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12. TEACHING METHODS FOR EARTH SCIENCE

INTRODUCTION

The Earth and environmental challenges facing our global society in the twenty-first century require robust understandings of the complexities of the ever-changing Earth system. Therefore it is critically important for Earth Science to be a central part of the secondary school science curriculum for all students, regardless of location or status. In some ways Earth Science may be considered the easiest of the science disciplines for students to learn about. After all, the Earth is all around us and we interact with it every day. Children are naturally curious about what the world is like and why things in the environment happen. Learning how to care for and preserve the environment for current and future living organisms, from pandas to polar bears to future generations of humans, is a natural source of motivation for students to learn about the Earth.

On the other hand, however, Earth Science is among the most challenging science subjects to teach, for two reasons. First, the Earth itself is 18 orders of magnitude larger than most classrooms. Earth processes operate at time and spatial scales that are much too large and slow to fit into a classroom for students to experience directly (Kastens & Rivet, 2010). In fact, research has shown that very large spatial and temporal scales are exceptionally difficult for people of all ages to grasp (Dodick & Orion, 2003; Kastens & Ishkikawa, 2006; Plummer, 2014). This leads to the second key challenge related to Earth Science education: although the Earth seems static and stable, it is in fact constantly changing in complex yet predictable ways. The dynamic interactions between the geosphere, hydrosphere, atmosphere and biosphere create complex phenomena that operate on a range of scales from seconds to millennia. But the consistency and complexity of these interactions between systems are difficult to observe, and are often overlooked or misunderstood in typical descriptions of the Earth's features and behaviours (Assaraf & Orion, 2005; Raia, 2008).

These factors mean that Earth Science teachers need to be well prepared not just in the centrally related disciplines of geology, hydrology, oceanography, atmospheric science and astronomy, but also possess a set of skills and knowledge that address the conceptual challenges of developing understandings of the full-scale Earth system while simultaneously leveraging the inherent interest and motivation of students in understanding the world around them. My course in the Science Education teacher

A. J. Sickel & S. B. Witzig (Eds.), Designing and Teaching the Secondary Science Methods Course, 207–221.

preparation program at Teachers College Columbia University is my best attempt to achieve these ambitious goals.

UNIVERSITY CONTEXT

My institution, Teachers College at Columbia University, is located in New York City, which is the largest city in New York State and the second largest city in the United States. Among other degrees, the Science Education program at Teachers College awards masters degrees in science teaching with teacher certification for grades 7–12 in New York State. New York State is one of the few states that certify secondary science teachers by discipline in one of four content areas: Biology, Chemistry, Physics and Earth Science. Our program provides specific courses and experiences to meet the instructional needs for pre-service teachers to become qualified in each of these areas, including content and teaching methods courses in Earth Science. These are the courses that I teach as part of this program.

New York State is also unique in that it has a long history of state assessments, particularly at the secondary level. These assessments are referred to as New York State Regents exams, and have been in existence since the 1960's. Regents exams are offered in subjects across the curriculum, including Earth Science, Biology, Chemistry and Physics exams for science (Liu & Fulmer, 2008). Students are required to pass a set of Regents exams, including two science exams in the areas of their choice, in order to receive a Regents-endorsed high school diploma. In our program, we emphasize preparation for teachers to address the state curriculum associated with the science Regents exams, although not exclusively so.

Teachers College is exclusively a graduate institution and awards only masters and doctoral degrees. Pre-service teachers are admitted to the program with a bachelors degree in the science discipline they are intending to be certified to teach, or at minimum with sufficient undergraduate course credits in that area. Our masters degree in Science Education with teacher certification program is a 14-month program. Pre-service teachers complete courses in a variety of areas including science content, teaching methods, literacy, differentiation and special education. They complete 100 hours of secondary classroom observations their first semester and two 6-week student teaching placements in the second semester, one in middle school (grades 7–8) and one in high school (grades 9–12). These classroom observations and teaching experiences are supported through university seminars on teaching and learning, which are completed concurrently with pre-service teachers' other coursework including methods courses but are distinct from those courses. In terms of methods courses, pre-service teachers take one general science methods course and one subject-specific methods course. The Earth Science methods course described here meets the subject-specific teaching methods requirement for those pre-service teachers intending to become certified as secondary Earth Science teachers in New York State.

The field of science education in the United States is currently in a transition, marked by challenging innovations in instruction, curriculum and assessment called for in the *Framework for K-12 Science Education* (National Research Council, 2012) and the *Next Generation Science Standards* (NGSS Lead States, 2013). This course, along with other courses across the science education program at Teachers College, strives to prepare the next generation of science teachers by equipping them with the knowledge, resources, and pedagogical expertise to address the new goals for science teaching and learning. In particular, recent iterations of the course have explicitly framed learning from the perspective of integrating disciplinary core ideas, crosscutting concepts, and science and engineering practices to develop robust three-dimensional science understanding of Earth science (Krajcik, Codere, Dahsah, Bayer, & Mun, 2014). This approach is reflected in both the class activities and overall structure of the course design, which is focused on developing pre-service teachers' pedagogical content knowledge for Earth Science teaching.

PLANNING: DISCUSSION OF COURSE DESIGN

As mentioned in the introduction, Earth Science is uniquely distinct from the other sciences in several different ways. These distinctions shape the goals and outcomes I have for the course, entitled "Teaching and Learning Concepts in Earth Science".

Philosophical Focus: Pedagogical Content Knowledge

The major outcomes of the course are driven by the goal of constructing a learning experience for pre-service teachers where they can develop their own pedagogical content knowledge for Earth Science teaching. Pedagogical content knowledge (PCK) refers to what teachers need to know about the content to help learners come to understand it (Gess-Newsome & Lederman, 2001; Magnusson, Krajick, & Borko, 1999). That means not only understanding the key ideas of the discipline, but also being aware of common student misconceptions, ability to make use of a wide array of different representations and explanations for concepts, knowledge of how to engage students in different forms of investigation, inquiry, and reasoning in the domain, and a suite of assessment tools and strategies to inform their instruction on an ongoing basis. The literature on science teachers' PCK informed both the pedagogical topics addressed in the course, as well as the focus and sequence of the short assignments and final project used to assess student growth and learning over the semester.

As teacher candidates come into the program with content knowledge in the discipline in the form of a bachelors degree or equivalent, I do not address the content included in a typical secondary Earth Science course in a systematic or comprehensive way. However, I do address key ideas and core concepts in the context of developing tools and strategies for pre-service teachers to build their PCK of those ideas through their own practice.

The following is the specific course objectives for this course as stated in the syllabus:

> This course is focused on developing your pedagogical content knowledge (PCK) in Earth Science. This includes exploring students' prior ideas about Earth processes; identifying key analogies, metaphors, and models to facilitate student thinking about specific ideas, developing demonstrations, activities and investigations about various Earth Science topics, and examining a variety of resources to use in your teaching of Earth Science. Each of these aspects of PCK will be examined in the context of important content and process ideas in the Earth Science fields. The major course goal is to provide you with appropriate experiences for initial growth as a professional educator who will teach Earth Science to middle and secondary students, and the knowledge and tools to develop your expertise further.

Course Sequence

The course is structured to address both pedagogical and Earth Science content objectives concurrently in the same lessons. The sequence of the lessons is planned first from a pedagogical perspective, considering how to best support pre-service teachers in building their pedagogical content knowledge. The order of these PCK topics generally follows a backwards design approach (Wiggins & McTighe, 2005). The beginning of the course starts first with how to articulate learning goals for three-dimensional understanding of Earth Science (Krajcik et al., 2014; National Research Council, 2012), then moves to ways to identify students' prior ideas of Earth science phenomena that inform instruction, which is then followed by developing expertise with a range of representations used in Earth science (including maps, graphs and models), and instructional strategies and approaches such as investigations and field work to achieve targeted Earth Science learning goals in the classroom. The Earth Science content topic for each week is selected to best support and illustrate the pedagogical focus of the lesson while ensuring that the overall breadth of key ideas in Earth Science are adequately addressed, in particular those that are included in the New York State Regents Earth Science curriculum for high school. While specifically attending to those content topics is important, they do not serve as the driving force for the planning of the course.

Course Structure and Assessments

During the semester pre-service teachers are assigned two types of readings in preparation for each week's lesson, one focused on the pedagogical topic and one on the Earth Science topic (Table 1). For example, in Week 2 pre-service teachers read a chapter from the text *Learning by Design* (Wiggins & McTighe, 2005) and an article that summarizes research on middle school students' understandings of basic

Table 1. Sequence of topics for Earth Science Methods course

Course session	*Pedagogical topic*	*Earth Science content topic*	*Assessment*
Week 1	Introduction, PCK	Nature of Earth Science	
Week 2	Learning goals	Solar system & celestial objects	
Week 3	Students' prior ideas	Causes of the seasons	Part 1 due
Week 4	Visualizations & diagrams	Convection & cycling; energy transfer	
Week 5	Models	Moon phases & eclipses	
Week 6	Maps & spatial reasoning	Plate tectonics; structure of Earth's interior	Part 2 due
Week 7	Data representations part 1: Graphs	Ocean circulation and tides	
Week 8	Data representations part 2: GIS	Topography & bathymetry	
Week 9	Investigations in Earth Science: Intro	Weathering	Part 3 due
Week 10	Investigations with models	Erosion & deposition; landforms	
Week 11	Investigations with data	Weather & climate patterns	
Week 12	Realia: Bringing Earth into the classroom	Rock types and rock cycle	Part 4 due
Week 13: FIELD TRIP TO CENTRAL PARK	Learning in the field	Geologic time; glacial geology	
Week 14	Human/environment interactions	Global climate change	
Week 15	Final presentations		Final project due

astronomy concepts (Trumper, 2001). Pre-service teachers are expected to come to class ready to discuss these readings in relation to the classroom activities and apply the science concepts to their work. Weekly attendance, participation and informed contributions to the class activities and discussion are significant parts of the course assessment, together constituting 20% of the final course grade.

In addition, there are four short assignments that pre-service teachers complete over the course of the semester. These assignments are each evaluated as 10% of the final course grade, and each constitutes a key part of the final class project,

which is to build a PCK resource guide for a particular Earth Science concept that can be shared with other members of the class. At the beginning of the semester each pre-service teacher selects a key concept in Earth Science that they want to focus on in these short assignments. The short assignments in turn ask pre-service teachers to consider the topic from different pedagogical perspectives. The Part 1 assignment asks them to describe the topic in terms of learning goals and state why it is important for teachers to teach and students to learn (which are not typically the same reason). The Part 2 assignment asks pre-service teachers to identify common conceptions and prior ideas that students may have about the topic, either through a literature review or by interviewing young people directly. The Part 3 assignment asks them to identify three different types of representations on the topic (a diagram, a model, and a data display) and critique each one for its affordances and limitations using a set of criteria developed in class (this process is illustrated in more detail in the next section). The Part 4 assignment asks pre-service teachers to develop or adapt an inquiry experience for students on the topic and describe the inquiry from both the students' and teacher's perspective.

The final project of the course, which contributes to 40% of the final course grade, brings together the short assignments into a comprehensive teaching resource on a particular Earth Science topic that the pre-service teachers can share with other members of the class. This project is described in more detail later in the chapter.

CLASSROOM PRACTICE: VIGNETTE OF A SIGNATURE LESSON

Here I present in depth the lesson where pre-service teachers learn about and critique representational diagrams of Earth system structures and processes, which then serves as the basis for the Part 3 portion of their final assignment. As the majority of Earth Science phenomena under study are too big or too slow to investigate directly in a classroom, representations of these phenomena abound in Earth science instruction and are essential tools that Earth scientists use to investigate and communicate explanations for how the Earth system operates (Kastens & Rivet, 2008). Thus understanding the roles, explanatory power, and limitations of a range of different kinds representations is central to learning and teaching in this field. This lesson is aimed towards developing pre-service teachers' PCK around representational diagrams and provides strategies for helping their students learn to use and critique diagrams effectively. Over the years I have selected a variety of different Earth Science topics to serve as the context for this lesson, including the structure of the atmosphere, energy movement (conduction, convection, and radiation) in the Earth system, and geologic time. In this vignette, the focus of this lesson is on understanding representations of the structure of the interior of the Earth.

I start the lesson by introducing the focus Earth Science topic for the day, in this case the structure of the interior of the Earth. I state that I first want to know what the pre-service teachers understand and how they visualize this important aspect of

the Earth that cannot be seen directly. I direct the pre-service teachers to each create their own diagrams of the Earth's interior structure.

After each pre-service teacher has individually created their own representation of the interior structure of the Earth, I ask them to compare their drawings in pairs or small groups. They are to discuss what is the same between the drawings, what is different, and why that might be. I ask them to pay attention to *what* was represented in the drawings and *how* it was represented, in terms of their commonalities and differences. The pairs or small groups talk for about five minutes, and then they share their comparisons in a whole class discussion. The features they tend to have in common include a circle or sphere that represents the Earth as a whole, some indication of interior layers, a thin or small surface layer, and some type of circular or central core. Differences often include the size or patterns used to mark the different layers, the use of labels or arrows, and the inclusion of any features on the surface of the Earth (such as mountains, oceans, or volcanoes).

After this brief class sharing, I then present some background on the use of representations and models in Earth Science. In a short PowerPoint presentation, I focus on the use of representations from a PCK perspective, and in particular on what teachers need to know about representations in order for them to be used as effective tools for teaching and learning. I explain to the class the following important considerations regarding the use of pictures and diagrams specifically in Earth Science teaching:

> When you think about teaching Earth Science, or any science, or any idea or concept, there are many modes used to transmit that knowledge, including representations of the concept or idea.
>
> In our class, we are considering what teachers need to know about those representations in order for them to be effective tools for teaching and learning. Today the focus is on teaching about the structure of the interior of the Earth and pictoral representations used to do this. Remember the things about PCK that we're been talking about in this class. We are trying to consider and develop that tacit knowledge that master teachers have developed about ways of teaching specific content ideas effectively and helping students understand these ideas and connect them to other understandings.

I have prepared a set of eight to ten representations of the interior structure of the Earth that I have gathered from websites and textbooks. I display the first one on the Smart Board or use a projector (Figure 1). I ask the class to brainstorm together some guidelines that they should consider when using the image with students, explaining to the class the following:

> Now when we as teachers are thinking about using certain pictures, diagrams, models, visualizations, animations, or analogies in the classroom we need to think about what they offer in terms of helping students grasp ideas, and what we need to be aware of so that they are used properly. What are some of the aspects of the picture that you need to consider?

Figure 1. First Earth structure image[1]
The image is presented to pre-service teachers in color, as follows: Ocean/blue, land/green, crust/brown, mantle/orange, outer core/tan, inner core/yellow

Together, we examine the first image on the screen and make a list on the board of observations and questions that teachers should ask themselves (and potentially their students) about this specific diagram. The class discussion starts with what the image is intended to show and possible (mis)interpretations of different features of the diagram including colors, shape, lines or arrows, and location or size of prominent features. For example, for the image in Figure 1, pre-service teachers note that it definitely represented the Earth because of the iconic globe features on the outside of the sphere. However, there is some possible confusion about the colored triangle-shaped features in the upper middle of the globe. Is it possible to look at the image and think that the layers inside the Earth only exist in that section of the Earth? Also, the pre-service teachers note that layers are not spheres, but triangle-like in shape. So does that indicate that the interior of the Earth is possibly a set of nested triangle layers? Then there is also the issue of colors. Are the yellow, orange, and red colors of the triangles meant to indicate there are just distinct layers, or do the colors convey some relative characteristic of the layers, such as temperature or density? Or, are the layers inside the Earth *actually* colored yellow, orange and red, in the way that the oceans on the exterior globe are blue similar to how they are in real life? In addition, there is also the issue of scale: the inner core looks to be about the size of Africa in the picture. Is this actually the size of the core? Through discussion we generally agree that this is not the case, but we note that there is no scale or key in this figure to help the learner interpret the shapes, sizes, or colors of the image features. This discussion raises an important point: images, figures and diagrams are produced and shared with a set of underlying assumptions

about the ways that the image represents the concept, process or structure it is trying to convey. But oftentimes we don't recognize or acknowledge these assumptions. Rather, we use our own prior knowledge and experiences to draw conclusions about what the representation is trying to convey. However, when we use these figures and images with our students, they may *or may not* bring the same prior knowledge and experiences to their interpretations. Thus it is important to be clear with students about what they understand, what their alternate interpretations could be, and how to support them in developing the skills and knowledge to effective use these and other similar diagrams.

As pre-service teachers are discussing the image, I create a running list of questions, topics and features on the board: What is the diagram trying to show? What do the colors indicate? What do the shapes mean? What does the relative size/scale of objects show? What do the arrows/lines mean? What features are showing context or points of reference? Is there a title? Is there a key? These questions written on the board then begin to frame the list of criteria by which teachers should critique each of the images or representations they use as part of their instruction, with respect to their goals for student learning.

This process is repeated with the second image of the interior of the Earth that I show on the Smart Board or projector (Figure 2). Once displayed, I ask the class to examine this image using our current list of critique criteria, and to consider two additional questions: (a) what is this figure trying to convey? and (b) how is it similar and different from the first figure?

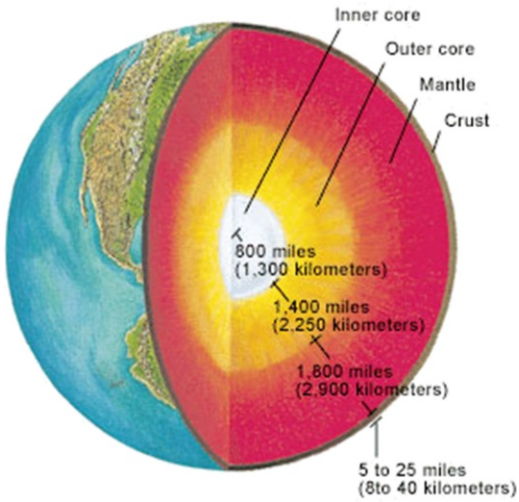

Figure 2. Second image of the interior of the Earth[2]
The image is presented to pre-service teachers in color, as follows: Ocean/blue, land/green, crust/grey, mantle/red, outer core/yellow, inner core/white

This comparison between the two images leads to an interesting discussion about representations. The pre-service teachers see how the globe is similarly represented, but the interior of the Earth is quite different. In this figure, they can see the layers as concentric spheres rather than nested triangles. They note that the labels are present, and this image includes a scale that indicates depth. A key observation is that the colors used for the layers have some differences when compared to the previous image. This leads to another important class discussion about the *affordances* of each image. What is this image good at helping learners understand, that the first image was not? Through discussion, the class comes to understand the point that not all representations of a specific Earth process or phenomena are equal; different images foreground different aspects of the complexity of the real world. It is important for them as future teachers to pay attention to the alignment between their learning goals for their students and what the representation conveys most effectively. If the representation and the learning goals for a particular topic are not in alignment, the representation may simply lead to confusion for their future students, and it is time to look for a different representation.

I repeat this critique and discussion process further with three or four additional images of the interior structure of the Earth (Figure 3). For each image, we together as a class compare it to the previous diagrams in terms of its affordances, strengths and weaknesses. After each discussion we add to or amend our class list of critique criteria questions that I have written on the board.

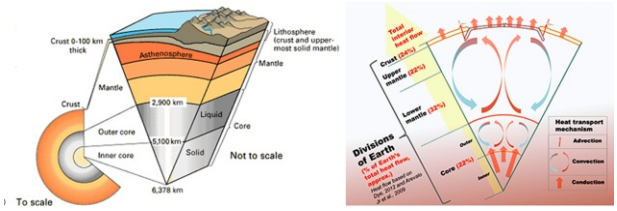

Figure 3. Additional diagrams of Earth's interior[3]

Then the class breaks into groups of three or four pre-service teachers. I give each group the same selection of three additional pictures, and together they discuss and apply the class criteria to critiquing the affordances and limitations of each image. Each person in the group is responsible for taking notes on one of the images. Then I jigsaw the class, grouping together all the pre-service teachers who took notes on image 1, image 2, and image 3 together. In these new groups, the pre-service teachers share and compare their critiques of that image. The focus questions for this sharing time include, was the use of the class criteria consistent? And, where are the areas of confusion, or places where the criteria need more clarification or specificity?

Each group shares the findings from the jigsaw discussions, and together we refine and finalize the criteria to use when considering what diagrams, figures, images and models to use as part of their instruction. The pre-service teachers then apply these

class critique criteria to representations on a topic of their choice as part of their final project for the course.

As the class ends, I show the remaining several image slides of the topic for the day. I emphasize that there are *lots* of different ways to represent not only this idea, but all of the core ideas in Earth Science. I return to the point that it is a key part of Earth Science teachers' PCK for them to be aware of the range of different representations, and how to identify the affordances and limitations of these representations in ways that best meet the learning goals for their instruction and the needs of their students.

The walk-away points for this lesson are for pre-service teachers to be aware that all different representations have both affordances and limitations. There is no one representation that is going to perfectly show the science concept, and every representation is subject to multiple different interpretations. Thus it is critically important that as future teachers, they do not assume their students understand the science just by looking at a diagram. A range of different representations are often needed to help students understand the full breath of these complex Earth Science concepts and processes.

ASSESSMENT: SUMMATIVE PCK PROJECT

The key assessment for the class is for each pre-service teacher to develop a PCK resource guide for teaching a topic in Earth Science. The PCK resource guide that they create is a coherent 15 to 20-page compendium of instructional resources on a single topic in the Earth Science curriculum. It includes several parts, each of which has been built over the semester as part of the four short assignments: (a) a description of an Earth Science topic of their choosing; (b) alignment of that topic with state and national standards; (c) a summary of common misconceptions or prior ideas that students commonly have around the topic (from their own investigation or the literature); (d) three different kinds of representations and a critique of each using the set of review criteria we developed as a class; (e) a description of an inquiry investigation that integrates scientific practices and crosscutting concepts with their chosen topic and highlights key pedagogical strategies related to that topic, and (f) a list of three key resources that could be used by teachers and students to teach or learn more about their topic. These completed PCK guides are presented and shared with members of the class at the end of the semester. This means that as the pre-service teachers leave the class and move on to their first teaching positions, they each have a set of resources on a range of topics developed by their peers that they can use to start planning their own classroom lessons and units.

Although a bit unusual, there are several reasons for why I chose to have the final project for the course build from the series of short assignments over the semester. First, it gives pre-service teachers an opportunity to see how the different aspects of their developing Earth Science PCK are related and connected in the context of a single topic. Developing the project over time allows for reflection and revision of the different components (Reiser, 2004). It allows them to experience the process

of developing expertise in teaching one area of the Earth Science curriculum in depth, as a model for how they should go about learning and planning other areas of the curriculum. It also provides an opportunity to share that expertise with their classmates, fostering a community of learners in the course (Brown, 1997).

Evaluation of this summative project is conducted across several dimensions. The first dimension of evaluation is if the project is completed on time with all of the required components. The second dimension of the evaluation focuses on the understanding of the Earth Science topic chosen, and in particular, how the descriptions, representations and inquiry experiences described in the PCK guide reflect an understanding of the Earth Science concept, process, or idea in a way that is both accurate (absent of errors or inconsistencies) and is beyond what the target student population is expected to understand. Related to this point, it is important that the focus topic does not shift or expand in scope throughout the PCK guide.

A third dimension of evaluation of the PCK resource guide attends to the ways in which the guide reflects an understanding of how learners (the future students of the pre-service teachers) think about their chosen Earth Science topic. This aspect of the PCK resource guide is one that I have found to be particularly challenging for pre-service teachers. So often, pre-service teachers in my classes are able to describe what they would do as a teacher in the classroom, but struggle to consider and articulate both what students would be doing, and more importantly, *what students would be thinking* as they are engaged in learning about Earth Science. One place in the PCK resource guide where this is most visible is in the description of an inquiry investigation that students could conduct about the select topic of interest. In the PCK resource guide I ask the pre-service teachers to describe the inquiry investigation in two ways: first, to give a description of the investigation written from a student's perspective in the classroom – both what she is doing in the investigation, and *what she is thinking* while she is doing it. Second, the pre-service teachers then describe the investigation from a teacher's perspective, describing the directions, questions, prompts and supports that they would give in order to create the space for the students to investigate and learn. A quality evaluation of this part of the PCK resource guide indicates that pre-service teachers are able to distinguish between teacher instruction and student learning, and recognize that telling students what to do and what to know does not equate to student learning and understanding. This perspective is applied to all aspects of the PCK resource guide in the final evaluation.

DISCUSSION

The Earth Science methods course that I have described here is one approach for preparing future Earth Science teachers with the knowledge and skills needed to effectively instruct and support students in learning about important Earth processes, structures, and phenomena. In taking a pedagogical content knowledge approach to the design of the class, the resulting course focuses not as much on Earth Science content itself, but rather on the *learning* of Earth Science. This is an important

distinction from straight science content classes. While content understanding is undeniably important, solely being an expert in a disciplinary field is insufficient for becoming an effective teacher (Shulman, 1986). Rather, it is important for pre-service teachers to develop the tools, strategies and perspectives that can foster their own pedagogical content knowledge. This Earth Science methods course is designed to accomplish this particular goal.

One of the more effective ways I have found to develop pre-service teachers' pedagogical content knowledge is to encourage and support them to think about understanding Earth Science concepts from the perspective of the learners in their future classrooms. This means more than just asking them to put on a "student hat" and do the lessons and lab activities as pupils. Rather, it is about asking them to think hard about what students are *thinking* about during these lessons: how they would perceive the goals, how they may interpret the task, and the range of prior knowledge and real-world experiences that they would bring and apply to the lesson. By repeatedly engaging with this type of cognitive perspective-taking, my pre-service teachers develop a greater awareness of how their instruction, resources, and teaching strategies interact with students' meaning-making of Earth Science concepts, leading to more robust PCK for Earth Science teaching at the end of the course.

A second challenge for pre-service teachers is the ability to distinguish between classroom activities and legitimate student inquiry investigations in Earth Science. This is particularly challenging because of the nature of Earth Science as a scientific discipline, with its own unique forms of inquiry and evidence that are different from laboratory-based sciences such as chemistry or physics (Kastens & Rivet, 2008). Both field investigations and computer-based modelling are common approaches in Earth science inquiries, with value placed on identifying spatial and temporal patterns and examining interacting systems across scales (National Research Council, 2012; Rivet, 2016). One key strategy to accomplish this goal is not only to provide multiple examples of different types of student Earth Science inquiry that could be accomplished in secondary school classrooms, but for each, to clearly identify and discuss with the class how and why these inquiry experiences are different from a traditional Earth Science lessons or labs. Again, this often involves class discussions about the distinct nature of students' thinking and reasoning explicitly in Earth Science inquiry investigations, and pointing out where and how the teacher's instruction would support that kind of desired thinking and problem solving.

Third, I have as a central tenant to the design of this and all my classes that learning is not a passive act. Learning, whether it is about Earth Science concepts or teaching strategies, is an active and collaborative process (Blumenfeld et al., 1991). Thus in each lesson I aim to have multiple and varied opportunities for my pre-service teachers in the class to discuss, problem-solve, and learn together. I use a variety of different approaches to create these collaborative learning situations, including think-pair-share, jigsaw groups, count-offs, and other grouping strategies. I also almost always provide groups with poster paper and markers and ask them to write down or draw a summary or representation of their discussions to share with

the class. The paper and markers gives my pre-service teachers a way to express their ideas in a different medium, allows them to make their ideas visible and public, and helps to keep the groups' discussions productive and on task.

In addition to making my instruction more effective, these instructional strategies around focusing on student thinking, emphasizing inquiry, and supporting collaborative learning are also ones that I encourage my pre-service teachers to integrate and use in their own practice when they become classroom teachers. This kind of active engagement in a subject-specific pre-service teacher education setting is my way of demonstrating that Earth Science instruction should not be about lecture and delivery of content. Even though the Earth itself is many times larger than the size of a single classroom, learning about the Earth and all of its amazing processes and structures can be an engaging, fun, and rewarding process for not only my pre-service teachers, but their future students as well.

As with any instructional endeavour, I reflect continuously on ways in which this learning experience for pre-service teachers could be improved. One of the central challenges is the limited amount of time available for this course, necessitating making difficult choices regarding what areas to emphasize and what to leave out. For instance, while the focus on developing pedagogical content knowledge regarding pre-service teachers' learning in Earth Science is a primary focus of the course I designed, other important aspects of PCK are not as clearly addressed. These include understanding how to select, adapt, and organize quality curriculum materials, as well as develop a range of effective strategies for both formative and summative assessment in the Earth Science classroom. These central features of quality teaching could be incorporated more effectively into the lessons and assignments for the course. Additionally, the Earth Science content goals themselves are not systematically addressed in this course. While justified in the design choices made for the course, it leaves whatever incomplete or inaccurate understandings of Earth Science that pre-service teachers bring into the class largely unchallenged. One approach to addressing this difficulty that I have explored is to teach this course in conjunction with, or as a companion to, a content-focused Earth Science course taught by my colleagues in the Department of Earth and Environmental Sciences at Columbia University. While still in development, this approach may provide an exciting opportunity for pre-service teachers at both the secondary and potentially post-secondary level to develop powerfully integrated understandings that combine Earth Science content and pedagogical expertise.

NOTES

[1] By Original Mats Halldin Vectorization: Chabacano (File:Jordens inre.jpg) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/)], via Wikimedia Commons.

[2] By USGS (USGS page 'Inside the Earth' [1]) [Public domain], via Wikimedia.

[3] Picture 1: By Bkilli1 (Own work) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons; Picture 2: By NASA [Public domain], via Wikimedia Commons.

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