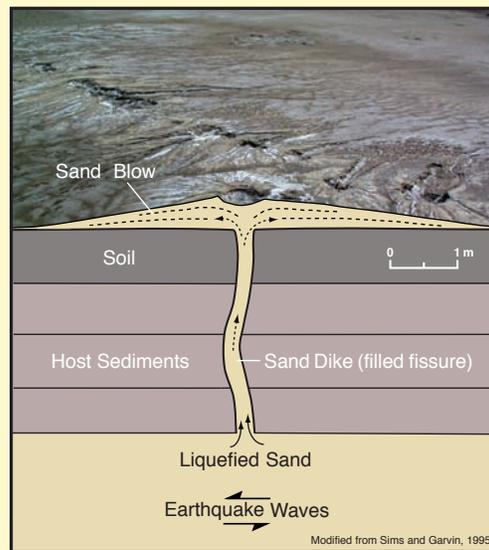
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About the Cover

Sand blows and related sand dikes result from liquefaction of water-saturated, sandy sediment in response to ground shaking produced by earthquakes of $M > 5$. As seismic waves pass through the sediment, pressure builds up in the water between the sand grains. If the pore-water pressure increases to the point that it equals the weight of the overlying soil, the sediment liquefies. Once liquefied, the pressurized water with entrained sand forcefully flows towards the ground surface. It intrudes pre-existing cracks or cracks and fissures that form as the overlying sediment founders into the liquefied sand or slides down slope. In cases, where the pressurized slurry of water and sand erupts to the ground surface, fountains may be observed and sand may be deposited on the surface around the vent to form a sand blow or sand volcano. Over time, soils form in the sand blows or they



are buried by other deposits preserving them in the geologic record. Cultural artifacts, organic material, and sediment above and below sand blows can be used to estimate their ages and the earthquakes that caused them.

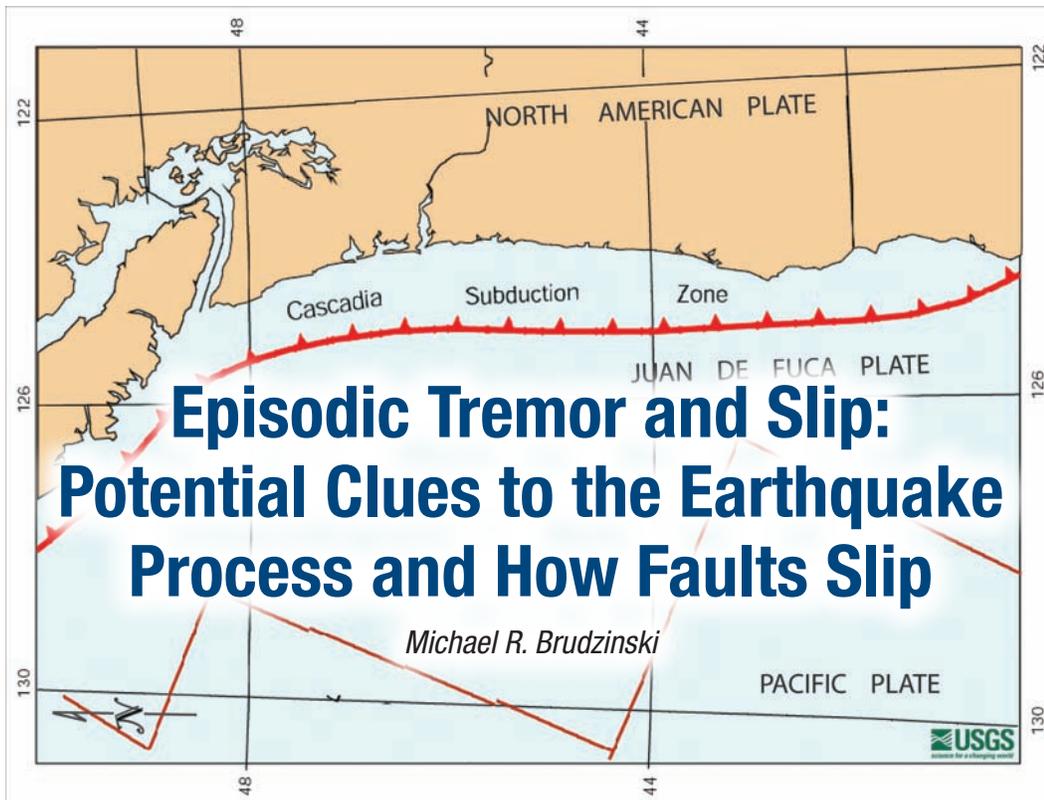
During the 1811-1812 New Madrid earthquakes, large sand blows formed over a very large area, about 10,000 km², and smaller sand blows formed more than 240 km from the inferred epicenters. Similar broad distributions of sand blows from other earthquakes around the world suggest that the New Madrid earthquakes were very large ($M > 7$) in magnitude. In addition to

these more recent events, hundreds of ancient sand blows, like the one shown in the cover photo, have been mapped and dated across the New Madrid region. Many formed about 1450 C.E. and 900 C.E. These are similar in size and in internal stratigraphy to sand blows that formed during the 1811-1812 New Madrid earthquakes. Their age, size, and areal distribution suggests that the New Madrid seismic zone produced earthquakes similar to those in 1811-1812 at least twice before. The paleoearthquake record of the region is incomplete prior to 900 C.E, but there are hints of other large earthquakes about 1000 and 2350 B.C.E.

For more information and additional references please see: <http://mptuttle.com/newmadrid1.html>

Sims, J.D., and Garvin, C.D., 1995, Recurrent liquefaction at Soda Lake, California, induced by the 1989 Loma Prieta earthquake, and 1990 and 1991 aftershocks: Implications for paleoseismicity studies, *Seismological Society of America Bulletin*, v. 85, p. 51-65.

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Abstract

Episodic tremor and slip (ETS) represents a newly discovered mode of fault behavior occurring just below the locked zone that generates great earthquakes. Initially discovered in subduction zones, this new slip mechanism can release energy equivalent to at least a magnitude 7 earthquake! While this is a tremendous energy release, no one ever feels these events because they occur as slow slip episodes lasting weeks or months. As the plates move, high-precision Global Positioning System (GPS) monuments record the magnitude and direction of motion while seismometers record the low amplitude seismic waves released. The importance of this discovery lies in its potential relationship to the part of faults that generate destructive earthquakes. Considering that ETS occurs immediately below to the locked zone of faults, it may be possible for energy released in slow slip episodes to concentrate stresses at the deep edge of the locked zone, incrementally bringing it closer to failure. Thus ETS episodes might be a trigger for great earthquakes or aid in monitoring the stress state of faults as they lead up to the big one.

Introduction

The growing awareness of societal problems caused by natural hazards has piqued the interest of many students who enter our classes. As Earth science educators it should be our goal to convert that interest into problem solving skills. There is possibly no better example than that for earthquakes, where the threat is ever present, but there are many unanswered questions about how and why earthquakes happen. All of these questions will require well-trained and creatively thinking students to help push the research to new discoveries as well as an educated citizenry to apply the science to hazard preparedness and mitigation. A recent discovery that has captured the attention of many geoscientists over the past decade is the observation of a new type of deformation occurring on the large faults between tectonic plates that is different from typical earthquakes. To

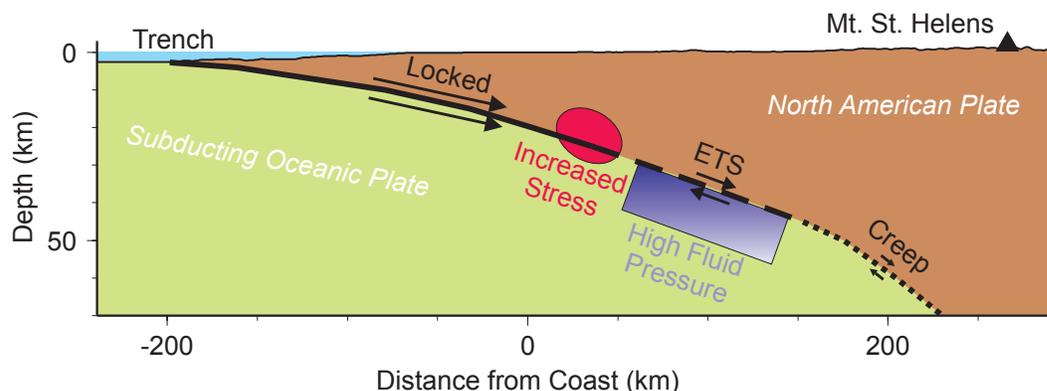
understand the importance of this new discovery and how it might inspire our students, we must first review the typical earthquake cycle.

As oceanic plates subduct into the mantle, friction on the interface with the overriding plate causes the plates to “lock” together along the megathrust zone (Figure 1, thick solid line). Here the upper plate is pulled down by the lower plate, building up elastic strain in the rocks along the fault, until the strain is relieved when the upper plate pops back up during a potentially devastating earthquake. The rapid fault motion in great (magnitude 8+) earthquakes can result in intense ground shaking and the displacement of ocean water that generates tsunamis, with the 2004 Sumatra great earthquake and tsunami serving as a particularly harrowing example. While much of the energy stored in subduction zones is released in these great megathrust earthquakes, recent GPS observations have revealed that the built-up elastic strain in subduction zones can be released through a process that is much less dramatic than a typical earthquake.

New Fault Behavior Discovered in Subduction Zones

To make these observations, high-precision GPS monuments were monitored continuously for motions over time as small as a millimeter per year. Careful analysis of the relative positions of instruments near the edge of the plate relative to those in the interior found that some instruments occasionally moved back toward the trench, instead of towards North America as would be expected along the convergence boundary in the Pacific Northwest. The magnitude and direction of this motion was similar to what might be expected during the several seconds of a magnitude 7 earthquake. However, this motion occurred much more gradually over the span of several weeks and in some cases over a year (e.g., Rogers & Dragert, 2003). This gradual release of the built-up elastic strain is now referred to as slow slip episodes. Curiously, the largest transient motions were not recorded at the coast above the locked zone (Figure 1, box A) but further inland (Figure 1, box B), suggesting slow slip occurs on the plate interface deeper than the region where great earthquakes are expected (Figure 1, dashed line). Discovering “hidden” slip on the fault equivalent to a magnitude 7 earthquake just below the zone of great earthquakes is cause for both excitement and concern. Further investigation revealed that the slow slip is episodic, sometimes with remarkably consistent frequency, such as the ~14 month recurrence interval seen between Seattle and Vancouver (Figure 2, box B) (e.g., Rogers & Dragert, 2003). This gives geophysicists the unprecedented luxury of being able to prepare for each event in advance and then watch closely for the start of each episode as the data streams in. This periodicity is not as consistent in other locations (Brudzinski & Allen, 2007), but most cases are more regular than typical earthquakes, suggesting that the frictional conditions on this portion of the fault cause it to be more predictable than where earthquakes occur.

Figure 1. Cross-section slice through a subduction zone illustrating how fault behavior, along the plate interface, changes with depth. At shallow depths, the subducting (green) plate drags the upper (brown) plate down as the fault between them is locked together along the megathrust (thick solid line). The rocks on either side of the fault bend to accommodate this elastic strain until the fault unlocks catastrophically in a great earthquake. At depths below ~30 km, we find evidence of a more gradual release of elastic strain through episodic tremor and slip (ETS, dashed line). This is a newly discovered type of fault behavior which appears to be promoted by high pore fluid pressure from subducting plate dehydration (blue shading). ETS is important as it frequently releases elastic strain energy equivalent to a magnitude 7 earthquake, which is thought to concentrate stresses (red shading) at the deep edge of the locked zone. At greater depths, the increasing pressures and temperatures prevent earthquakes and ETS and result in continuous creep along the plate interface (dotted line). The crust/mantle boundary has limited impact on the fault behavior and has been omitted from this figure to focus attention on the interface between the plates. This figure is vertically exaggerated by a factor of 2.



In addition to being recorded by GPS, slow slip typically corresponds to low-level seismic vibrations referred to as non-volcanic tremor (Figure 2, box B) that can be detected by seismometers. The term non-volcanic tremor was applied to these weak signals as they are emergent, meaning they are not impulsive like a single large earthquake (Figure 2, box A), but gradually appear out of the background noise and often undulate with slowly varying amplitudes (e.g., Obara, 2002) (Figure 1s). Volcanoes generate a similar, but larger and more obvious tremor that has been recognized for many years (Figure 2, box D). Non-volcanic tremor in subduction zones is different because it has a deep source region (Figure 1, dashed line), and it is not harmonic (cf., Figure 2, boxes B and D, bottom panel). The harmonic nature of volcanic tremor is thought to be caused by fluid moving through magma conduits, similar to the way air resonates in an organ pipe.

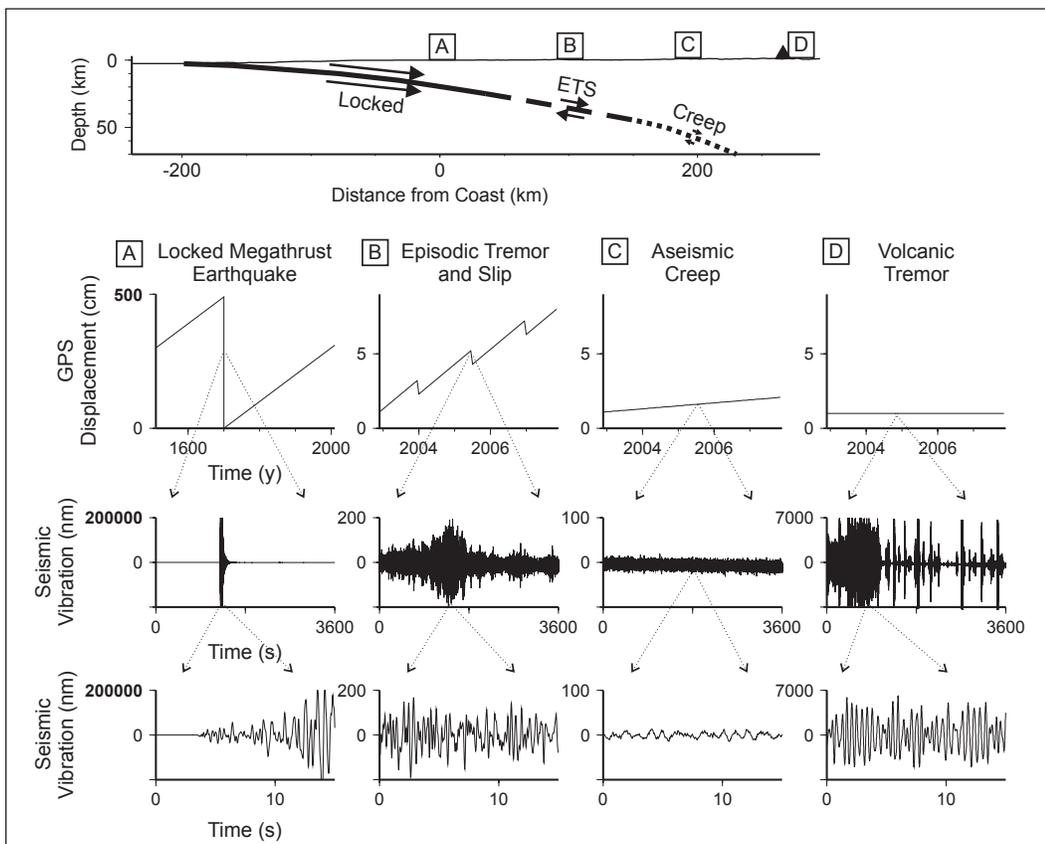


Figure 2. Example GPS data (middle panel) and seismic data (lower panels) recorded at different locations across a subduction zone. (top panel) Cross-section through a subduction zone illustrating 3 types of fault behavior: locked (solid), episodic tremor and slip (ETS, dashed), and creep (dotted). Boxes A through D show locations of seismic and GPS instruments above each of these 3 zones of the plate interface and one near a volcano (triangle) further inland. This cross-section is similar to Figure 1 but with no vertical exaggeration. [A] Instruments above the locked zone record linear trends in GPS data that indicate accumulation of elastic strain energy for hundreds of years. Eventually, a great earthquake occurs, causing several meters of displacement in just a few minutes with very strong seismic shaking. [B] Instruments above the ETS zone record episodes of slow slip with only millimeters of GPS displacement that last a few weeks to months and often recur every year or two. These episodes are typically accompanied by non-volcanic tremor that are small seismic vibrations that gradually emerge out of the background noise. [C] Instruments above the creep zone record very little change in GPS displacement over time with very small and constant seismic vibrations that are likely due to cultural or atmospheric noise. [D] Instruments near a volcano that are far from the plate boundary often see little change in displacement between eruptions, but they record periods of volcanic tremor. The bottom panel shows a short time scale to illustrate how volcanic tremor has repetitive, uniform pulse widths, while non-volcanic tremor has more irregular pulse widths, a key difference that led to the discovery of ETS. This harmonic nature of volcanic tremor is thought to be caused by fluid moving through conduits, similar to how air resonates an organ pipe. Non-volcanic tremor is not harmonic as it is thought to be caused by a swarm of small, low-frequency earthquakes with overlapping P and S waves.

Based on an analysis of non-volcanic tremor, it appears to be composed of swarms of so-called low frequency earthquakes, since typical earthquakes of similar magnitude would have more energy at higher frequencies. The swarm of seismic sources results in many overlapping signals on a seismogram (Figure 2, box B), making it difficult to discern individual P and S waves typically used to estimate key details about the earthquake source. Nevertheless, detailed processing techniques have been able to identify repeating P and S wave signals that indicate the depth and fault motion are consistent with the majority of non-volcanic tremor produced by shear faulting along the plate interface (Ide, Shelly, & Beroza, 2007). These motions are consistent with slow slip motions that regularly relieve the built-up elastic strain along the fault and relax the deep crust. However, the summed magnitude of slip from non-volcanic tremor is still considerably less than that from geodetically recorded slow slip, such that the combination is still mostly an aseismic slip process.

Part of the reason non-volcanic tremor remained undiscovered through seismic analysis until the last decade was that its signal is close to wind or cultural noise (Figure 2, box C), and when combined with its weak and undulating nature, it typically looks like slightly more than normal background noise on an individual seismogram. The key indicator that it is indeed generated by a tectonic source is that the signals correlate at several stations over distances of up to 100 km, whereas cultural noise is different at every station. The situation is analogous to other discoveries in geology, where key features in rocks remain unnoticed for a many years until someone goes looking for a specific feature. What helped draw the attention of many geophysicists is the remarkable correlation in space and time between the geodetic signatures of slow slip and the seismic signals of non-volcanic tremor (e.g., Rogers & Dragert, 2003) (Figure 2, box B).

Physical Causes for Slow Slip Behavior

Episodic tremor and slip (ETS) is exciting to scientists because it occurs at the deep edge of great earthquakes where rupture often begins, indicating that ETS could help explain why great earthquakes are restricted to certain parts of the plate interface. As mentioned earlier, these great earthquakes are thought to result from frictional behavior on the fault between the plates. In order to understand why slow slip occurs we need to examine the physics of faulting in detail. Under the right conditions, which are typically met at shallow depths in the Earth's crust (Figure 1, thick solid line), the friction on the fault while stationary is larger than the friction on the fault once the fault is moving. As a result, an instability is formed once a fault begins to rupture, and the rupture is able to continue quickly causing an earthquake until something stops it, such as a bend in the fault. As pressures increase with depth in the Earth, a region is reached where there is no longer a decrease in friction after the fault starts to slip (Figure 1, dotted line). At these depths, this lack of decreased friction when the fault is in motion prevents fault slip from becoming an earthquake. As a result, the fault creeps along at a stable rate.

In between the locked and creeping regions (Figure 1, dashed line), theory predicts the possibility that slow slip rupture can be initiated due to the presence of high fluid pressures that “lighten the load” of the overriding plate thereby reducing the friction (e.g., Liu & Rice, 2007). We believe this is occurring as the subducting oceanic plate loses its water on its descent into the Earth, and a seal above the plate interface could cause fluids to build up along the fault (Figure 1, blue shading). Seismic waves traveling through the source region of ETS show unusually slow speeds and elastic properties consistent with fluid overpressuring (e.g., Audet, Bostock, Christensen, & Peacock, 2009). Further evidence for this comes from another set of observations showing that ETS can be dynamically triggered by tidal forces (e.g., Rubinstein, La Rocca, Vidale, Creager, & Wech, 2008) or passing surface waves from a large earthquake (e.g., Rubinstein et al., 2007). Since normal earthquakes on strong faults are rarely triggered by tides and surface waves, such response to smaller stresses indicates the fault is weaker. Fluid overpressuring is a worthy candidate for weakening or drastically

reducing friction on the fault (e.g., Thomas, Nadeau, & Burgmann, 2009).

Why is ETS an Important Discovery?

The importance of ETS to the general public lies in its potential relationship to great earthquakes. Considering that ETS occurs near the deepest extent of where earthquakes rupture (Figure 1, dashed vs. solid line), one can simply use the location of ETS to estimate how far inland future great earthquake ruptures will extend (Chapman & Melbourne, 2009). In the Pacific Northwest (Figure 3), the spatial extent of the last great earthquake in 1700 is not well determined, making hazard estimates more difficult. Here, ETS occurs further inland than previous estimates of the extent of the great earthquake rupture. This suggests strong ground shaking could extend further inland towards cities like Seattle, Portland and Vancouver, and there are active discussions about how to incorporate this information into seismic hazard assessment.

The proximity of ETS to the zone of great earthquakes indicates that stress release in slow slip episodes could concentrate stresses at the deep edge of the locked zone (Figure 1, red ellipse), incrementally bringing it closer to failure (Dragert, Wang, & Rogers, 2004).

If true, ETS could be thought of as “tickling the dragon’s belly” such that great earthquakes would be more likely during or just after an ETS event. Regardless of whether ETS has a causative relationship with great earthquakes, ETS may still be useful in monitoring the stress state of faults as they lead up to the big one. Changes in the location, recurrence, or migration of ETS phenomena could all serve as indicators of the increasing likelihood of earthquake rupture. Unfortunately, the closely spaced instrumentation necessary to fully test hypotheses regarding ETS and the earthquake cycle has not yet existed in areas where the handful of great earthquakes have occurred over the past decade. While no one hopes for a great earthquake, scientists continue to prepare to catch the next big one with a better distribution of higher quality instrumentation.

ETS on Other Fault Types

Although the majority of this article has focused on ETS behavior in subduction zones (e.g., Cascadia, Japan, Mexico, Alaska, Costa Rica), there are indications that ETS, or aspects of it, occur on other faults as well. A series of slow slip episodes have been recorded on the south flank of Kilauea (e.g., Montgomery-Brown, Segall, & Miklius, 2009), where the weight of erupted rock is causing it to slough away along nearly horizontal faults. In this case, slow slip episodes are not accompanied by non-volcanic tremor but they are accompanied by a swarm of regular earthquakes.

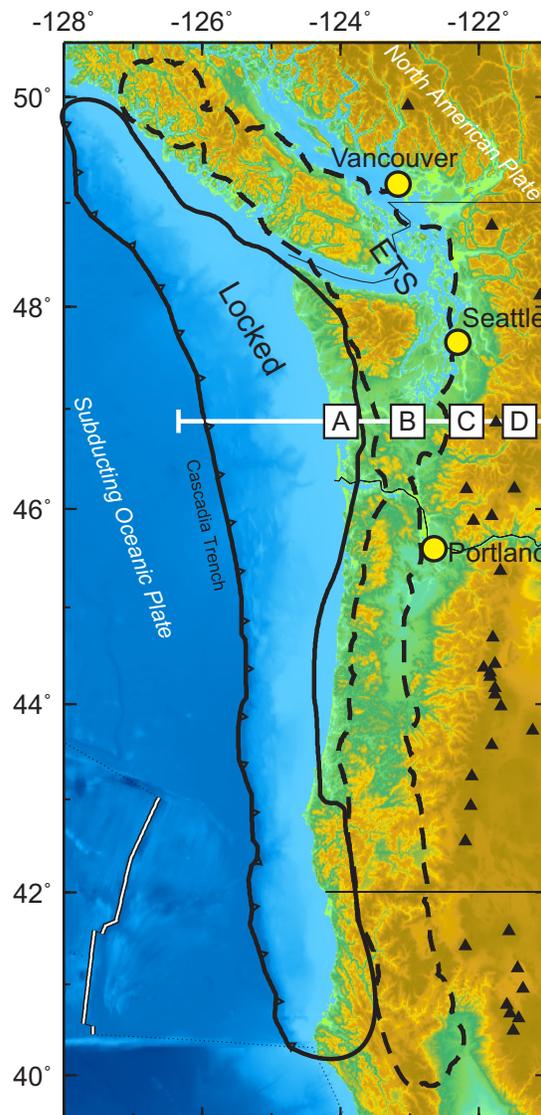


Figure 3. Map of the Pacific Northwest showing regions affected by the fault interface between the subducting oceanic plate and the overriding North American plate. Since the last great earthquake occurred in 1700, scientists have tried to estimate where the fault is locked (solid curve) to predict where the next great earthquake will occur. The region of the fault producing episodic tremor and slip (ETS, dashed curve) occurs slightly inland of these estimates of where the earthquake will occur. If the locked zone actually extends all the way up to the edge of the ETS zone, the next great earthquake will bring seismic shaking further inland and closer to Seattle, Portland, and Vancouver (yellow circles). Cascades volcanoes are shown as triangles. The white line indicates the location of the cross section shown in Figures 1 and 2. Boxes A-D indicate locations of seismic and GPS instruments for which data is shown in Figure 2.

About the Author

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The San Andreas Fault has also shown evidence for slow slip (Linde, Gladwin, Johnston, Gwyther, & Bilham, 1996) and non-volcanic tremor (Nadeau & Dolenc, 2005), but they have not yet been recorded in the same part of the fault. The tremor observations, though, are particularly intriguing since a magnitude 6 earthquake occurred in the region where tremor was discovered, and there have been clear indications of changes in tremor patterns leading up to and following the earthquake (e.g., Nadeau & Guilhem, 2009).

Episodic slow slip and non-volcanic tremor appear to occur in a range of environments and understanding this newly discovered phenomena is helping us decipher the physics of earthquakes. While we are in no position to use ETS to predict earthquakes, such observations give hope to the prospects of using ETS to better understand when and where earthquakes will occur. And considering the sobering history of failed prospects in earthquake prediction (e.g., Hough, 2009), any hope is good news.

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Episodic Tremor and Slip in a Middle School Classroom? Absolutely!

Relevance and Kinesthetic Methodologies Merit Inclusion in 8th Grade Earth/Space Science Class

Roger Groom, Shelley Olds, Robert F. Butler and Jenda Johnson

Photo by Steve Smith

Abstract

Episodic Tremor and Slip is a valuable tool in Earth Science classrooms to teach about new understandings of subduction zones. The relation of these boundary systems to natural hazards is real and relevant as witnessed in Sumatra and Chile. Through a suite of three lessons students learn about high-precision Global Positioning System (GPS) technology, how to interpret GPS data time series plots, and determine the general motion trend of a tectonic plate. Building on their understanding of GPS, students are prepared to discover the evidence of episodic tremor and slip events and appreciate the significance of these phenomena in forecasting megathrust earthquakes and tsunamis.

Relevance of Episodic Tremor and Slip

The relatively recent discovery of Episodic Tremor and Slip (ETS) in the Cascadia Subduction Zone (CSZ), which has a geologic configuration similar to Sumatra and Chile, has highlighted the potentially devastating earthquake potential in the Pacific Northwest. Until recently, motion on subduction zone faults was assumed to be constant in direction and speed between major earthquakes. However, in the Pacific Northwest the local ground motions measured by Global Positioning System (GPS) technology, revealed a current trend of motion to the northeast, indicating that the North America plate and the subducting Juan de Fuca plate are locked along their plate margins. Furthermore, an unexpected finding over the past decade revealed periods of slow ground motion back to the southwest. Since then, these slow slip events, known as ETS, have been correlated with seismic tremors lasting over a one or two week period. ETS events occur so slowly that only sensitive instruments can detect their occurrence. ETS events are of great interest because over time they may add potential energy to the locked section of the subduction zone, incrementally bringing it closer to failure. Eventually, this energy will be released as a tremendous megathrust earthquake affecting the Pacific Northwest region, including Portland and Seattle, and creating tsunamis that will inundate the Pacific Northwest coastline. For a more in-depth description of ETS behavior and causes, see pages 7-12 in this issue.

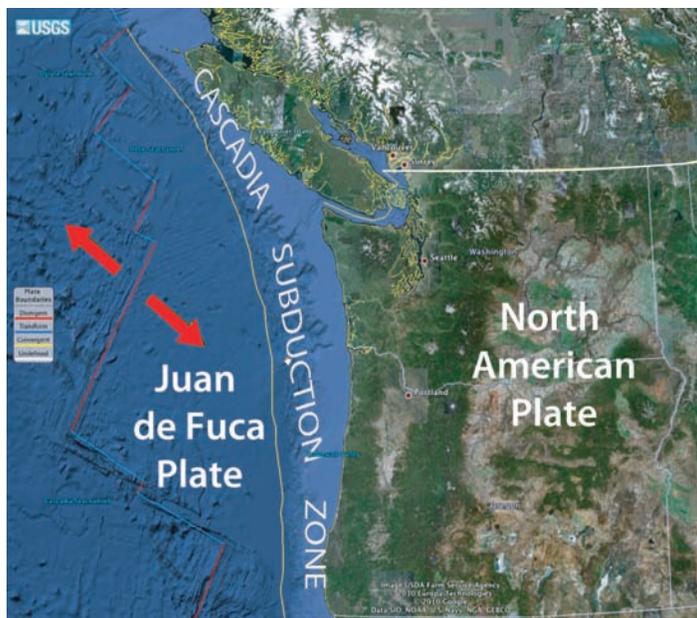


Figure 1. Regional map of the Pacific Northwest showing the relative positions of the subducting Juan De Fuca plate and the overriding North American plate.

This recent discovery of a new fault behavior, and its relationship to potentially devastating megathrust earthquakes, provides a powerful teaching opportunity for middle school Earth Science students, especially those who live in the Pacific Northwest. Through the study of the intriguing mechanism of ETS, students gain a deeper understanding of convergent boundaries and are exposed to new technologies that are extending our knowledge of these boundary systems. Such instruction also increases the awareness of potential hazards associated with subduction zone earthquakes and tsunamis, thereby helping to raise public awareness of these hazards within the United States. As evidenced by Hurricane Katrina in 2005, the impact of natural disasters is not limited to the region directly affected by the event. The lessons and built-in kinesthetic modeling activities described in this article provide students with the tools to comprehend the processes involved, especially because they may be happening right under their feet.

Teaching Sequence

Originally developed in 2006 during a UNAVCO Master Teacher in Residence program, the Cascadia and Episodic Tremor and Slip learning activities have been collaboratively refined, field tested with students, and presented to Earth Science teachers during multiple workshops, including the Teachers on the Leading Edge program (2008-2010). Students learn about Episodic Tremor and Slip by analyzing authentic high-precision GPS data. There are many benefits of using GPS data to teach Episodic Tremor and Slip:

- GPS is cutting-edge technology that is familiar to students and has broad applicability in the geosciences.
- Using real-time, freely accessible, GPS data builds interest and awareness,
- Analyzing GPS data supports math (particularly graphing skills), technology, geography, earth science, and process of science standards.
- GPS data can be presented as a class demonstration or via interactive whiteboards, printed for student classroom use, or accessed in a computer lab.
- Can be differentiated to address a diversity of learners.

To provide students with the tools to understand GPS data and comprehend the big picture of ETS and its importance, we present the following three activities:

- 1) Gumdrop Introduction to GPS;
- 2) “Locked and Loading” to explore regional deformation and to practice the process of potential and kinetic energy; and
- 3) Episodic Tremor and Slip – the Case of the Mystery Earthquakes.

As presented, the sequence takes 8-10, 50-minute periods. However, the sequence can also be shortened or lengthened to fit your own teaching situation. Prior to the teaching sequence, students should know the basics of plate tectonics. A complete description of the suite of three activities including modifications and extensions is available online through *ETS in the Pacific Northwest* (Groom, 2011).

Gumdrop Introduction to GPS

Time

2 – 3, 50-minute periods depending on student comfort level with interpreting graphs.

The teaching sequence begins with an explanation of how GPS works and how the motion of GPS stations, permanently attached to the ground, can be measured on the scale of millimeters per years. Students interpret GPS data time series plots to determine the motion of different GPS stations.

Lesson Objectives

- Build and use a model of a GPS monument
- Understand the power of high-precision GPS to monitor movement of Earth's surface
- Learn to read and interpret GPS time series plots
- Graph the direction and speed of a GPS station's motion
- Visualize deformation of the North American continental margin due to subduction of the Juan de Fuca plate

Students first build 'gumdrop' GPS receivers (Figure 2) to use in a hands-on, follow-along exercise to learn to pinpoint a location on the Earth's surface using multiple satellites. Students are then introduced to GPS time series graphs and use these graphs to interpret the data from three GPS stations along a west to east transect across Washington. Two short video tutorials illustrating this are available online at the Incorporated Research Institutions for Seismology (IRIS) website (IRIS, n.d.). Students move



Figure 2. Classroom set of student-made gumdrop GPS monuments

their gumdrop models along the mapped data to simulate the motion of the GPS station and the earth beneath it over time; a process that helps kinesthetic learners translate graphed data to movement. Finally, by looking at the transect stations, students graph and model the deformation of the western margin of the North American plate. Along this single transect, movement is largely to the northeast due to the subducting Juan de Fuca plate. Students notice that the far western edge of the North American plate has greater northeast movement compared to the urban corridor, while further inland (central WA and OR) isn't moving northeast. The next question to address is whether the entire Pacific Northwest margin is behaving similarly.

Locked and Loading

Time

1 ½ - 2 periods

In this activity, students analyze multiple west-to-east transects of GPS data through Washington and Oregon to attain a regional view of how the North America plate is "locked and loading" along its western margin in the Pacific Northwest.

Lesson Objectives

- Interpret multiple GPS data time series plots
- Compare and contrast motions of different GPS stations across the geographic area
- Propose an explanation for patterns in GPS motion
- Visualize deformation of the North American continental margin due to subduction of the Juan de Fuca plate
- Recognize long-term effects of the locked and loading margin and societal ramifications for Pacific Northwest

Through illustrations and discussion students learn that the North American and Juan de Fuca plates are locked together along the western margin of the North American plate. As the Juan de Fuca Plate pushes the North American Plate margin toward the northeast, potential energy continues to build in this zone, loading the Pacific Northwestern margin with potential energy. The phrase “Locked and Loading” is used to describe this process along the margin. Groups of students are provided with data from different sets of GPS stations in west-to-east transects and plot the velocities of the GPS motion on a map grid. Class data is compiled onto a single map to show the entire regional perspective (Figure 2) allowing students to visualize the motions at each GPS station. Students discuss the implications of the changes in velocities, are lead to the realization that the continental margin is being compressed (loading with potential energy), and that given enough time, the sudden release of this potential energy in a megathrust earthquake and the resultant tsunami is a significant hazard for regions bordering subduction zones.

Episodic Tremor and Slip: the Case of the Mystery Earthquakes

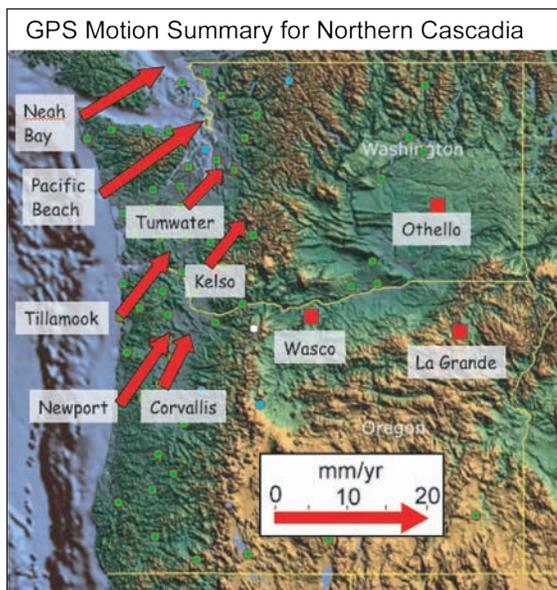


Figure 3. Plotted GPS vectors in Pacific Northwest. Red arrows show direction and magnitude of motion. The deformation along continental margin compared to inland areas illustrates how the plate is locked and loading.

Time:

4 – 5 periods

Students examine GPS time series plots to analyze Episodic, Tremor, and Slip (ETS) events, use kinesthetic activities to model processes occurring on the subducting plate, and forecast the potential slip between the Juan de Fuca and North American tectonic plates.

Lesson Objectives

- Realize that science is a constant accumulation of data that builds upon itself
- Understand the role of technology in the advancement of science
- Interpret patterns in data to recognize cause and effect of ETS
- Describe important natural hazards in the Pacific Northwest
- Model Earth processes through the use of hands-on manipulatives

Instruction begins with a review of the Cascadia region and the general northeast motion of the continental margin. Then, the story of the mysterious silent seismic tremors begins to engage students in the instruction. Students learn about the process of science and scientific collaboration through story-discovery: how scientists collecting tremor data originally thought that the tremors resulted from instrument error or noise from wind; once the GPS ‘slip’ data and the tremor data were plotted on the same timeline, scientists realized the tremors truly were seismic in origin and that these events were in fact real and correlated! Students discover ETS by looking

at the evidence of seismic tremor and slip data. Once the correlation between the two is realized, students view animations that mimic ground motion during ETS events. They discover that ETS is a highly episodic Earth phenomenon with a frequency of approximately every 14 months. This allows scientists to anticipate when slow slip will occur and to monitor it. Based on the GPS time series plots, students forecast which areas will have an ETS event and predict what the GPS data time series plots would look like.

Along the far western edge of the North American plate, the plate is continuously deforming to the northeast. A few hundred kilometers inland, GPS data reveals very little motion at all. So why is there this difference in motion? To explore this discrepant data, students observe warmed lasagna noodles (Figure 4) as a model of the effect of temperature on a subducting pasta 'slab'. The warmer noodle is more ductile and bends far easier than the cold, brittle section. Students relate the noodle to the subducting Juan de Fuca plate. The cooler, shallower regions (closer to the coast) are more brittle, 'stick' to the North American plate above and are more likely to rupture with a sudden release of energy. Meanwhile, the plate further inland is deeper in the crust, warmer, and 'slips' quietly beneath the North American plate. To help map the pasta noodle model to Earth processes, students study a 3-grid animation that summarizes the movement of the entire region (Figure 5).

After discussing the pasta-model results, a 'two-block' kinesthetic activity, an adapted version of the Earthquake Machine (Hubenthal, 2008), allows students to model the build-up of stored energy and its effect on the locked zone. Two



Figure 4. Students use lasagna noodles to model how differences in depth of the subducting oceanic slab affect its elasticity.

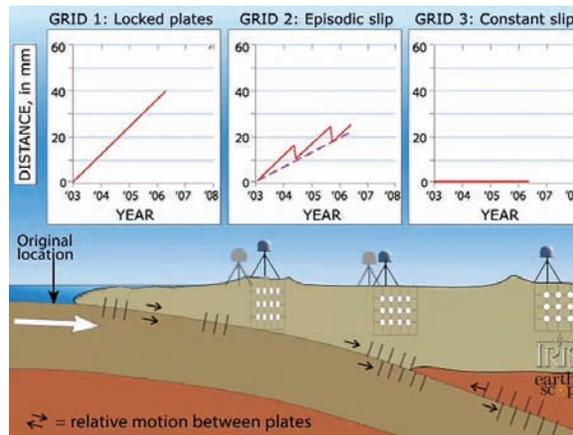


Figure 5. Screen shot of ETS animation showing different GPS data sets correlated to the locked section, slip section, and interior of the subduction zone.

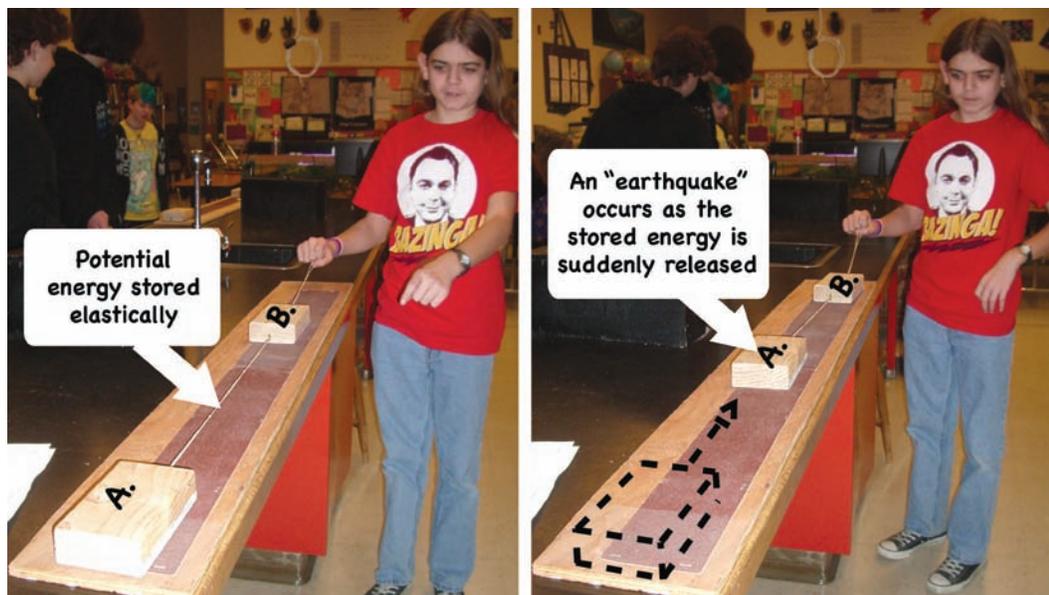
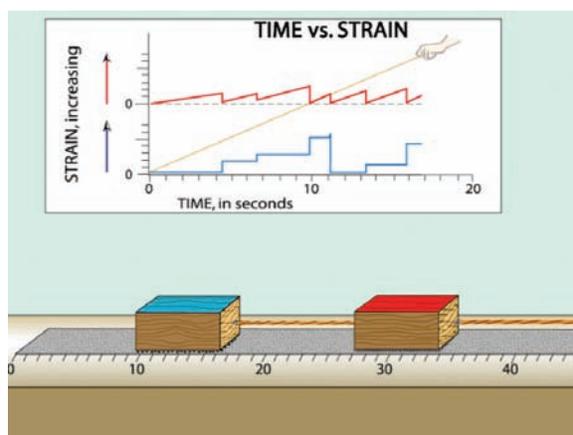


Figure 6. Student using a 'two-block' earthquake machine. Left photo: Potential energy is stored elastically as the student gently pulls on block(B). Right photo: Block (A), representing the locked section of the subduction zone, suddenly lurches forward as the stored energy is released in an "earthquake".

wooden blocks, each with sand paper glued or stapled to their lower sides, are connected together with a few thin, rubber bands and sit on a long strip of sandpaper which is taped to a desk (or mounted on strips of wood for easy portability). The leading block (representing the region inland exhibiting ETS) has fine-grit sandpaper on the bottom while the trailing block (representing the locked-zone along the continental margin) has rough-grit sandpaper on the bottom. As students steadily pull on a rubber band connected to the leading block, the leading ‘ETS slip-zone’ block will nudge forward every so often, simulating an ETS event. The rubber band connecting the two blocks stretches, loading (storing) potential energy. When enough potential energy is stored in the trailing ‘locked zone’ the trailing block lunges forward in less frequent but dramatic energy releases (megathrust earthquakes) (Figure 6). Animations of this movement graph the strain and distance

Figure 7. Screenshot of animation illustrates the build-up of strain in trailing block system with each small-scale release of strain in the leading block.



moved for each block, helping to solidify the concepts learned in the kinesthetic activity and provide an opportunity to discuss concepts learned and/or needing clarification. (Figure 7). These animations are also useful for teachers that are unable to do the hands-on activity.

Students relate the two-block model to a megathrust earthquake and the tsunami hazard of a massive shift of the ocean floor, in the final “Why You Need to Know This!” portion of the ETS lesson.

Based on the ‘slip deficit’ building in the locked zone over 500 years (the average time between the megathrust earthquake events in the Cascadia region) students calculate the potential slip distance that could occur from a future megathrust earthquake and discuss how ETS can be used to forecast times of higher likelihood of these dangerous quakes. This discussion can lead naturally into a deeper discussion of societal impacts and steps students can take to mitigate the risks of living in an earthquake hazard zone.

Conclusion

Depending on the teaching approach, implementing this suite of lessons may require a time investment of up to two weeks. While this may seem like a lot of time, the breadth of math, technology, geography, earth science, and physics standards supported make it a worthwhile investment. The process of learning about GPS and ETS is vital to students that live, or at some point in their future, may live in the Pacific Northwest or near another subduction zone. As we have learned through other large natural disasters, such as Katrina, the impact of natural disasters is not limited to the region directly affected by the event and can have long term effects throughout society. Geological hazards are real, and with the methodologies described, the animations, the kinesthetic modeling, and the build-up of content knowledge in science and math, students are able to learn deeply about these hazards while practicing sound science process skills. The Pacific Northwest Seismic Network has a deep tremor blog (Blog for ETS of Summer, 2010, n.d.) that students can access to learn when the next event is forecast to occur. In the end, students understand ETS and its relation to natural hazards, are intrigued by the story of its discovery, and are eager to share their new found knowledge, which may be vital to their family’s safety.

So, should Episodic Tremor and Slip be taught in a middle school classroom? Absolutely!

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WINDOWS TO THE UNIVERSE

Windows to the Universe Schedule of Workshops NSTA National Conference, March 9 – 12, 2011 San Francisco

Thursday, March 10

- Activities from Across the Earth System 8:00-9:00am Moscone Center, 220 & 222
- Tackling the Global Warming Challenge 9:30-10:30am Marriott San Francisco Marquis, Yerba Buena Salon 11
- Playing with Ecosystem Science: Informal Modeling Games 12:30-1:30pm Marriott San Francisco Marquis, Yerba Buena Salon 11

Friday, March 11

- Point, Game, Set, Match 12:30-1:30pm Hilton San Fran Union Square, Continental 3
- Beyond Mere Attraction: Measuring Magnetism 2:00-3:00pm Moscone Center, 220 & 222

Saturday, March 12

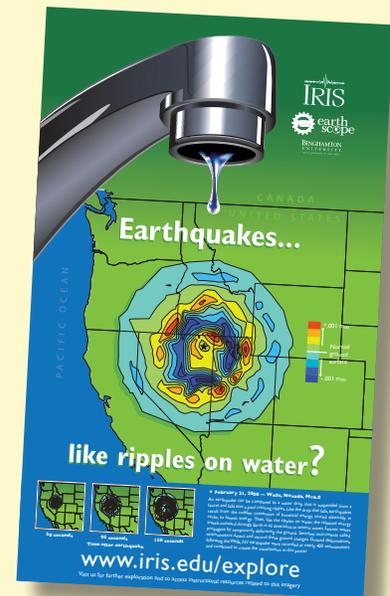
- Virtual Labs in the Earth Sciences: Melting Ice, Warming Climate, and Ballooning Through the Stratosphere 9:30-10:30am Moscone Center, 232 & 234

Windows to the Universe is a project of the National Earth Science Teachers Association

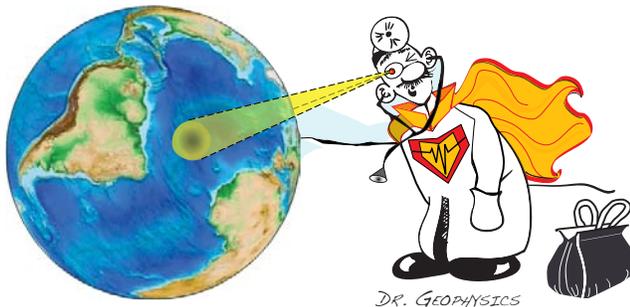
About the poster

The poster featured in this issue combines a visualization of ground motion resulting from the February 21, 2008 M 6.0 earthquake that occurred near Wells, NV, with the image of a faucet to illustrate a classic Earth science functional analogy: “Seismic waves radiate outward from an earthquake’s epicenter like ripples on water”. For students this discrepant image attracts attention and links the unfamiliar concept of the spreading out of seismic waves (the target) to a similar but more familiar scenario of ripples on water radiating outwards in all directions after a droplet or pebble falls onto it (the analog). Additionally the material is made approachable by using a clean artistic design, ideas students are likely to have experienced, and a prominent URL where students to learn more. When presented at the beginning of seismic waves instruction, this poster and its question (Earthquakes... like ripples on water?) becomes the catalyst for student-generated questions, inquiry, and learning.

- To learn more about the poster or to request a copy visit <http://www.iris.edu/hq/explore>
- To learn more about the ground motion visualizations used in the poster see http://www.iris.edu/hq/waves_about
- For ideas on using ground motion visualizations in classroom instruction see USArray Visualizations Show Seismic Waves Sweeping Across the U.S in this issue.



Wish you had super-vision?

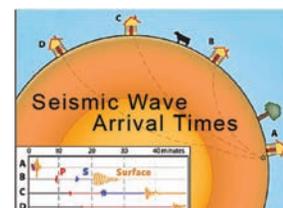
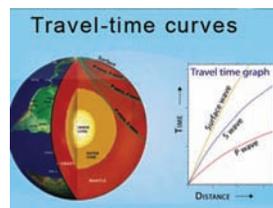
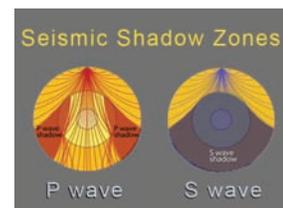


IRIS Animations offer an accessible view of seismological concepts such as:

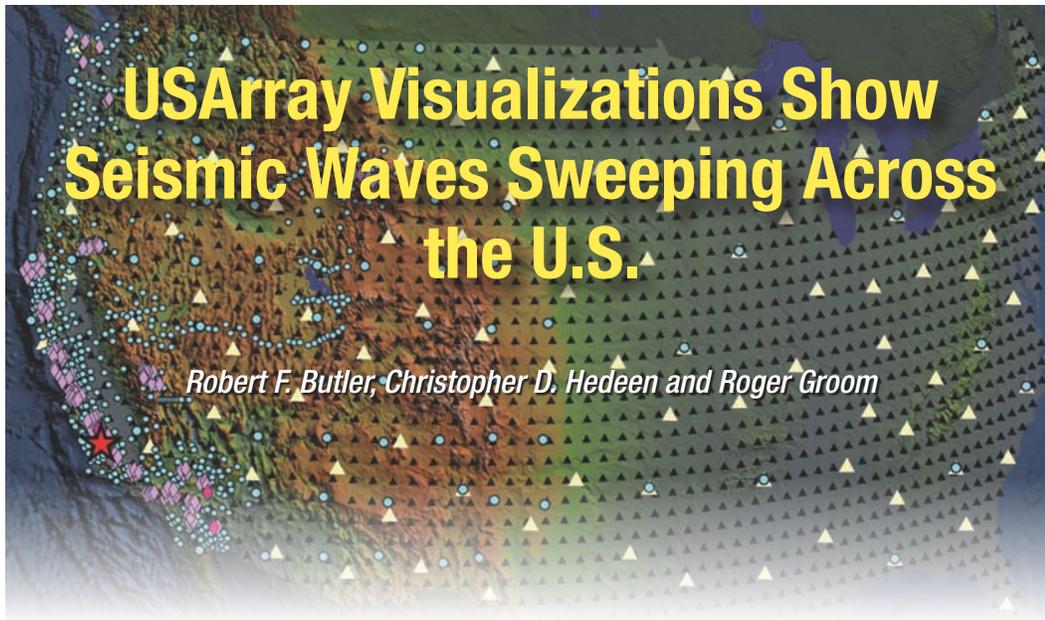
- How do we capture the motion of an earthquake?
- Where do travel-time graphs come from?
- How do earthquakes reveal secrets of Earth's interior?
- Why do seismic waves travel a curving path through the Earth?
- How do P & S waves give evidence for a liquid outer core?
- Can an earthquake be compared to a drop of water on a pond?



Seismologists do have powers...using seismic energy from earthquakes scientists can “see” deep inside the Earth. Now you and your students can too!



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Abstract

USArray is a collection of high-precision seismometers that record seismic waves from worldwide earthquakes with unprecedented spatial resolution. Visualizations of seismic waves sweeping across USArray provide visual reinforcement of seismic wave properties including the relative speeds of P (pressure), S (shear), and surface waves.

Introduction

Helping students understand properties of seismic waves is fundamental to teaching about earthquakes, seismology, and the internal structure of the Earth. There are many ways to introduce students to types of seismic waves and their properties. Each pedagogical approach emphasizes the two families of seismic body waves, P (= compressional) and S (= shear) waves, that travel through the interior of the Earth and the surface waves that travel around Earth's perimeter as they oscillate the crust and uppermost part of the mantle. Braille (2010a) provides background on seismic waves and computer animations of the different types of waves. Braille (2005, 2010b) explains how a single Slinky® can be used to demonstrate P and S motions along one ray path while multiple Sinkys® can be used to demonstrate wave fronts radiating away from a concentrated source like an earthquake. The freeware PC computer program Seismic Waves illustrates the propagation of P, S, and surface waves from an earthquake around and through the Earth (Jones, 2010). This computer program is an effective way for students to get the "big picture" of seismic waves travelling from an earthquake to distant locations as they refract and reflect (bend and bounce) at boundaries between internal zones of our planet. Taking students through this progression of seismic waves from a single ray path, to wave fronts of multiple rays, then to the global view of P, S, and surface waves travelling through and around Earth allows students to build their understanding of seismic waves in a logical fashion. The dense array of transportable seismometers known as USArray offers teachers and students an additional step in this progression through the ability to visualize seismic waves sweeping across North America.

EarthScope is a ten-year series of geophysical experiments to explore the structure of the North American continent and the underlying mantle (EarthScope, 2010). One component of EarthScope is USArray, a transportable network of 400 high-precision seismometers spaced about 70 kilome-

Figure 1. USArray seismometer deployment map. Starting in 2004, the array collected data over the western U.S. and has stepped progressively across the U.S. to its present location in the central portion of the contiguous 48 states.



ters apart (Figure 1). During the course of the EarthScope Project, seismometers will have occupied almost 2000 sites as the array steps across the contiguous 48 states and Alaska. These seismometers remain in one location for about 24 months before being moved to their next station. In this fashion, USArray is stepping across the U.S. recording minute vibrations of Earth's surface caused by thousands of worldwide earthquakes each year. Research seismologists are analyzing

these data to produce detailed three-dimensional images of the crust and upper mantle much like a radiologist uses thousands of X-rays shot through the human body in many directions to “see” details of internal organs. In this article, we describe how visualizations of seismic waves, recorded by USArray, allow visualization of seismic wave propagation as never before and how these visualizations can be used in middle school and high school Earth Science teaching.

USArray Visualizations

USArray visualizations provide a unique and powerful view of seismic wave propagation. The most time-efficient and effective way to learn to interpret USArray visualizations is to work through the tutorial provided by the Incorporated Research Institutes for Seismology (IRIS, 2010). Before beginning instruction, it is important to spend time studying each tutorial section to become familiar with the methods used to display the ground motions detected by USArray. In fact, the tutorial can also be shown as part of whole class instruction in a middle school or explored individually by high school students as an introduction to the USArray visualizations. Before you leave this tutorial, you should download the high-resolution visualization QuickTime file by clicking on the label “Hi-Res 36MB” beneath the second visualization window in Tutorial #5 (IRIS, 2007a). The downloaded file should have a QuickTime icon with name “mariana_globe”. You will use this visualization in the classroom demonstration described below.

Contrasting Velocities of Different Seismic Waves

The second visualization of Tutorial #5 shows seismic waves from a magnitude 7.4 earthquake in the Mariana Islands sweeping across the USArray seismometers. This earthquake occurred on September 28, 2007 when the array was located across the western U.S. The visualization starts with a global view of the wave fronts of P, S, and surface waves radiating away from the epicenter in the Mariana Islands of the western Pacific Ocean. On the visualization, P waves are color coded green while S waves are colored red and surface waves are shown in yellow. We offer two tips to help you and your students get the most out of the global view in this visualization while avoiding potential misconceptions: (1) It can be helpful to compliment the “flat screen” global view on the visualization by holding a globe and pointing out the locations of the epicenter and USArray to reinforce the actual three-dimensional spherical geometry. (2) On the visualization, the wave fronts of the P and S waves (body waves) appear as expanding circles with the epicenter at the center of those circles. To avoid the potential misconception that P and S waves travel only along the surface but faster than the seismic surface waves, these USArray visualizations can be supplemented with a program that illustrates how body waves propagate through Earth's interior. The *Seismic Waves* program is particularly effective for this purpose (Jones, 2005).

Following the global view, the visualization zooms in on USArray in the western U.S. as P, S, and surface wave fronts sweep across the collection of seismometers (Figure 2). On this view, the speeds of travel of different waves are visibly distinguishable with P waves travelling faster than S waves that in turn travel faster than surface waves. Students in our middle-school, high-school, and undergraduate Earth Science classes indicate that such visualizations are a very effective as a visual reinforcement of the contrasting velocities of seismic waves discussed in class. Our students often comment that the USArray visualization is the most effective item they have seen, heard, or read that helps them understand the relative speeds of seismic waves.

Measuring Seismic Wave Travel Times

To get more out of this visualization, examine the travel times for P, S, and surface waves from the earthquake to USArray and determine the times required for these waves to cross the array. Time is shown on the bottom left corner of the lower inset of the visualization. The format for the time stamp is YYYY DDD HH MM SS with time in Greenwich Mean Time. For example, the origin time for the Mariana Islands earthquake at 13:38:58 on September 28, 2007 translates to 2007 271 13 38 58, the time stamp on the first frame of the visualization. Carefully examine details of timing of the seismic waves. For example, use the fast-forward, rewind and pause buttons of your media player to control the visualization to determine exactly when the first S wave arrive in the northwest corner of USArray? In this way, the times of arrival of P, S, and surface waves at the USArray station nearest the earthquake in northwest Washington (Forks, WA station about



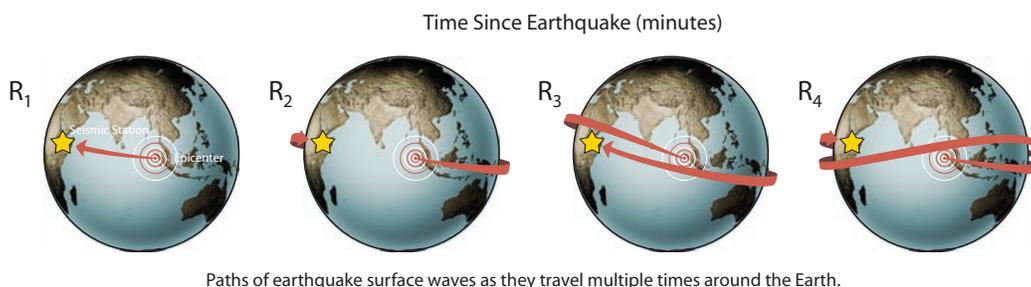
Figure 2. Shear (S) waves from September 28, 2007 Mariana Islands earthquake crossing USArray. Each seismometer recording an upwards motion of Earth's surface is shown by a blue circle while each seismometer recording a downwards motion is shown by a red circle. The pattern of red and blue dots indicates that two full S waves fit within the long dimension of the seismometer array. The red line on the map indicates the front of the series of S waves. Top inset illustrates an edge-on view of seismic waves travelling perpendicular to the wave fronts. Bottom inset illustrates the seismogram recorded by the station circled with red line in southern Oregon. The red line on the seismogram is the time mark.

Observation units	Time (GMT)	Travel Time (HH MM SS)
Earthquake occurs in Mariana Islands	13 38 58	00 00 00
1st P wave arrives in northwest WA	13 50 13	00 11 15
1st P wave leaves southeast AZ	13 51 43	00 12 45
Time for P wave to cross USArray		00 01 30
1st S wave arrives in northwest WA	13 59 33	00 20 35
1st S wave leaves southeast AZ	14 02 23	00 23 25
Time for S wave to cross USArray		00 02 50
1st surface wave arrives in northwest WA	14 16 33	00 37 35
1st surface wave leaves southeast AZ	14 25 18	00 46 20
Time for surface wave to cross USArray		00 08 45
Surface wave arrives in southeast AZ after travelling the long way around Earth from Mariana Islands to USArray!	15 51 38	02 12 40

Table 1. Travel times for P, S, and surface waves from earthquake in Mariana Islands to USArray seismic stations.

8400 km [$\sim 76^\circ$ epicentral distance] from the earthquake) and farthest from the earthquake in southeast Arizona (Douglas, AZ station about 10,300 km [$\sim 93^\circ$ epicentral distance] from the earthquake) have been determined and are listed in Table 1. These arrival times and the time required for P, S, and surface waves to cross USArray, nicely demonstrate the relative speeds of different types of seismic waves. While textbooks describe how P waves are faster than S waves that in turn are faster than surface waves, this visualization of seismic waves quantitatively reinforces these important concepts. You can turn this segment of the classroom demonstration into an inquiry lesson by giving students the “mariana_globe” visualization and having them determine the arrival times.

Even after the P, S, and surface waves from the Mariana Islands earthquake have swept across USArray, there is still more information to be gathered from careful analysis of this visualization. After the surface waves leave USArray, there are other waves that continue to be detected by the seismometers. These include P and S waves that have reflected and refracted at Earth’s internal boundaries such as the boundary between the mantle and outer core and between the inner and outer core. At about 70 minutes (4200 seconds) after the earthquake, some well-defined waves



Paths of earthquake surface waves as they travel multiple times around the Earth.

Figure 3. Paths of travel of surface waves from the great Sumatra – Andaman Islands earthquake of December 26, 2004 observed from a seismic station in east Africa. R1 is the first arriving surface wave that travelled directly from the earthquake westward to the station while R2 is the second arriving surface wave that travelled eastward the long way from the earthquake to the station. R3 and R4 are surface waves that travelled more than once around the planet to the station in a westward and eastward direction, respectively.

to northwest arrives in southeast Arizona. This is the surface wave that travelled the long way (29,600 km!) around the Earth from the Mariana Islands to USArray. Figure 3 shows the paths of surface waves that can travel multiple times around the Earth. It is astonishing that seismic waves that have travelled all the way around planet Earth can still be detected by sensitive seismometers! Great earthquakes, like the December 26, 2004 magnitude 9.2 Sumatra earthquake, generate seismic waves that are detectable after several passages around the globe. In fact, great earthquakes cause the Earth to vibrate like a bell in “free oscillations” that can last for several days after the earthquake.

Accessing and Using USArray Visualizations from Other Earthquakes

The generation of visualizations of the data from the USArray has become an automated process at the IRIS Data Management Center. As a result, hundreds of visualizations are available for download from this archive (IRIS, 2007b). The most effective way to search for a visualization is to know the date of the earthquake. For example, the visualization for the magnitude 7.9 Sichuan earthquake that took more than 85,000 lives on May 12, 2008 can be located by searching on the date using the format 2008/05/12. Once you have located the desired earthquake in the archive, you can view the visualization by simply clicking on the link to the visualization in the right hand column. To find visualizations for earthquakes recorded when USArray was located in your region, you can use figure 1 to determine when the array was in your area then search the archive for notable events during that interval. There are many possibilities for computer lab activities in which students can search the archive for visualizations. For example, the visualization for the Wells, Nevada earthquake of February 21, 2008 (IRIS, 2008) is a favorite because the earthquake occurred within USArray and the radiation of seismic waves away from the epicenter is quite dramatic. A classroom

traverse from southeast to northwest across USArray. These are P waves then S waves that have travelled the long way around the Earth from the Mariana Islands to USArray. At about 2 hours and 13 minutes after the earthquake, a yellow line travelling from southeast

poster titled “Earthquakes like ripples on water?” and an activity featuring seismic waves radiating from this earthquake are available from IRIS (2010). Indeed the poster featuring the Wells, Nevada earthquake is included in this issue of *The Earth Scientist* to serve as an invitation to students as they begin studies of earthquakes and seismology.

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Note: A PDF with “live” links to the Internet resources below can be retrieved from <http://orgs.up.edu/totle/index.php?q=node/413>

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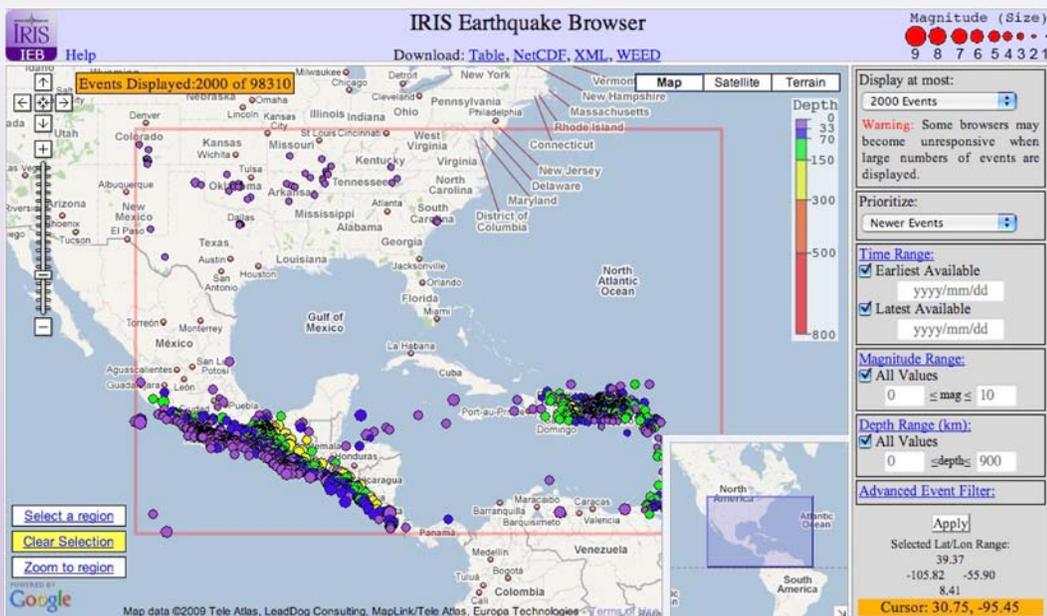
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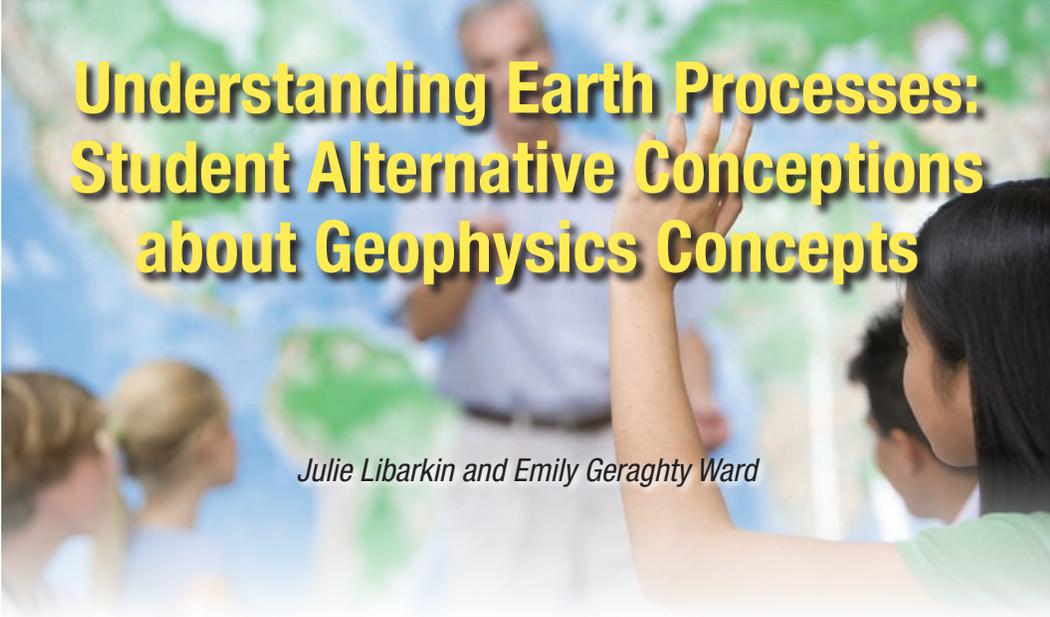
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Understanding Earth Processes: Student Alternative Conceptions about Geophysics Concepts

Julie Libarkin and Emily Geraghty Ward

Abstract

Understanding student ideas about science is an important part of instruction, and can provide the insight needed to help students build deep conceptual understanding. Geophysical phenomena, particularly gravity and geomagnetism, play an important role in our understanding of the Earth. The mechanisms by which mountains are built, the nature of plate tectonic movement over time, and even the structure of the planet are all explored through the use of geophysical data. Students hold a wide array of alternative conceptions about geophysics, and some of these ideas persist despite instruction and expertise. We present a brief review of the literature on students' conceptions of geophysical topics and make suggestions for use of research-based alternative conceptions in the classroom.

Introduction

The interdisciplinary field of geophysics plays an important role in classroom instruction about many geoscience topics. For example, concepts like gravity are necessary to understand phenomena such as the ocean tides while a conceptual understanding of magnetism is needed to explain the origin of the Northern Lights. Likewise, physics is both inherent to the forces responsible for plate tectonic processes and the backdrop for the geophysical techniques that were central to the development of plate tectonic theory. With the push toward involving real-world scenarios and problem-based learning in today's science classrooms, designing classroom activities requires attention to the latest findings in science. Hence, instructors may incorporate data gathered from modern techniques such as gravity anomalies, LiDAR, and magnetic imaging, for example, to build an understanding of geoscience phenomena in subfields as diverse as glaciology, paleontology, and petroleum geology.

Student conceptions about geoscience topics have gained significant attention in recent years, spurred by similar work in other fields as well as from recognition of the importance of student ideas in designing effective instruction. This research spans the K-college continuum, and has occurred in the U.S. and abroad. Comprehensive reviews covering a wide range of studies and suggestions for instruction are available in Dove (1998), King (2008) and Cheek (2010). For this

paper, we focus on those conceptions pertaining to geophysics and offer recommendations on how to use these conceptions to inform instruction and facilitate student learning. You will notice that we use the term “alternative conception” rather than “misconception” throughout this paper. While scientists favor “misconception”, science educators have pointed out that students’ alternative ideas can be based on deep reasoning and can contain elements of correct models, rather than simply being incorrect. For this reason, we favor “alternative conception” when discussing students’ non-scientific ideas.

Student Ideas about Geophysics

We broadly interpret “geophysics” to mean those concepts typically classified within the domain of geophysics, such as seismology, as well as geoscience phenomena that are explained through inherently physical principles. Research on student conceptions about geomagnetism and Earth’s gravitational field is well developed, with some work evident in other geophysical areas, such as seismology. The first author has participated in research on conceptual understanding with children as young as 6, with middle school, high school and college students, and with graduate students and expert geoscientists. Data collected over the past decade has revealed a startling persistence in alternative conceptions across all ages and groups. Although our research was not designed to collect ideas about geophysics, per se, the totality of the peer-reviewed literature and our own data provide insight into those ideas that are most common and may persist despite instruction. We have summarized some of the most prevalent ideas below.

Geomagnetism and Earth’s Gravitational Field

The origins of the Earth’s magnetic and gravitational fields, as well as their effects, are a mystery to many students. Very often, the cause and effect of each of these fields are confused with the other, resulting in reasoning that is far afield from scientific models. For example, students often reason about what would happen on Earth as the result of simple changes to Earth’s magnetism or gravity. In an interview, one college student reasoned about the result of the Earth’s magnetic field vanishing:

Question: *“So if we didn’t have a magnetic field, like let’s say you and I were walking hand in hand down the street and the magnetic field just disappeared, what would happen?”*

Response: *“If it disappeared, in theory it seems like everything would just fly off into space.”*

The expressed idea that the magnetic field keeps objects at Earth’s surface is quite prevalent in our research. Students similarly believe that magnetism plays a role in keeping satellites in orbit. Common ideas about the origin of gravity include gravity being produced by: Earth’s rotation, the geomagnetic field, material beneath Earth’s surface, Earth’s planetary position, and the Moon (e.g., Asghar & Libarkin, 2010). The Earth’s magnetic field, in addition to being confounded with the gravitational field, is believed by many students to originate from magnets or magnetic rocks at the Earth’s poles (Marques & Thompson, 1997), stripes on the sea floor, or a magnet in Earth’s core.

Other Ideas

Student ideas about the forces responsible for the movement of material on Earth, both at the surface and within the planet, are influenced by common alternative conceptions about physics and geophysics. Regardless of whether or not students are considering movement of ice, tectonic plates, or mountains, student ideas about pressure, gravity, magnetism and geophysical processes influence ideas about movement. For example, students may believe that magnetic polar wander (Marques & Thompson, 1997), magnetic stripes on the ocean floor, ocean currents, or earthquakes cause tectonic plate motion. Similarly, many students believe that rocks subside to form ocean basins

(Marques & Thompson, 1997), and that a release of internal pressure causes rocks to move, forming mountains. Similar alternative conceptions about movement of other material, such as glaciers or sediment, are quite common and well documented in the literature (e.g., Cheek, 2010).

Research into student ideas about other geophysical concepts is growing, although much research remains to be done. Study of student conceptions about earthquakes is increasing in young children, in college students, and in countries where earthquakes are an active hazard (e.g., Rakkapao, Arayathanitkul, & Pananont, 2009). These emerging data indicate that students have a weak grasp of the meaning of “earthquake”, literally equating earthquakes to shaking rather than energy release, and find many of the fundamentals of seismology, such as wave types, confusing. By extension, students’ ability to reason about the evidence underlying models of Earth’s interior is shaky (e.g., King, 2002). Analysis of student conceptions about other domains of geophysics, such as seismic refraction, warrants significant further research.

Persistence of Ideas

Research indicates that alternative conceptions about geophysics may persist well beyond secondary school, even among experts. This persistence may result from the fact that most undergraduate and graduate faculty, and perhaps even teachers, assume that students hold a basic scientific understanding of gravity, magnetism, force, and other physical concepts. For example, published work (Asghar & Libarkin, 2010) indicates that students’ conceptual understanding in entry-level geoscience courses looks much like that of young children when it comes to ideas about the cause of Earth’s gravity. In fact, we have found that advanced undergraduate majors, graduate students and even college faculty teaching in related Earth sciences hold alternative conceptions about geophysics and the role of physical principles in explaining Earth processes. In interviews with college students, graduate students and expert geoscience faculty, Clark (2009) documented persistence of the idea that subducting plates melt to produce surface volcanism. This alternative conception may result from, or be reinforced by, a misunderstanding of the scientific model for subduction-related melting as well as observations. Dewatering of minerals in subducting plates produces melts in overlying asthenosphere, which then rise towards Earth’s surface. The concept of dewatering is not clearly explained in entry-level texts or online resources; melting and dewatering can easily become confused within the complex model that is plate tectonics. In addition, the idea of a melting plate does not contradict observations; the melts produced by a subducting plate and the melts produced by asthenosphere will be compositionally similar to anyone but a trained petrologist. Being able to reason that the asthenosphere melts, rather than the subducting plate, requires an understanding that a subducting plate is too cold to melt at the depths (and pressures) at which magmas are being produced. (The fact that even expert geologists do not independently utilize this reasoning suggests that many people will still hold alternative conceptions related to fundamental aspects of the plate tectonic model even after instruction (Clark, 2009). Once we recognize that alternative conceptions are both common and to be expected, we can use them as a starting point for engaging students in deep thinking about geophysics.

Implications for Instruction

We argue that geoscience is particularly hard-pressed for opportunities that encourage students to challenge their models about phenomena because many geologic processes have occurred in the past, and hence are un-testable, or occur at physical or temporal scales that inhibit direct observation. Below, we suggest ways in which student conceptions about geophysics can be used to alter instruction and engage students in deeper thinking (e.g., Libarkin & Stokes, in press).

Using student alternative conceptions in instruction

Using knowledge about student alternative conceptions to help students uncover their own ideas may be the most powerful, and simple, use of conceptions research (Strike and Posner, 1992; diSessa, 2006; Aikenhead & Jegede, 1999). We suggest that encouraging students to draw, write, and talk about ideas is vital for encouraging students to evaluate and rethink their alternative conceptions. Teachers can utilize these techniques at the beginning of a school year, or during instruction as a way to introduce a new subject. By determining what students think prior to instruction, teachers will gain an understanding of their students' strengths, as well as those areas that need to be addressed in order for students to grasp geophysics concepts. With this knowledge, teachers can tailor their instruction to build upon student strengths and address areas of difficulty.

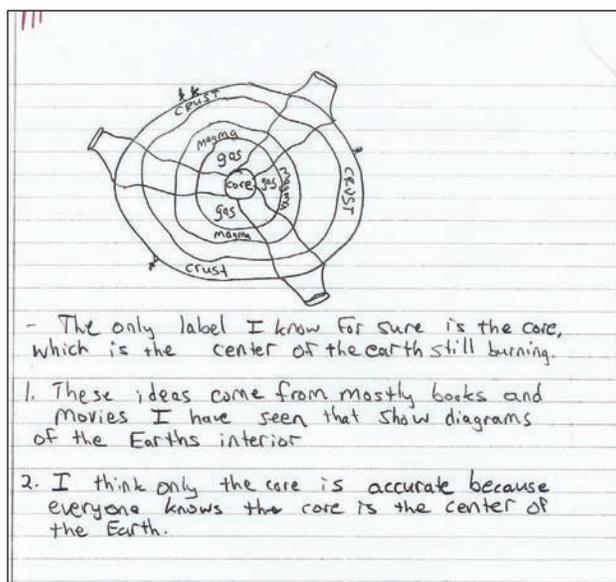


Figure 1. An example student drawing related to the structure of Earth's interior. The student was prompted to draw a model of the Earth's interior, including the source of lava. Drawings such as this can be used to scaffold to other ideas about geophysics. For example, placement of earthquake wave ray paths within the context of this model would either challenge the student's model or provide additional insight into alternative conceptions about earthquakes.

The approach used to encourage students to think deeply about their own ideas depends on student age, as many approaches that might be used for older students are inappropriate for students that are much younger. However, we have found that methods used with younger students are actually quite effective for use with older students, even those in advanced secondary or college courses. Ideas held by younger students, particularly those who are just beginning to write and read, can be illuminated through drawings (Fig. 1) and classroom discussion. In the geosciences, for example, drawings have been used across many age groups to investigate plate tectonic and related conceptions (e.g., Gobert, 2000; Sibley, 2005). We note that understanding how a scientist illustrates a concept is an important step to using student drawings to identify concepts that might need additional discussion in the classroom. Student drawings can be compared to scientific models, such as those available through the U.S. Geological Survey (e.g., <http://pubs.usgs.gov/gip/dynamic/dynamic.html>). We also recommend asking a scientist to make a drawing for you. Overall, we

have found that geologists are more than willing to assist us in classroom instruction or research by providing their own responses to the types of questions we generally ask students.

Although drawings provide excellent opportunities for students to express their conceptual understanding, subsequent classroom discussion, one-on-one conversation, in-class questions (Fig. 2), or other opportunities for students to verbally explore their ideas gives both students and teachers insight into concepts that are difficult to understand. Verbal expression of ideas gives students the opportunity to learn from one another, and become more confident in their own knowledge as they use it to help a classmate. By posing questions to students in class, having them make predictions about geophysical processes, and allowing them to manipulate and/or collect geophysical data, students have the opportunity to challenge their own ideas and gather evidence that supports scientific thinking. A good example of an activity that provides students with the opportunity to construct their own knowledge is Sawyer's "Discovering Plate Boundaries" activity (<http://plateboundary.rice.edu/intro.html>). This exercise provides students with opportunities to make predictions about where tectonic plate boundaries should occur, and to use geophysical and other evidence to reason to the plate tectonic model. In our own instruction with undergraduate non-majors, we use this activity after first prompting students to draw pictures of tectonic plates and provide written explanations for plate tectonic phenomena. We follow the activity with additional probing about student ideas, giving us insight into concepts that might need additional attention.

Alignment with National Standards

Although states maintain their own standards for K-12 science education, national standards provide a relevant foundation for placing alternative conceptions in an instructional context. In Table 1, exemplar national standards have been aligned with alternative conceptions that have been identified in students through conceptions research, as described above. Bringing an awareness of these conceptions into the classroom can provide a bridge between scientific and students' ideas, particularly when designing and delivering instruction.

Conclusions

Educators have the ability to design and implement effective instruction that accounts for the importance of students' prior knowledge in learning science. With an awareness of students' alternative conceptions of gravity and magnetism, educators can guide students in thinking deeply about geophysical conceptions and work with students' conceptual frameworks to facilitate student learning. Whether through use of challenging multiple-choice questions grounded in student conceptions, through student drawings and classroom discussion, or through other techniques, educators can use student ideas to improve their instructional practice. These same methods can be used to assess student learning following instructional interventions that target specific concepts in geophysics.

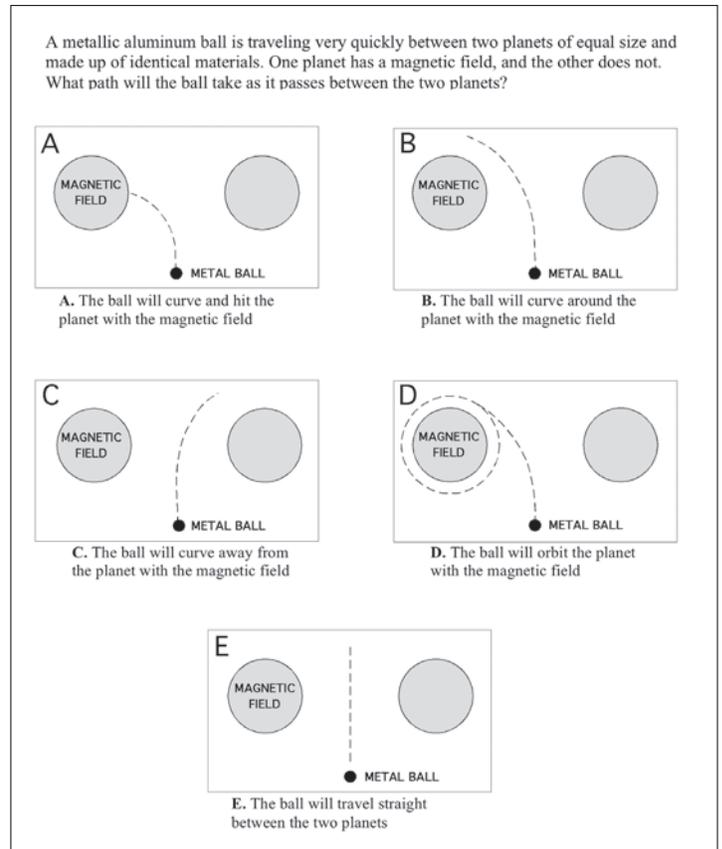


Figure 2. An example of a question that could be asked to generate class discussion with regard to gravity and magnetism. This particular question is part of the Geoscience Concept Inventory (GCI), which contains questions designed from common alternative conceptions held by freshman-level college students in non-science courses. Although the GCI was designed for this student population, the questions can be modified to align with student ideas common to middle and high school Earth Science courses.

Table 1. Alignment between Earth-related national standards and research-based alternative conceptions in geophysics.

Grade Level	National Standard (AAAS, 2003)	Example Alternative Conceptions
K-2	Chunks of rocks come in many sizes and shapes, from boulders to grains of sand and even smaller. 4C/P1	Rocks are heavy or dense; lighter materials cannot be rocks. Rocks form at Earth's surface due to heating or air pressure.
3-5	Things on or near the earth are pulled toward it by the earth's gravity. 4B/E1	Alternative conceptions for cause of gravity include Earth's rotation, magnetism, and planetary position.
6-8	Everything on or near the earth is pulled toward the earth's center by gravitational force. 4B/M3	The Earth's magnetic core causes gravity.
6-8	...Mountains form as two continental plates, or an ocean plate and a continental plate, press together. 4C/M12	Mountains form from a build-up of pressure in Earth's core.
9-12	Scientific evidence indicates that some rock layers are several billion years old. 4C/H6	Earth formed exactly as it appears today. Radioactivity is something created by people.

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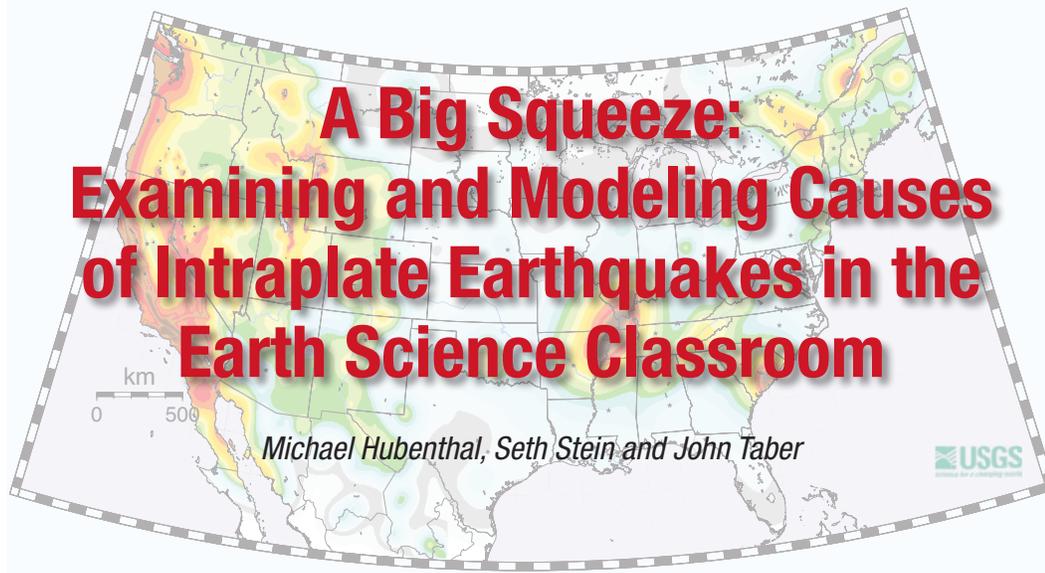
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Abstract

Recent research suggests that the mechanics of earthquakes that occur within plate boundaries, regions called intraplate seismic zones, require a significantly more complex model than at plate boundaries. The implications of this research are fueling both scientific and societal debates because scientific understanding of intraplate earthquakes has significant implications on hazard assessments for such regions. To help students develop a conceptual model of the underpinning phenomena of intraplate earthquakes, this article links our current understanding of intraplate seismicity to a physical model useful for classroom instruction.

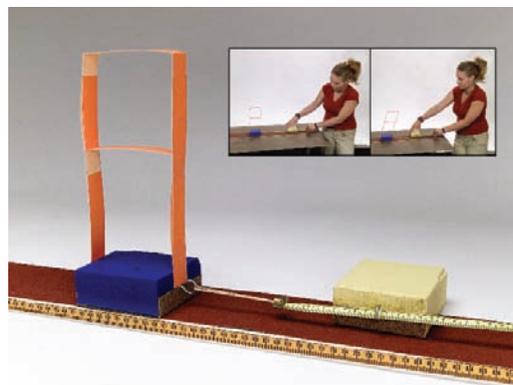
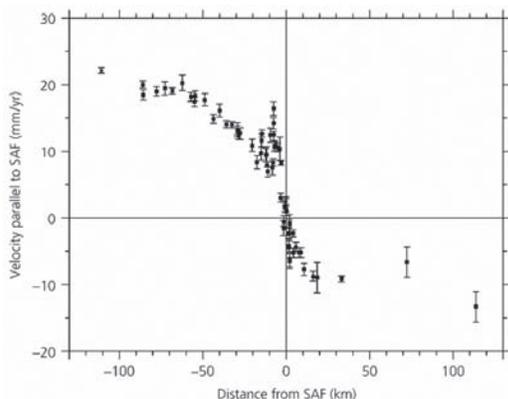
Introduction

Earthquakes that occur within plate boundaries, called intraplate earthquakes, have long intrigued both students and educators. Classroom exploration of U.S. seismicity and hazards maps inevitably generates numerous questions from the learners regarding the New Madrid Seismic Zone (NMSZ). Unfortunately, many earth science teachers are not prepared to exploit this interest by discussing the ongoing debate regarding the seismic hazard in the region. Instead, they are likely to respond to such questions by stating only that these issues are not well understood. Such a response is likely the result of two factors; 1) many teachers lack adequate knowledge of the current understanding of intraplate seismic zones and 2) teachers lack adequate instructional tools to convey such content to students. To empower teachers, this article summarizes ideas about the mechanisms of intraplate seismic zones and links these to a physical model useful for exploring this phenomena and the debate surrounding it.

Intraplate Seismic Zones: NMSZ as a Laboratory

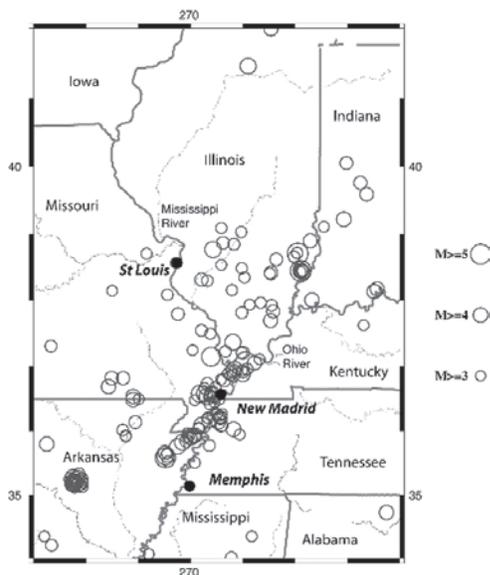
Harry Reid, following his investigation of the 1906 San Francisco earthquake, proposed what has become the commonly accepted explanation for earthquakes. His *elastic rebound theory* states that earthquakes occur when elastic strain builds up over time due to motion between the two sides of an active fault. This energy is stored elastically in rocks until eventually the stress on the fault exceeds its frictional strength. When this critical value is reached, accumulated elastic strain is released as the fault slips in an earthquake. This cycle then repeats to produce another earthquake on the fault. This idea is well established in plate boundary regions, where motion across faults

Figure 1. Left – GPS data across the San Andreas fault. This data shows the accumulation of elastic strain (Z.-K. Shen). Right – The Earthquake Machine Lite. By pulling the rubber band connected to the block with the paper building, this simple stick-slip model illustrates the accumulation and sudden release of elastic strain (Hubenthal et al, 2008).



results from the constant motion of Earth’s tectonic plates. In the classroom the process can be beautifully shown by GPS data that record the accumulating strain, is relatively intuitive and comprehensible to students, and can be modeled with students (Figure 1).

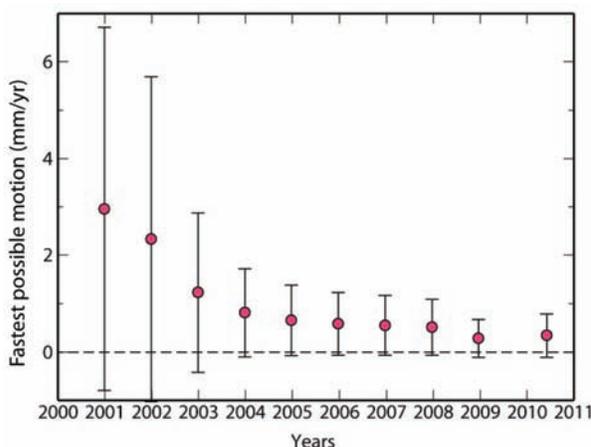
Figure 2. The New Madrid Seismic Zone (NMSZ). Locations of earthquakes between 1975 and 2008 in and around the NMSZ.



However, when this notion is applied to intra-plate earthquakes, the simplicity of the theory fails to adequately explain our observations. The NMSZ is an example of this incongruity (Figure 2). Here, large (magnitude 7+) earthquakes felt across the Midwest occurred in 1811 and 1812, small earthquakes occur today, and the deformation of landforms and sediments (see About the Cover, page 6 of this issue) provide evidence of large earthquakes (magnitude 7 to 8) over the past 4500 years (Tuttle et al., 2005; Stein, 2011). Viewed through the lens of the elastic rebound theory, one would expect to see strain building up for another large earthquake. However, a GPS study across the NMSZ in 1996 failed to find such an accumulation (Newman et al., 1999). Successive studies since then have

confirmed this surprising result with progressively higher precision (Figure 3). A recent analysis shows that present-day motions within 200 km of the NMSZ are indistinguishable from zero and less than 0.2 mm/yr or roughly the thickness of a piece of fishing line (Calais & Stein, 2009). Thus,

Figure 3. GPS data across the NMSZ. Successive GPS studies in the New Madrid area show that motion across the entire region is at best, very small. At this rate, 10,000 years would be required to accumulate enough slip for a magnitude 7 earthquake, and a magnitude 8 would require 100,000 years (Calais, 2010).



the NMSZ appears, from the surface, to be deforming far more slowly than expected if large earthquakes are to continue to occur as they have in the past.

The challenge is how to reconcile the discrepancy between this GPS data with the history of seismic activity in this region that continues on today. In one view, the ongoing seismicity is evidence that the processes that produced large

events in the past are still at work today. In this view, seemingly contradictory GPS observations are attributed to models that suggest that unlike in plate boundary settings, little deformation will occur across intraplate seismic zones. These models propose that large events are either triggered by local driving forces such as sudden weakening of the crust or reflect continuing release of stress accumulated over times much longer than the past few thousand years (Smalley et al, 2005). If these models are correct, earthquakes similar to the 1811-1812 events can be expected with an average recurrence time of 500 years (Tuttle et al., 2002).

An alternative explanation for the discrepancy suggests that the development of strain in intraplate seismic zones results from interactions among all the faults in the region. Although each fault behaves according to the elastic rebound theory, the faults together form a complex system that cannot be understood by merely considering behaviors of any individual fault. For example, a large earthquake on one fault might not only release stress on that fault, but would also change the stress on other segments of that fault or nearby faults. Furthermore, long periods of mechanical locking or clusters of repeated earthquakes on one fault could affect the loading rate on neighboring faults. The rate of strain accumulation on any given fault varies depending on the forces acting within the plate, the geometry of the fault system, and the response of both the faults and the material between them to stress. As a result, the locations of large earthquakes within intraplate systems might be expected to vary in space and time. In this view, the small earthquakes that occur today are more likely to be aftershocks of past large earthquakes than indicators of where future ones will occur.

This hypothesis is illustrated by data from another intraplate seismic zone, the North China Seismic Zone. Here earthquakes have been recorded both historically by humans and in the deformation of landforms and sediments, with the historic record extending back to 1300A.D. In Figure 4 we see that the seismicity clusters on one region of faults, and then migrates both spatially and temporally in an unpredictable pattern to another region. Ultimately, no large ($M > 7$) events ruptured the same fault segment twice during this time period.

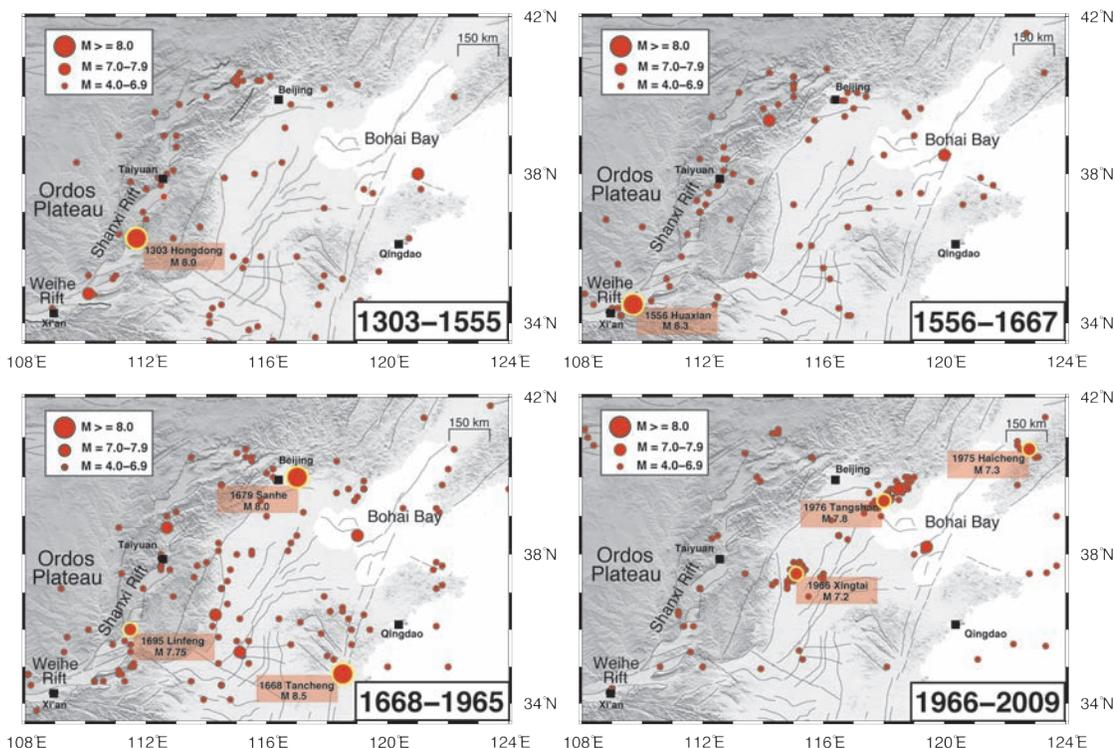


Figure 4. Seismicity in North China (1303 –2009). Note how the seismicity and large earthquakes cluster and migrate across the intraplate seismic zone as time progresses. Ultimately, no large ($M > 7$) events ruptured the same fault segment twice during this time period. (adapted from Liu et al., 2011)

Representing Intraplate Seismic Systems in the Classroom

As introduced previously, the scale of the mechanics of intraplate earthquakes, both spatially and temporally, is quite large. As a result such concepts are abstract for students. One strategy to aid in concept development is to connect learning concepts, the target, with familiar concepts, an analog that shares attributes with the target (Cawelti, 2004). This connection of target to analog occurs through a process of mapping, or identifying relevant attributes of both the target and the analog and defining a correspondence between the two. Ultimately, mapping enables learners to develop a mental model, or way of understanding the process under investigation, based on their own experience. Well-selected analogies also have an added benefit of having the power to interest and excite student learning (Harrison, 2002).

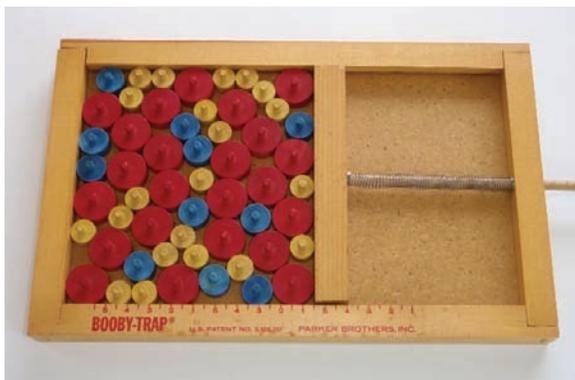


Figure 5. Booby Trap™. A 1960's era board game that can model the complex distribution of stress, both pre and post earthquake, across intraplate seismic zones.

R. Smalley of the University of Memphis has pointed out that the classic game Booby Trap™ functions in a way that is useful when conceptualizing intraplate systems. The game (Figure 5) consists of a spring loaded game board and small round playing pieces. The object of Booby Trap™ is to remove the most pieces from the board while causing the slider bar to move the least. To do this, players attempt to visually identify pieces that have the least stress on them. The challenge of the game stems from the complexity and geometry of stress transfer within the system and the inherent limitations of using visual resources to gauge “loading”. These challenging elements make Booby Trap™ a model for thinking and learning about intraplate seismicity.

Learners are unlikely to have the background experiences and knowledge upon which to view the model from the same perspective as the instructor (Greca & Moreira, 2000). Therefore, care and time must be taken to make the mapping explicit. In this case, we can think of the game board as an intraplate seismic zone spanning several thousand square kilometers. The borders between playing pieces represent the complex fault systems between crustal blocks. The game board's spring loaded “tension bar” presses on the pieces, distributing stress across the playing pieces. This distribution of stress from a distant force is similar, albeit simpler, to Earth's tectonic processes that slowly and steadily stress intraplate systems.

Because Earth materials are elastic, rates of loading on the various fault segments within the intraplate seismic zone are variable. Over time, the accumulation of elastic strain on a fault segment within the region will exceed the frictional strength of the fault. Once this threshold is reached, the elastic strain in that area is released as an earthquake. We model this process by removing “loaded” pieces from the playing area. After a playing piece is removed the sudden forward movement of the tension bar represents the occurrence of an earthquake. As in Earth, stress is redistributed across the system following an “earthquake”. Frequently, the pattern of loading is difficult to predict; the loading of some pieces increases while other pieces remain the same or are left with little stress on them.

Although Booby Trap™ functions in a way that maps nicely to Earth processes, it is a simplification of a complex Earth system. To fully interpret the model, the differences between the model and reality should also be emphasized. This is particularly important for high school students, who often think of physical models as copies of reality rather than representations (Grosslight et al. 1991). For example, the model has a number of obvious shortcomings such as its scale and composition, and that the applied stress is unidirectional and essentially constant. In contrast, tectonic plates are extremely large, heterogeneous, and are loaded in complex ways that result in variations to the stress applied to any intraplate seismic zone.

Using the Model for Student Instruction

The goal of this instruction is to encourage students' development of a mental model for intraplate seismic zones that include the following elements:

- Elastic rebound theory describes individual faults' behavior and appears to adequately describe temporal and spatial patterns of seismicity across plate boundary regions.
- Intraplate seismic zones
- are more complex than plate boundaries and the elastic rebound theory applied to any individual fault appears inadequate to explain temporal and spatial patterns of seismicity,
- may distribute stress and thus earthquakes across all the faults within the zone in a complex pattern that varies temporally.
- transfer stress within the system, following an earthquake, in a way that is difficult to predict
- It is unclear whether past locations of earthquakes are predictors of future events in intraplate seismic zones.

To convey this content we propose an instructional sequence (Table 1) that begins with a game of Booby Trap™. While seemingly off topic, this step is important as it ensures that all students are familiar with the functioning of the analog. Next, we introduce the NMSZ and gauge student's

Table 1. Positioning Booby Trap™ instructionally. Use of the model is positioned within a learning cycle to maximize classroom impact.

An online version of this table, with clickable links for resources, is available at http://www.iris.edu/hq/resource/booby_trap

Learning Cycle	Description	Resources
Prerequisite Instruction	Introduce and explore elastic rebound theory as a mechanism for earthquakes	<ul style="list-style-type: none"> • Earthquake Machine model • Elastic rebound animations • GPS data: both across the San Andreas boundary, and a more regional view of plate motions.
Open	Have students play Booby Trap™ as class under flexcam or in small groups	Booby Trap™ is available online for ~ \$15
Prior Knowledge	<p>Introduce intraplate seismic zones by exploring and describing the following with your students</p> <ul style="list-style-type: none"> • US Hazard Map • Description of 1811-1812 events • Paleoseismic record of historical earthquakes in NMSZ • Current seismicity in NMSZ <p>Ask students to predict a mechanism for large earthquakes in this region and what they think the current pattern of seismicity suggests for the future?</p>	<ul style="list-style-type: none"> • U.S. Hazard Map • Map of NMSZ • Description of 1811-1812 events (including photos, eye witness accounts, earthquake summary, etc.) • Description of paleoseismic evidence • Current seismicity of the NMSZ
Explore/Explain	<ul style="list-style-type: none"> • Introduce GPS data across the NMSZ and compare to student predictions. • Explore study of the North China Seismic Zone • Reintroduce the Booby Trap™ as a model with explicit mapping between target and analogy. • Lead guided discovery of Booby Trap™ 	<ul style="list-style-type: none"> • GPS data across the NMSZ • Example from North China Seismic Zone • Mapping of intraplate seismic zones to Booby Trap™ from this article
Reflect	Journal-write on their conception of the relationship between elastic rebound theory and intraplate earthquakes.	
Apply	Assign Is the Midwest's NMSZ a Serious Threat for student reading. Discuss in small groups.	Page 17 of Earthquake Threat: Is the U.S. Ready for a Seismic Catastrophe? See additional readings below.

Additional readings for teachers or students

USGS Fact Sheet - Earthquake Hazard in the New Madrid Seismic Zone Remains a Concern

USGS Fact Sheet - Hazard in the Heart Land

Stein, S., Disaster Deferred: How New Science is Changing our View of Earthquake Hazards in the Midwest, Columbia University Press, 2010

Billitteri, T. (2010). Earthquake Threat: Is the U.S. Ready for a Seismic Catastrophe? *CQ Researcher*, 20(14), 313-336.

Nova Science Now - Earthquakes in the Midwest

prior knowledge by asking them to make predictions about the mechanics of the NMSZ and future seismicity. Based on a growing body of literature suggesting that guided discovery is more effective than pure discovery (e.g. Mayer, 2008) we elaborate on a series of prompts useful to encourage students' exploration of the physical model. To further refine student's mental models, students reflect on their understanding through journaling, with feedback from the instructor. The instruction concludes by encouraging students to read a one-page article on the scientific debate and applying their new knowledge through peer discussions. For brevity, the discussion below only expands on the guided inquiry with the model.

Begin by randomly seating the colored pieces into the playing area. Gently release the slider so it applies stress to the pieces. Place the game under a flexcam or a webcam, projected onto a screen, so students can see the model. Next, based on the discussion in the previous section, identify the germane elements of Booby Trap™ and define how these elements correspond to intraplate seismic zones for the students.

Ask students to think about stress distribution across the playing area. Will this be even or will some pieces be under more stress than others? To visualize the stress distribution in the system, ask volunteers to come up, examine the board (feeling pieces is allowable) and remove a piece that is unlikely to cause an earthquake. Repeat this until no "free" pieces remain. Now the complex web of stress is revealed across the playing area. Ask students to compare the web with their predictions prior to removing the pieces.

Next, reset the board. This time, ask students to identify a piece they perceive as being most likely to cause the slider to move. Again ask for student volunteers to come up and pull out that piece while all students make the following observations:

- What happened when the piece was removed?
- Did it move a little or a lot? Was this motion more or less than you anticipated?
- How was the stress transferred to other nearby pieces?
- After the piece has been removed encourage the volunteer to examine or "feel" the stress in the pieces in the area where the block was removed.
- Has the stress been released from that area or is it still there? If there, has it increased or decreased?
- Are there other ways we could better measure stress than our eyes?

Repeat this procedure until students have an adequate opportunity to see how the system behaves. Ask students if they could predict whether or not there will be stress on any particular piece in the area after another piece has been removed.

This final question is analogous to the one currently facing scientists that study the NMSZ. We know there have been earthquakes in NMSZ in the past. We also have other examples that suggest that the stress doesn't rebuild quickly on the same fault within intraplate seismic zones. Thus, the science community is currently debating the details of strain accumulation in NMSZ and the implication of this accumulation for how communities should balance resources spent preparing for earthquakes with other community needs. Using the resources identified in Table 1, readers are encouraged to explore the details of this ongoing debate for themselves and, depending on the level of your students, encourage them to learn more as well.

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Sessions at the 2011 NSTA National Conference

Thursday, March 10 8:00–9:00 AM

Teaching Earth Science Content with iPods, Laptops & Portable Accelerometers

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Explore a variety of strategies for using accelerometers in modern “gizmos” as a hook to teach students about seismic waves and earthquakes.

Thursday, March 10 2:00–3:00 PM

Help Your Students Discover Earth’s Layered Interior with Seismic Data

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Explore new discoveries about Earth’s dynamic interior. This activity allows students to discover or dispel the presence of Earth’s layers using seismic data.

Friday, March 11 9:30–10:30 AM

National Earth Science Teachers Association Geology Share-a-thon

Moscone Center, Meeting Room 134

Friday, March 11 9:30–10:30 AM

Visualizing the Unviewable: Simple Models to Activate Your Earthquake Instruction

Moscone Center, Meeting Room 220 & 222

Explore a collection of simple physical models designed to aid in developing students’ understanding of abstract earthquake related concepts

Saturday, March 12 9:30–10:30 AM

National Earth Science Teachers Association Earthquakes and Seismology Share-a-thon

Moscone Center, Meeting Room 134

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National Earth Science Teachers Association Events at 2011 San Francisco NSTA Conference



Friday, March 11

- 9:30-10:30 **NESTA Geology Share-a-Thon**, Moscone, Meeting Room Hall D
- 11:00-12:00 **NESTA Oceans & Atmospheres Share-a-Thon**, Moscone, Meeting Room Hall D
- 12:30-1:30 **NESTA Space Science Share-a-Thon**, Moscone, Meeting Room Hall D
- 2:00-3:00 **American Geophysical Union Lecture!**
"Our Eye on the Sun - the Latest from SDO - the Solar Dynamics Observatory", by Dr. Todd Hoeksema, Moscone 104
- 6:30-8:00 **NESTA Friends of Earth Science Reception**, Marriott San Francisco Marquis, Club Room

Saturday, March 12

NESTA Earth and Space Science Resource Day: Earthquake Hazards and Seismology

All events at the Moscone Center, Meeting Room Hall D, except Breakfast

- 7:00-8:30 **NESTA Resource Day Breakfast**
"Bringing a earthquake seismology into your classroom with the Quake-Catcher Network", Prof. Jesse Lawrence, Stanford University, Marriott San Francisco Marquis, Nob Hill A
- 9:30-10:30 **NESTA Earthquake Hazards and Seismology Share-a-Thon**
- 11:30-2:30 **Three NESTA Advances in Earth and Space Science Lectures!**
 - 11:30-12:30 **"Earthquake Forecasting in California"**, by Cynthia Pridmore, California Geological Survey
 - 12:30-1:30 **"Imaging the Earth Beneath our Feet – Pictures of the Earthquake-Producing Machinery in the Western US and Alaska"**, by Dr. Gary Fuis, USGS
 - 1:30-2:30 **"The Tortoise and the Hare: A Tale of Faults that Creep"**, by Prof. Matthew d'Alessio, Cal State Northridge
- 3:30-5:00 **NESTA Rock and Mineral Raffle**
- 5:00-6:30 **NESTA Annual Membership Meeting**



THE EARTH SCIENTIST (TES) MANUSCRIPT GUIDELINES

NESTA encourages articles that provide exemplary state-of-the-art tested classroom activities and background science content relevant to K-12 classroom Earth and Space Science teachers.

- Original material only; references must be properly cited according to APA style manual
- Clean and concise writing style, spell checked and grammar checked
- Demonstrates clear classroom relevance

Format Specifications

- Manuscripts should be submitted electronically – Microsoft Word (PC or Mac)
- Length of manuscript should not exceed 2000 words.
- All submissions must include a summary/abstract.
- Photos and graphs: should be submitted as separate files, of excellent quality and in PDF, EPS, TIFF or JPEG format. 300 dpi minimum resolution. Color or black and white are both accepted.
 - Photos/charts should not be embedded in the Word file. References to photo/chart placement may be made in the body of the article identified with some marker: <Figure 1 here> or [Figure 1 in this area].
- Figures should be numbered and include captions (Figure 1. XYZ.).
 - Captions may be included with photo/chart reference or at the end of the article.
- If using pictures with people, a signed model release will be required for EACH individual whose face is recognizable.
- Each article must include: author(s) names, the school/organizations, mailing address, home and work phone numbers (which will not be published), and e-mail addresses.

Review

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by Bruce Hall, Membership Coordinator

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Below: An IRIS field technician does a final check of a seismograph installed in a rural area of China, about 100 km from Beijing, while a local village resident observes. This instrument is part of a cooperative project comparing intermediate period surface waves generated by long-source-duration mining explosions in China and Wyoming. You can find more on the project at <http://www.iris.edu/hq/gallery/photo/4157>

Photo by Chis Hayward.

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