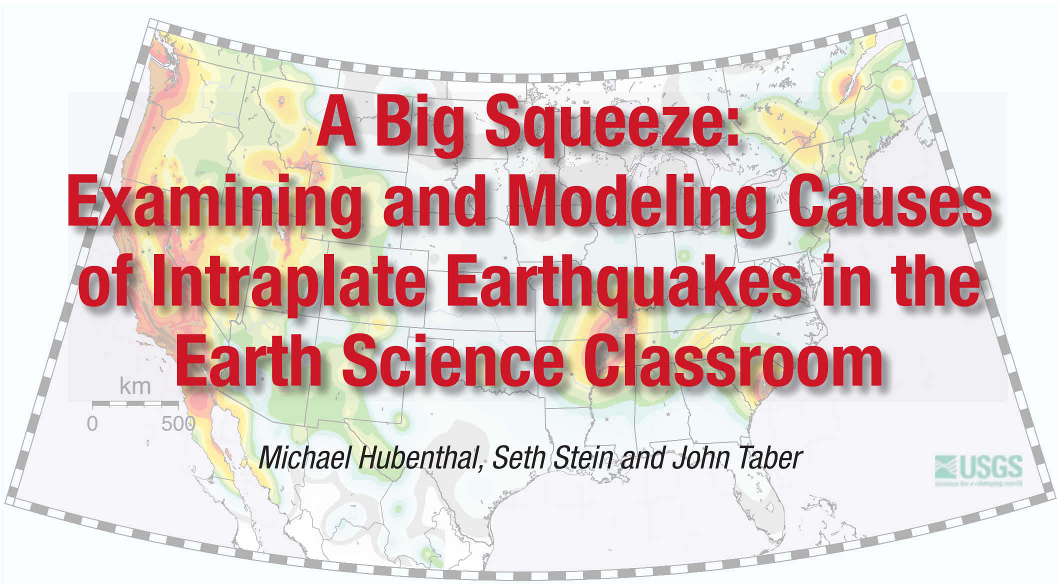

A Big Squeeze: Examining and Modeling Causes of Intraplate Earthquakes in the Earth Science Classroom

Michael Hubenthal, Seth Stein and John Taber

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

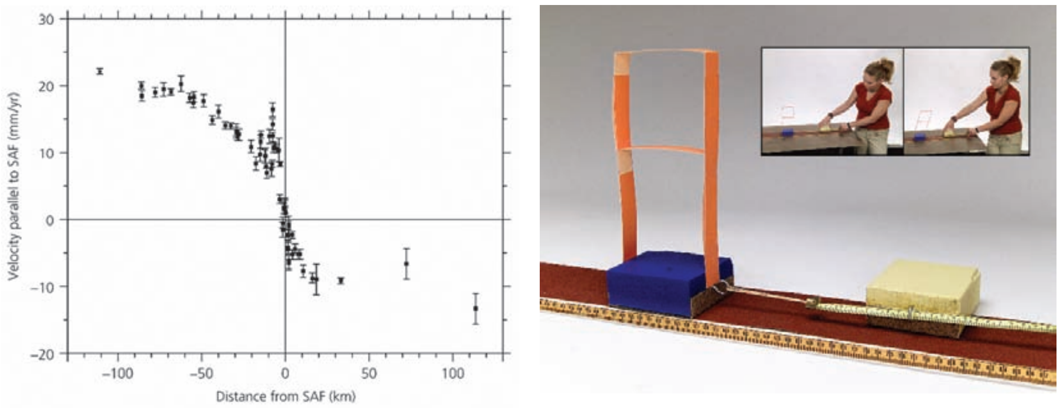

Figure 1. Left – GPS data across the San Andreas fault. This data shows the accumulation of elastic strain (Z.-K. Shen). Right – The Earthquake Machine Lite. By pulling the rubber band connected to the block with the paper building, this simple stick-slip model illustrates the accumulation and sudden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

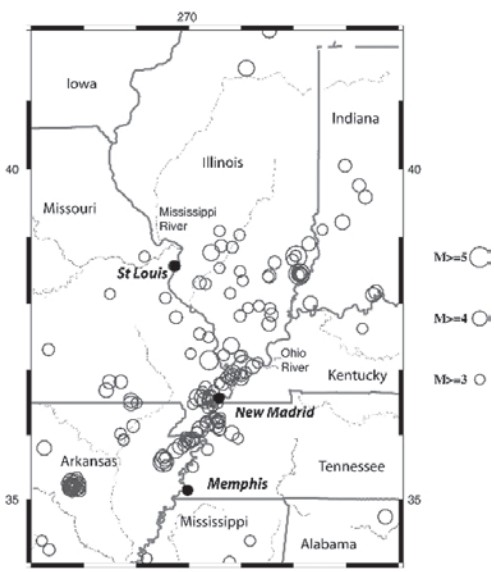

Figure 2. The New Madrid Seismic Zone (NMSZ). Locations of earthquakes between 1975 and 2008 in and around the NMSZ.

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, 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.

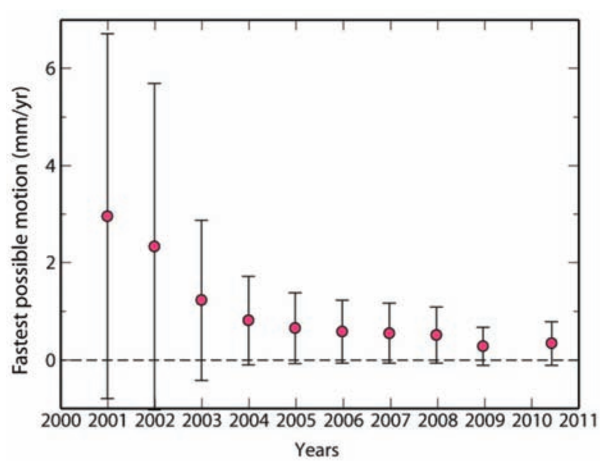

Figure 3. GPS data across the NMSZ. Successive GPS studies in the New Madrid area show that motion across the entire region is at best, very small. At this rate, 10,000 years would be required to accumulate enough slip for a magnitude 7 earthquake, and a magnitude 8 would require 100,000 years (Calais,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

The 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.

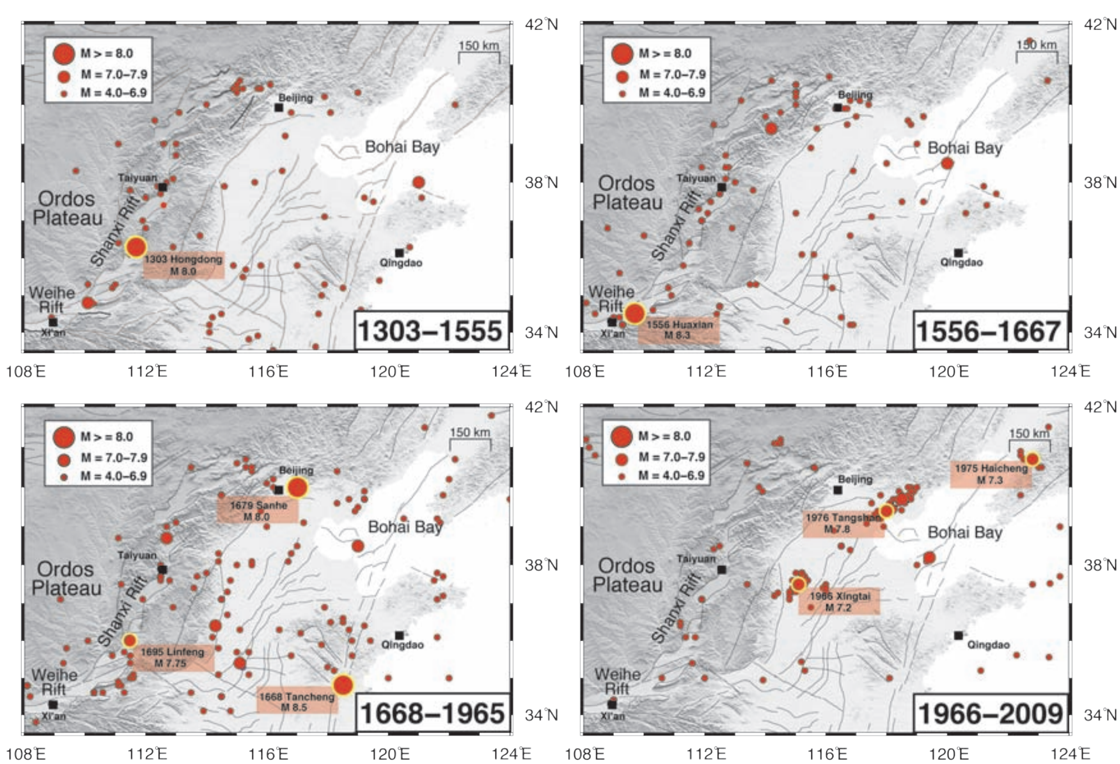

Figure 4. Seismicity in North China (1303 –2009). Note how the seismicity and large earthquakes cluster and migrate across the intraplate seismic zone as time progresses. Ultimately, no large (M>7) events ruptured the same fault segment twice during this time period. (adapted from Liu et al., 2011)

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).

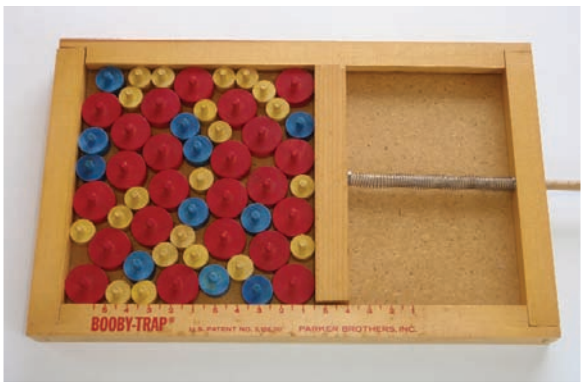

Figure 5. Booby Trap™. A 1960's era board game that can model the complex distribution of stress, both pre and post earthquake, across intraplate seismic zones.

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 seemly 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 TrapTM 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	• 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 TrapTM as class under flexcam or in small groups	Booby TrapTM is available online for ~ $15
Prior Knowledge	Introduce intraplate seismic zones by exploring and describing the following with your students • US Hazard Map • Description of 1811-1812 events • Paleoseismic record of historical earthquakes in NMSZ • Current seismicity in NMSZ Ask students to predict a mechanism for large earthquakes in this region and what they thing the current pattern of seismicity suggests for the future?	• 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	• Introduce GPS data across the NMSZ and compare to student predictions. • Explore study of the North China Seismic Zone • Reintroduce the Booby TrapTM as a model with explicit mapping between target and analogy. • Lead guided discovery of Booby TrapTM	• GPS data across the NMSZ • Example from North China Seismic Zone • Mapping of intraplate seismic zones to Booby TrapTM 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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