CHAPTER

12

No Rock Is Accidental! Stratigraphy, Structure, and Tectonics in the Wilson Cycle

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OUTLINE

1 INTRODUCTION

The Wilson cycle model (Fig. 1) is a pedagogic tool we used in an introductory exercise in an advanced undergraduate geology course synthesizing stratigraphy, structure, and tectonics, with more than a passing nod to petrology. Stratigraphy, structure, and tectonics have historically not been compatible topics. The evidence for this is plain if you sit in on courses of stratigraphy and structural geology. There is little overlap of subject, evidence, techniques, or tools. Yet stratigraphy and structure are clearly related because both result from the dissipation of tectonic energy; for example, the tectonic energy required to create a depositional basin, and then the tectonic energy required to deform it. Correspondingly, the evidence of this tectonic energy often exists on the same outcrop at the same time. Yet a stratigrapher may not be cognizant of the structural evidence, and vice versa.

Our approach to integrating structural geology and stratigraphy in the context of tectonics was to use a Wilson cycle model as a theoretical tool to demonstrate how various topics in the Earth sciences are related for understanding Earth history. Structure, stratigraphy, and tectonics are naturally part of an integrated whole: the Earth as a "machine"—a system of interacting parts that, through time, produced the Earth of today. This concept of the Earth as a "machine" goes back to James Hutton, as Stephen Baxter (2006) explains Hutton's philosophical framework: "The whole of his argument is an elegant interplay of three key metaphors: the Earth as an orderly Newtonian system, as orderly as the heavens; the Earth as a machine, like Watt's steam engines; and the Earth as a body of cycles of renewal, like Harvey's circulating blood." A corollary of this is that the rocks we see in an outcrop are the result of many interacting processes, and it takes systematic training to have the vision to see them all, at the same time. The authors know from developing this course that we can be blind or myopic about certain things in an outcrop; that what is "information" in one discipline is "noise" to someone trained differently. It takes practice to see with a trained eye what a colleague in a

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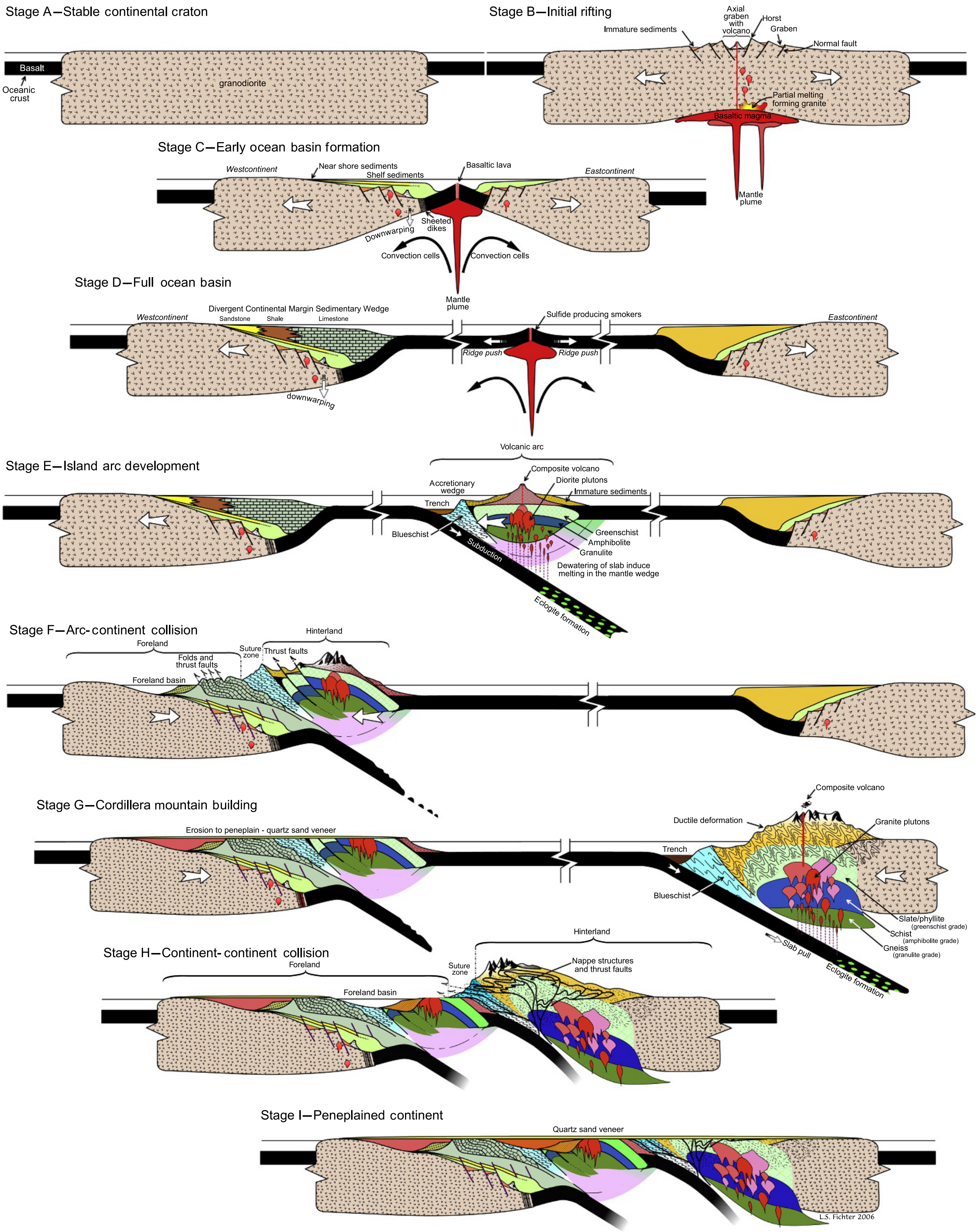


FIG. 1 A Wilson Cycle model showing the tectonic events during the opening and closing of an ocean basin.

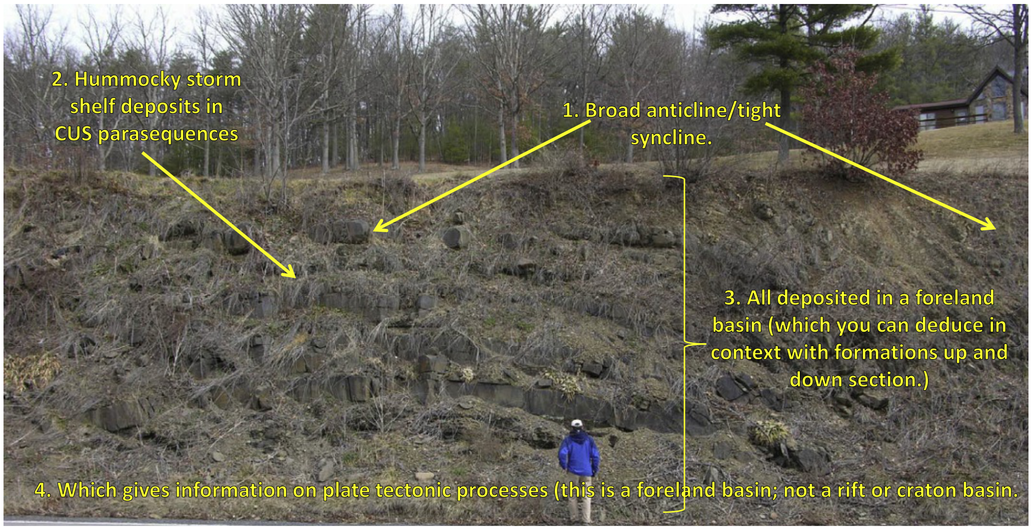


FIG. 2 A typical outcrop we visit on one of the SST field trips. It contains information on: (1) structural tectonics: rheology of folds and faults, (2) sedimentologic/stratigraphic: the depositional energies that produced these hummocky parasequences can form in this stratigraphic position only because tectonic processes created the conditions, (3) foreland basin tectonics; the size, shape, and history of the basin, and (4) plate tectonics: this is a foreland basin, not a rift or cratonic basin.

different discipline sees intuitively, especially when the last time you seriously thought about other disciplinary evidence was in a course taken years before (the authors who co-teach this course are a stratigrapher and structural geologist). It took us several years co-teaching the stratigraphy, structure, tectonics (SST) course to begin to see and have as much interest in the parts of the outcrop that are not our specialty.

Becoming technically proficient in any one discipline requires focused attention. And undergraduate instructors might argue that such integration is the work of graduate school. Yet we know that graduate school training does not broaden a student's perspective but rather narrows the focus to specific sub-disciplinary techniques and concepts. Therefore if we want to give prospective geoscientists the holistic integrated synthesis of their discipline, the most natural place to do it is at the undergraduate level using the Wilson cycle model. Practically, this is manifested on several field trips in the SST course. At each outcrop, we acknowledged that what we observed resulted from several kinds of energy, and we systematically examined each of them.

For example, the outcrop in Fig. 2 is typical of the exposures we visited. It contains several kinds of information, including, but not confined, to the following: (1) Structure: the rheology of folded and faulted rocks. The obvious feature is the anticline-syncline couplet; but they are asymmetric, second order in size, and therefore part of a regionally fractal hierarchy of structures. (2) Sedimentology/stratigraphy: the depositional energies that produced these coarsening upward hummocky parasequences can form in this stratigraphic position only because eustasy, along with tectonic and sediment loading processes, created the accommodation space appropriate to allow hummocky cross-stratification to form at this level in the stratigraphic section, and not some other level. (3) Foreland basin tectonics: we cannot see the foreland basin at a single outcrop, but when combined with sedimentary sequences up and down section, and in reference to theoretical stratigraphic models (e.g. Diecchio and Fichter, 2015), we can deduce the size, shape, and history of the basin. (4) Plate tectonics: "no rock is accidental;" as the Wilson cycle models, specific rocks form in specific tectonic regimes for specific reasons. Not only can we deduce this is a foreland basin, and not a rift or cratonic basin, but in conjunction with regional rocks found up and down section, we can deduce the series of plate tectonic events responsible for the region.

The Wilson cycle labs are deliberately designed to inculcate the habits of mind—both empirical and theoretical—necessary to be aware of and interpret all the features visible on an outcrop, and to deduce all of the structural, stratigraphic, sedimentologic, tectonic, etc. events required to create what we see. It is acceptable to choose to ignore certain kinds of evidence on an outcrop, but only as a deliberate act and not a default out of ignorance.

2 NO ROCK IS ACCIDENTAL

This exercise encompasses two labs at the beginning of the semester and is based on the premise that all rocks form in specific tectonic terranes from specific tectonic and petrogenesis processes; that is, "no rock is accidental." We want to specify in a Wilson cycle/plate tectonic model (Fig. 1) which rocks will form where, why, and how, and from what protoliths. To achieve this, we must not only be able to identify rock types but also posit theoretical evolutionary models that explain why specific rocks form in certain tectonic regimes, but not others. But, more important, this must be a predictive model, the goal of which is to be able to visit any outcrop, examine those rocks, and develop a deductive argument of the tectonic/environmental conditions that must have existed at that spot at the time those rocks were forming. The "Integrating Structural and Stratigraphic Field Data" exercise (Whitmeyer and Fichter, this volume) asks them to use the Wilson Cycle model for rock evolution that they developed in this "No Rock is Accidental" exercise to construct a tectonic history of the Mid-Atlantic region.

The Wilson cycle is a theoretical model for the opening and closing of an ocean basin, originally framed by J. Tuzo Wilson (1966) in the early days of the plate tectonic revolution. Wilson's goal was to suggest the existence of a proto-Atlantic ocean that closed prior to the opening of the present-day Atlantic Ocean. Subsequent to Wilson's original paper, the "Wilson Cycle" concept was developed as a basic model that highlights most plate tectonic processes, at least for the eastern margin of North America (Dietz, 1972). The Wilson cycle model in Fig. 1 was derived from Wilson's original conception and is the simplest theoretical model that incorporates most of the plate tectonic processes on Earth but also can be used to specify the tectonic, petrologic, and environmental conditions under which each rock forms (e.g. Whitmeyer et al., 2007).

We use the Wilson cycle model (Fig. 1) as a heuristic model in the introductory historical geology course (GEOL 230—Evolution of the Earth, James Madison University) and in an upper level core course (GEOL 387—Stratigraphy, Structure and Tectonics, James Madison University; abbreviated as SST; Fichter and Whitmeyer, 2014) to inculcate the connections between rocks, environments, and tectonics. More specifically, the Wilson cycle model is used to explicate rock evolutionary processes. That is, how rocks transform through fractionating and self-organizing evolutionary processes (Fichter et al., 2010) from a posited ultramafic parent rock into all the other igneous, sedimentary, and metamorphic rocks found on Earth. In this manner, the Wilson cycle model leads to the concept of what we call the Tectonic Rock Cycle (Fig. 3). Unlike the traditional circular rock cycle that posits that all rocks can be transformed into other rocks through an internally closed system (e.g., Tarbuck et al., 2017, among many others), the Tectonic Rock Cycle incorporates the processes by which rocks evolve, and the tectonic and environmental conditions under which each rock forms, but it is an open loop. Every cycle fractionates out additional minerals and rocks such that the ratios of different rocks change through time as the geosphere evolves.

The Wilson and Tectonic Rock Cycles are explored more fully in Fichter (1996, 1999), and Whitmeyer et al. (2007). Copies of the Wilson cycle model are available in 8.5 × 11, 11 × 17, and poster-sized versions, Fichter and Whitmeyer (2018). Representative PowerPoint presentations are also available showing how we develop the Wilson cycle and

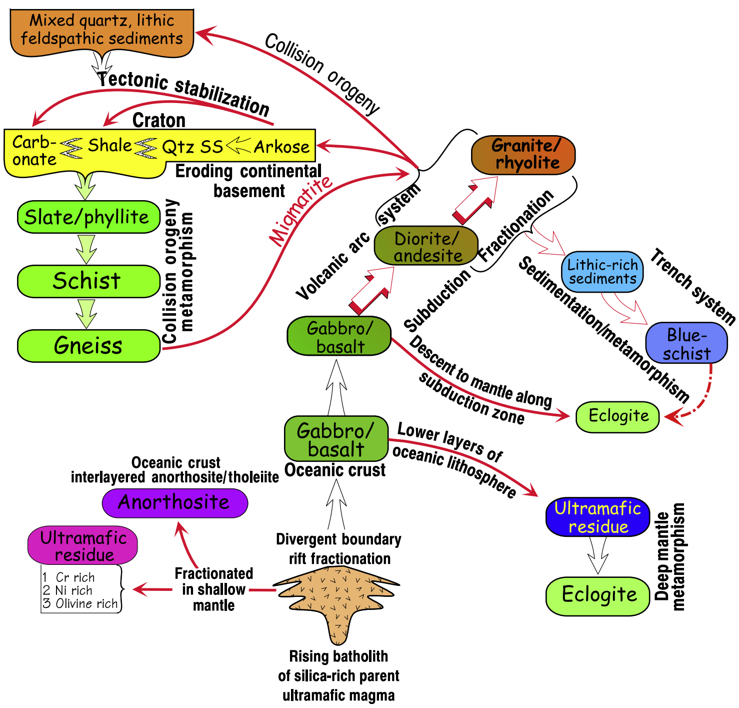


FIG. 3 The tectonic rock cycle. See text for description and references.

Tectonic Rock cycle models in historical geology. Permission is granted for teachers to use and modify these resources in any way they choose, as long as this article is cited.

The learning in SST unfolds in increasing depth and sophistication throughout the semester, but the process is initiated in the first few weeks—the first two Wilson cycle labs—where the pedagogic tone and strategies are first set out.

3 SCIENCE AS A SOCRATIC SEMINAR

As pedagogy, the SST labs are conducted as Socratic seminars, although instead of examining a text, we examine a rock. "The Socratic seminar is a formal discussion, based on a text, in which the leader asks open-ended questions. Within the context of the discussion, students listen closely to the comments of others, thinking critically for themselves, and articulate their own thoughts and their responses to the thoughts of others" (Israel, 2002). We do not set out to tell the students anything, although with more complex rocks, it may be necessary to introduce new theoretical models during the discussions. The questions and discussions focus on specific rock samples where each rock has a story to tell, and we must begin by observing the rock and the information it contains.

Acting as a seminar leader is a challenge for instructors who have spent years standing up in front of a class and professing. Rhetorical questions are not very useful, yet we cannot stand the uncomfortable silence that follows a penetrating question. Every second of silence increases the anxiety level until it exceeds some threshold, and then we just give up and blurt out the answer.

In a Socratic seminar, silence is followed by a different question, one we hope will give students a different perspective, an opening they can begin to utilize. If this does not work, the instructor follows with a different question. In other cases, the silence after a question is followed up by a directive to observe again, more thoroughly, or differently. Go test the rock with acid, or look at the rock under a microscope and come back with your observations. This often provokes new questions that are productive and reveal some insight from the students.

In a seminar, student questions are usually answered with a question. We presume that students ask a question because they are uncertain and do not know how to proceed, so the instructor has to be astute enough to sense what the block is, and by asking a useful return question, open up a new path of investigation. Of course, students also often ask questions because they have been trained to think that the answer, rather than the process, is what is most important. Or, they are trying to game the system. An effective seminar leader does not provide that satisfaction.

Although seminar-labs are often difficult to run effectively at first, the work of the instructor—the seminar leader—is simply to ask questions. Instructors ask about the mineralogy, about the fabric or internal structures, about the energy conditions under which each component of the rock was formed, and the theoretical models used to determine that. For example, what are the temperature/specific gravity conditions laid out in Bowen's Reaction Series, or a metamorphic T/P phase diagram? What does the maturity of a rock tell us about weathering and sorting processes? "If you don't remember, go look it up." Only after these questions are answered can we move on to petrogenesis and tectonic interpretations.

These seminar-labs turn out to be very satisfying. Students seem to genuinely enjoy the challenge—especially if they are well mentored in a supportive atmosphere—and when finished, they feel they have accomplished something. And the instructors also find the labs engaging and stimulating. We roughly know what the outcome of the investigations need to look like but have little control over the path the students take to get there. Each team of students comes in with a different combination of knowledge, skills, and understanding, and each start with a different rock, so the seminar takes a different trajectory every time. However, we certainly come to understand what students know and do not know, what they can and cannot do, and what more we have to do to help prepare them better. This is not last year's group of students with the accumulated knowledge of the entire course, but a new group of novices. It has helped us refine the design of the rest of the SST course to remedy weaknesses, and introduce better models.

4 A RATIONALE FOR THE WILSON AND TECTONIC ROCK CYCLE MODELS

> "All models are wrong, but some models are useful." (***Box, 1979***)

One of the purposes of science is to find the simplest explanations—the simplest models—for the phenomena of the world. This idea goes back at least to Galileo and the beginning of the laws of mechanics. William of Ockham in the Principle of Parsimony argued that, all things being equal, the simplest explanation is always to be preferred (Sober, 2015)—in science's case as mathematical models. Modeling moved into thermodynamics with Fourier's (1822) law of heat flow, again a very simple model. And even though thermodynamics evolved to greater complexity, presentations still begin with Fourier's law. And in the 20th century, Einstein (2009) continued this simplicity principle by stating that the goal of theoretical physics was to find "supreme purity, clarity, and certainty, at the cost of completeness." This principle has been recognized by a number of people. Joanna Macy (1991) for example refers to it as "Mutual Causality." It has also been described as "Dependent Co-Arising."

Earth scientists, of course, deal with more complicated phenomena than the classical sciences—there are more degrees of freedom. Instead of crisp algebraic equations, fuzzy equations would be the more realistic scenarios to explain natural phenomena. But in Earth studies, the central and most synthesizing model taught in introductory courses is still the traditional circular rock cycle—the principle that all rocks can be transformed into other rocks (e.g., Tarbuck et al., 2017, among many others). As with any simple model, the circular rock cycle is both true,… and a lie. Part of its simplicity is because, in acknowledgment to classical science principles, the circular rock cycle assumes a steady state, equilibrium Earth. But one of the other conclusions of the Earth sciences is that the Earth has evolved through time, which means the Earth is not an equilibrium system (Fichter et al., 2009). For example, we know that Archaean environments were markedly different from those today (e.g., Dilek and Furnes, 2014), and from that initiation the geosphere, atmosphere, biosphere, and hydrosphere have coevolved, each modifying and being modified by the others.

The circular rock cycle, even though it is "wrong," is useful, especially in introductory courses. It was useful in fixidist geosynclinal days, and it is still useful in today's mobilist plate tectonic modeling. But it is incomplete, and in upper level courses certainly too simple. We have developed the Wilson and Tectonic Rock Cycles to reflect more advanced, but still simple, concepts of Earth processes. The Tectonic Rock Cycle (Fichter, 1996, 1999; Whitmeyer et al., 2007) differs from the circular rock cycle in that it explicitly includes rock evolution through time, and does so in a plate tectonic framework. The model is available at the web site accompanying this paper in pdf and PowerPoint formats (Fichter and Whitmeyer, 2018).

The Wilson cycle model is initially introduced in lower-level historical geology lectures where it is designed to explore and incorporate many geologic concepts developed throughout the semester. In a lower level course, the presentation is relatively simple, using the kinds of basic rocks learned in an introductory geology course. However, it also explores how plate tectonic and structural geology principles relate to Earth materials. In the upper-level SST course, we expand on this foundation and use the Wilson Cycle model to explain the depositional and tectonic processes that formed rocks typically found in the Mid-Atlantic region of the Appalachians. By using specific rock samples that students will see later in the field, students develop a useful tectonic framework for their subsequent fieldwork and regional tectonic syntheses (e.g., Whitmeyer and Fichter, this volume).

5 WILSON CYCLE MODEL SEMINAR-LAB EXERCISES: AN INTRODUCTION TO STRATIGRAPHY, STRUCTURE, AND TECTONICS

There are three pedagogic steps to the exercise:

Pedagogic Step One: Prerequisites

The prerequisites to these seminar-labs include knowledge of: (1) basic mineral/rock identification and interpretation using keys, (2) principles of plate tectonic theory, and (3) knowledge of the Wilson Cycle model. If these concepts are taught in an introductory physical or historical geology class, the Wilson Cycle seminar-labs come at the end of that semester as a unifying and synthesizing model of all that has come earlier in their geological education. In a lecture situation, the Wilson Cycle model is followed by the Tectonic Rock Cycle model (Fichter, 1996, 1999; Whitmeyer et al., 2007).

In an advanced class the Wilson Cycle seminar-labs serve as a connecting link between what students have learned in earlier courses and what is to be further developed in the upper level course. That is, our upper level course (SST) starts off with this synthesizing lab to review what students learned in previous classes and to set the tone for the semester. One way or another, students will need a systematic introduction to the Wilson and Tectonic Rock Cycles before pursuing the labs described later in the text.

Pedagogic Step Two: Rock Identification

This first lab begins with this introduction, which is meant as both information and to set the tone for the lab:

"These exercises assume you have been introduced to mineral and rock identification, a variety of petrologic and structural theoretical models (e.g., Bowen's Reaction series, and stress/strain diagrams), and plate tectonic concepts. During the semester, you will be introduced to more advanced theoretical models as necessary. We do not plan a systematic review of rock classification and interpretations here, assuming you have already learned that. But we will be identifying, talking about, and interpreting rocks all semester, both in lecture and especially on the field trips. If you need to refresh your memory on rock classification, identification, and petrogenesis, there are keys and diagrams at the back of this exercise to help you do that. But at the same time, this lab is an opportunity to do some of that review and start thinking seriously about rocks and their interpretation. As you work to identify the rocks, talk among yourselves, and ask us all the questions you want (although questions may often be answered with other questions)."

The sample keys and diagrams mentioned in the instructions are available at the website (Fichter and Whitmeyer, 2018). We would prefer to use formal classifications learned in petrology for identifying rocks, but students typically have not been introduced to them yet. The keys we use are more intricate and parse out rocks more finely than those normally found in introductory courses. Still, we emphasize that a key is tool for identification and not a formal classification.

In this rock identification seminar-lab, students are required to recall and use principles they have learned in previous courses, or other parts of this course, but which they may not yet have been asked to integrate. Sometimes the struggles that students have tells us that our development of ideas in other courses has not done a good job of preparing them to make the connections between rock evolution and tectonics. On the other hand, we have a lot of control over the difficulty and sophistication of the exercise by the rocks we choose to have them analyze. In an introductory physical or historical geology class, the rocks are straightforward, and easy to identify and interpret; for example, a diorite, quartz sandstone, or schist.

In an advanced class, the rocks we use are more difficult because they represent not idealized specimens but the more realistic samples we find on the outcrop. These rocks might, for example, involve a plutonic charnockite that is now a protomylonite, with a greenschist overprint, or a rock containing a Bouma sequence where they have to identify the QFL of the sandstone, as well as recognize the association of layers that make it a Bouma sequence and not a hummocky sequence. This presumes that students have already learned the principles that allow them to make these determinations. In our upper level course, we have the ability to choose local rocks from outcrops we visit on field trips. Some of these are atypical or unusual samples, and for students to analyze them requires a lot of close mentoring during the lab. It is challenging for them and us but allows us to get beyond simple-minded approaches to rock identification and analysis.

Further instructions in the lab exercise are listed here. Fig. 4 is a representative data sheet mentioned in the instructions:

- ☐ *There are 20 rocks to identify. The rocks are in no particular order; completely random.*
- ☐ *They are mixed igneous, sedimentary, and metamorphic.*
- ☐ *Some of the rocks are not the usual specimens you find in an introductory geology lab but may be common on Earth.*

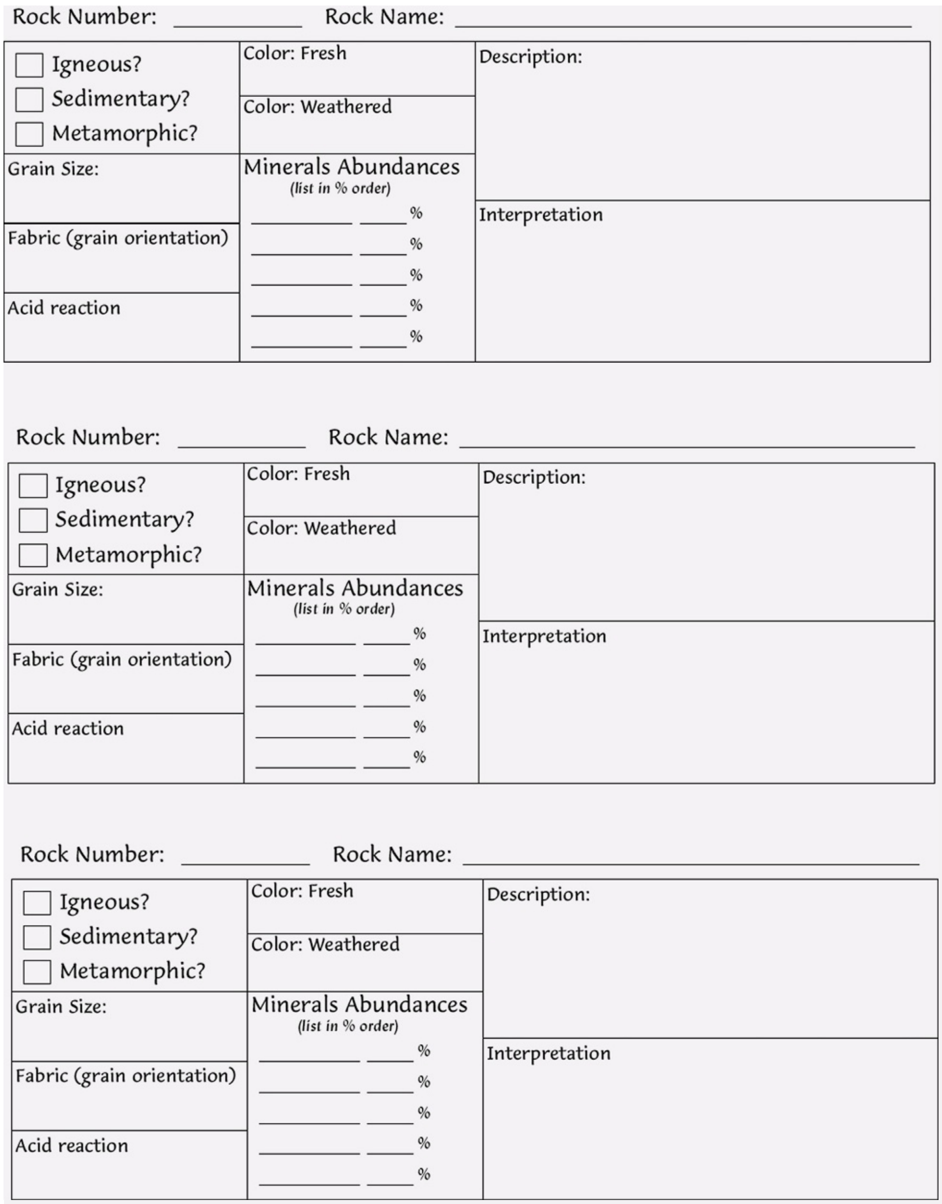
Also:

- ☐ *At the back are some keys, tables, charts, and diagrams that will help with your identifications and interpretations. Poster-sized versions of these are in the lab.*
- ☐ *Data sheets are provided to focus your observations and learn to take systematic notes. They are not meant to be exhaustive; just a place to put your observations. But you should examine the rocks as carefully as you can, and describe them as fully as you can. If the table here is inadequate, develop your own.*

Expectations:

- ☐ *You must have all 20 rocks analyzed and identified by the beginning of the next lab. If you do not finish during this lab period, continue to work on it during the next week.*
- ☐ *At the beginning of the next lab, we will ask each of you individually or as a team to stand up in front of the class and talk about what you know about one of the rocks (we choose the rock). The rocks will be chosen more or less at random when you come up. You will talk maybe a minute, not more than two minutes about your rock. This must be extemporaneous, followed by a Q and A where anyone can ask you about the rock.*

When classes are large, we omit the extemporaneous rock reviews mentioned in the instructions; semesters are just too short. We also have solution keys to the rock identifications, and if a team can demonstrate to us they have done a thorough analysis, we allow them to read the key. A few sample key-descriptions are in the following table; we deliberately chose to illustrate some of the more complex specimens we use. Most of the 20 rocks are not as difficult as these. But by now we have incorporated about


Rock Number: ___________ Rock Name: ___________________________________

☐ Igneous?
☐ Sedimentary?
☐ Metamorphic?
Color: Fresh
Color: Weathered
Description:
Grain Size:
Fabric (grain orientation)
Acid reaction
Minerals Abundances
(list in % order)
_________ _____%
_________ _____%
_________ _____%
_________ _____%
_________ _____%
Interpretation

Rock Number: ___________ Rock Name: ___________________________________

☐ Igneous?
☐ Sedimentary?
☐ Metamorphic?
Color: Fresh
Color: Weathered
Description:
Grain Size:
Fabric (grain orientation)
Acid reaction
Minerals Abundances
(list in % order)
_________ _____%
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_________ _____%
Interpretation

Rock Number: ___________ Rock Name: ___________________________________

☐ Igneous?
☐ Sedimentary?
☐ Metamorphic?
Color: Fresh
Color: Weathered
Description:
Grain Size:
Fabric (grain orientation)
Acid reaction
Minerals Abundances
(list in % order)
_________ _____%
_________ _____%
_________ _____%
_________ _____%
_________ _____%
Interpretation

FIG. 4 Representative data sheets used in the rock identification lab; many variations are possible. It is just a format for organization observations.

a dozen local rocks that will be seen on field trips. The advantage of seeing and analyzing these rocks in this lab is that we don't have to try and explain them or their theoretical models, on the outcrop, to 30 or more students, next to a noisy highway, in the rain.

Sample Descriptions of Rocks Used in Lab

2. Dolomite (three specimens)	*OB, Ordovician Beekmantown Formation. One specimen is a gray ribbon rock; the second is a grayish-white algal laminated dolomite that reacts poorly with acid; and the third specimen is a gritty medium-gray dolomite (described as sugary) with white veins filled with rhombohedral dolomite; it is an evaporate deposit; vugs with white crystals originally filled with gypsum. Tropical tidal flat facies*
7. Mylonitic augen charnockite granite	*Garth Run locality; a sheared 1150 charnockite; now a mylonite; compare with specimen 12. Notice large feldspar crystals that are tending to elongate; this is the result of the shearing*

9. Meta-quartz sandstone interbedded with phyllite	*CH, Cambrian Harpers Formation. Base of Blue Ridge, Page Co, Virginia. Hummocky cross stratification; note the bundles of laminations that pinch laterally and intersect other bundles of laminations*
13. Sequence of biosparmicrite, fine laminated sand, and shale	*OR, Ordovician Reedsville Formation. Germany Valley, West Virginia. Hummocky sequences; look for fine tapering laminations in the sand unit. Can you determine which way is up? Reedsville is dominantly hummocky sequences representing storm events but is randomly interbedded with biospar/biomicrite facies. Biospar-mics are often deposited in large ripples and likely represent separate events from the hummocky sequences. These units are thin enough that this most likely represents a distal storm shelf environment*
16. Anorthosite/Gabbro	*Dark gray color, but look for iridescence on plagioclase feldspars; some pyroxene present (amount determines whether it falls into anorthosite or gabbro category.) Associated with AMCG (Anorthosite-Mangerite-Charnockite-Granodiorite suite) igneous suite found in the Blue Ridge province. A deep plutonic rock. Also found in the Ophiolite suite*
19. Amygdaloidal basalt—now greenschist facies	*CC, Cambrian Catoctin formation. From along Skyline Drive, Blue Ridge province. About 550 Ma. Metamorphosed to greenschist during the Alleghanian. This is a rough specimen (weathered and a bit beat up), but note the quartz blebs. The first instinct is to call them pebbles but they are amygdules that started off as versicles in a vesicular basalt later filled in with quartz during the metamorphism; sometimes amygdules are epidote. In other places, the Cactoctin has columnar jointing and brecciated zones that represent the bottom of a lava flow. Extruded subareally at the initiation of oceanic crust formation during rifting of Rodinia*

Pedagogic Step Three: No Rock Is Accidental: Rock Genesis and Terrane Interpretation in the Wilson Cycle

This second lab tends to be free-wheeling. The rock trays are set out, and everybody has a copy of the instructions and Wilson Cycle model but with specific locations identified by letter. Poster-sized copies of the same Wilson Cycle model are posted around the room. People are milling around, and there is a cacophony of conversations as each team debates their choices. The instructors and assistants wander around, listening to the debates but intervening only rarely. We do answer questions but in the same seminar-lab strategy as before; a direct question is answered with a counter-question, always with the intent of helping them discover their own understanding. The only exception is, the instructors/teaching assistants have keys to the rock locations and a student team is allowed to ask, “Did specimen 6 form at location J”? Once they explain their reasoning, and it is satisfactory, the answer is always a simple “yes” or “no”. But, a “no” may be followed by a redirect question.

This lab contains five sections, but for us the main ones are 1 and 2; the other exercises 3, 4, and 5 have been done in an earlier course. The instructions given to students for each section are listed in the following text.

We begin in Part One with a quick review of plate tectonic terranes[1] because the Wilson Cycle model is based on them and we need a common terminology. If they already know it, students are instructed to move on.

Part One—Plate Tectonic Relationships

The following is a cross-section (Fig. 5) of a portion of the Earth’s lithosphere. Label it with the following plate tectonic terranes. Forearc, Backarc, Craton, Remnant ocean basin, Paired metamorphic belt; Foreland, Hinterland, Hotspot, all plate boundaries.

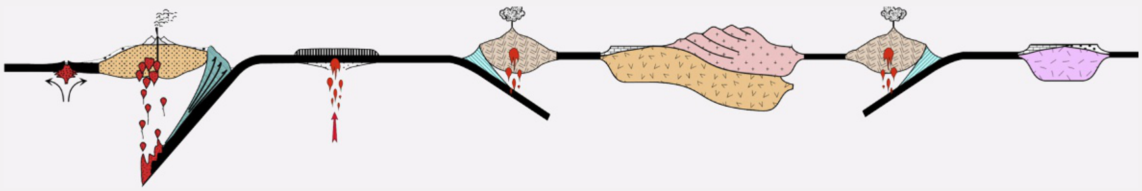


FIG. 5 Thumbnail model of various plate tectonic terranes and boundaries.

[1] Terrane is defined as a fault-bounded area or region with a distinctive stratigraphy, structure, and geological history. We alter this slightly to also include distinctive bodies of rock formed at different times and separated by major unconformities.

Part Two—Rock Generation in the Wilson Cycle

Instructions:

- ☐ *Wilson Cycle Model: you are provided with a model of the Wilson Cycle with terrane locations identified by letter.*
- ☐ *Rocks: From the selection of 20 rocks you identified last week, choose the one best rock that most likely formed in the tectonic terrane at the indicated lettered locations on the Wilson Cycle cross-sections. More than one rock may fit the location, but there is only one best specimen.*
  - *Note you have 20 rocks to work with, but there are only 13 terrane locations identified on the Wilson Cycle, meaning there are 7 orphan rocks you will not use.*
  - *In the following spaces, briefly explain the process by which each rock formed. It is important to integrate everything you already know: plate tectonic processes and the specific conditions under which each rock forms, including structure.*
- ☐ *You are encouraged to work together with your partners on this project and test the specimens any way you want. Talking, debating, throwing ideas around, and sorting out what you know and what you don't know is part of the process.*
- ☐ *Be able to explain your identifications and analysis so that both you and your listener are sure you understand why no rock is accidental.*

As a further guide, we provide pithy descriptions to match each location indicated on the Wilson Cycle model. Experience tells us that these descriptions are not a giveaway. The descriptions are, of course, specific to the rock samples available. A few examples are provided here.

Location A: Rock Number: _________ Name Rock: ___________________________.

Extrusive igneous rock ejected onto a continental surface above a hot spot during the initiation of a rifting event (now low grade metamorphosed by a later event).

☐ *Describe the tectonics and processes of formation.*

Location D: Rock Number: _________ Name Rock: ___________________________.

Extrusive mafic igneous rock ejected at a subaqueous oceanic rift center.

☐ *Describe the tectonics and processes of formation.*

Location J: Rock Number: _________ Name Rock: ___________________________.

Sediments deposited in a shallow marine shelf within a prograding foreland basin created by the collision between a volcanic arc and a continent.

☐ *Describe the tectonics and processes of formation.*

We usually do not have time to do Part Three, but suggest it would be good practice and a way to study for a subsequent test. We provide a table on which students can record their observations but have not included it here.

Part Three—Orphan Rocks

Instructions:

- ☐ *You have seven rocks left over. Try to decide where in the Wilson Cycle these rocks might be best found, and the rock genesis/tectonic conditions of formation.*
- ☐ *When finished, ask your instructors to check your analyses.*

Part Four is based on the premise that, when mapping regional geology, it is common to cross a fault and move from one terrane into another that often exhibits very different rocks and structures. Hence the idea of the out-of-place or "suspect" terrane (e.g., McPhee, 1983). The challenge in Part Four is to take cross-section I, the final stage in the Wilson Cycle model, enlarged in Fig. 6 (the upper cross-section identifies the terranes with letters, whereas the lower cross-section includes the solutions), and deconstruct its history. That is, for each terrane letter on the cross-section in Fig. 6, deduce in which stage of the opening and closing of the Wilson Cycle model it reasonably formed in. Students do this by examining the Wilson Cycle model stage by stage to determine where the rocks associated with a letter first appear. Ideally students ultimately develop the capability to accurately place rock samples in their tectonic setting using only the final stage (Stage I) of the Wilson Cycle.

We do Parts Four and Five in our historical geology class and so skip them in SST, except to suggest that students would likely find it useful as a review. On our field trips, they get a lot of practice doing this kind of deconstruction. We provide a table for them to record their observations but have not included it here.

Part Four—Tectonic Stages and Terranes in the Wilson Cycle

"No Rock is Accidental", but any particular rock may form or be found more than once in a Wilson Cycle. Fig. 6 is a copy of Stage I of the Wilson Cycle identifying by letter the various terranes generated during the 10 stages of one Wilson Cycle.

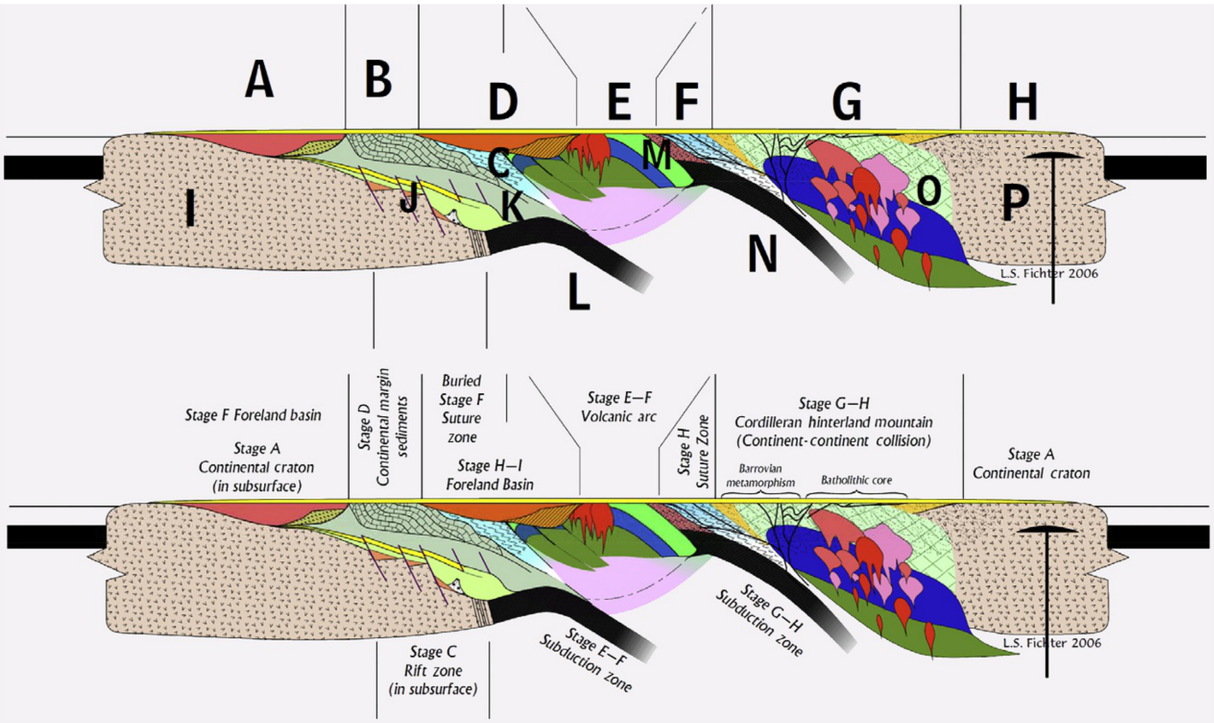


FIG. 6 Final Stage I in the Wilson Cycle model. The letters refer to various tectonic terranes developed during the opening and closing of the ocean basin.

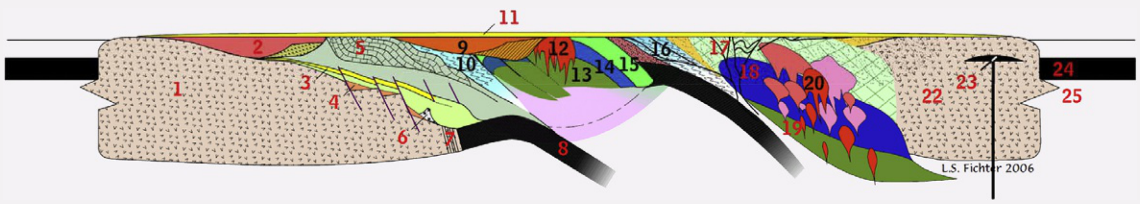


FIG. 7 Final Stage I in the Wilson Cycle model with specific rock groups identified by number. In the exercise the goal it to describe and explain the rocks that would be found under each number.

Instructions:

- ☐ *For each terrane in the figure, identify the Wilson Cycle stage it was generated in.*
- ☐ *Identify from among our 20 rocks those that can reasonably be found in each tectonic terrane.*

Part Five is more of a challenge and is not based on any specimens we provide. Instead they are to deduce what rock would reasonably form at each numbered location on Fig. 7. We provide a table to record their observations that is not included here.

Part Five—Rocks in the Wilson Cycle

Note: Do not use the rock specimens in the trays! This problem is about being able to predict what a rock will be based on its location in the Wilson cross-section.

Fig. 7 is a cross-section of the final stage of the Wilson Cycle. For each numbered location, predict the kind of rock that would form there. These are not the rocks you identified earlier, but rocks you would predict would be found at each of these locations. You should be able to identify in which stage of the Wilson Cycle each rock formed, and identify the rock found at each numbered location.

6 TESTING YOUR KNOWLEDGE OF THE WILSON CYCLE

The work of a field geologist is to read great events in the rocks that compose the Earth's crust.

We have to learn our geology twice: Once in the classroom where it is primarily theoretical and again in the field where it is primarily empirical. No amount of classroom learning can completely prepare us for understanding geology in the field; we have to see it. The sophistication of a geologist is how confidently we can go back and forth between theory and field observation, and knowing which is appropriate under what circumstances. This is a learned skill.[2]

The Wilson Cycle is a theoretical model. It is neither true nor false. It is a tool. The value of theoretical training is two-fold and complimentary. First, a theory tells you what to look for while in the field. If a theoretical model is true then we should find certain relationships. In addition, a theoretical model is predictive. In the field, with widely scattered outcrops, it allows us to reconstruct and make sense of how they formed.

Second, the field evidence allows us to test a theoretical model's predictions. Two science philosophers had important things to say about this.[3]

Classically, the goal of science was to find **T**ruth: to see God's mind at work. Karl Popper, beginning in 1919 (1992, 2002; but also see 1980 for a concise explanation of Popper's ideas), however echoing David Hume, demonstrated that **T**ruth is impossible. Prior to Popper, if a theory was thought to be "true" it was by definition scientific. Because finding **T**ruth is impossible, Popper changed the question to "When should a theory be ranked as scientific?" He wanted to distinguish between science and pseudoscience. Hume and Popper also argued that there is no such thing as an unbiased observation. It is psychologically and logically impossible, and because scientific investigation begins with observations of nature, our "data" is suspect from the beginning.

For a theory to be scientific, it must be falsifiable; that is, it must make predictions capable of being empirically demonstrated untrue. The theory has to take risks. A theory that is not refutable by any conceivable event is nonscientific. If the prediction is empirically verified, the theory is strengthened but not proven true. No observation can prove a theory true. If, however, the prediction is not empirically verified, it means the theory has been falsified and it must be discarded or reformulated to account for the new information.

Thomas Kuhn (1971) argued that, unlike the common misperception that science is a continuous progress—the continuous accumulation of true knowledge—science goes through periods of Normal Science (what he called puzzle solving within a universally accepted paradigm),[4] followed by Revolutions that completely change the way we see the world. To summarize, all theories are potentially wrong—as Popper demonstrated—we just don't know ahead of time how they are wrong.

Echoing Popper's seminal works, Kuhn argues falsification begins during normal science with the accumulation of anomalies—observations or facts that do not fit into the accepted paradigm or theory. Anomalies may arise by a chance observation of a rare phenomenon, or when a theory makes a false prediction, or with an anomalous experimental outcome, but can arise in other ways. Within the accepted paradigm the anomalies are inexplicable; they do not make sense and are often conveniently ignored (it's a rare scientist who publishes data that they cannot explain and/or does not support their argument). But, when enough anomalies accumulate, or when a seminal anomaly appears to seriously challenge the accepted paradigm, science enters a period of "extraordinary science", during which research is strongly focused on the anomalies that do not fit into, or are not explainable by, the paradigm. Kuhn also states that the scientists most likely to discover and pursue anomalies that lead to revolutions are the most experienced, the most learned, and the ones who have the deepest understanding of the reigning paradigm and theories. (For an alternative view, see Sulloway, 1996.)

For our purposes, mastery of geological theories serves two purposes. First, theories guide our observations and help us understand our observations in the field. But, equally important, they should help us recognize anomalies—predictions that are not true, or new observations that the theory has not accounted for. Every genuine test of a theory is an attempt to falsify it or to refute it. Ideally, we want to force the Wilson Cycle theory to make a prediction that turns out to be empirically false. We then have a chance to learn something new, or deepen our understanding of existing concepts.

However, all of this is predicated on you (the geologist) having thoroughly mastered the theory; as we say, "inside out, upside down, and backward". Thus next we suggest some exercises for testing your mastery of key concepts of the Wilson Cycle.

[2] An example we commonly hear from novice geologists is a statement such as, "If this is the Martinsburg formation, it must contain Bouma sequences." That is backward; you cannot use an interpretation—theory—to justify what must be an observation.

[3] This very pithy summary of the work of Popper and Kuhn necessarily contains distortions. We recommend that you refer to the works of these authors in their original forms.

[4] Kuhn defined paradigms as "universally recognized scientific achievements that for a time provide model problems and solutions to a community of practitioners". Within a paradigm are various theories, which explicate the details of the paradigm.

Exercise 1

Mastering Wilson Cycle Theory: Stages and Tectonic Regimes in the Wilson Cycle

Fig. 6 contains two cross-sections representing the final Stage I of the Wilson Cycle model (shown previously in Fig. 1). They contain the sum total of all the events and outcomes of the model.

The upper cross-section represents the amalgamation of several tectonic terranes labeled A through P, each representing a specific set of geologic conditions (tectonics, temperature/pressure conditions, depositional basin type, etc.) that existed at the time of the terrane's formation. Each geologic condition, of course, has its own descriptive theoretical models (e.g., phase diagrams, rheological models, isostatic principles, depositional system models, flow regimes, etc.). There are multiple layers of interpretation.

The term ***tectonic regime*** refers to a distinctive plate tectonic setting; for example, fore arcs, back arcs, divergent plate boundaries, etc.

Instructions:

1. If you are not familiar with the Wilson Cycle model, review Fig. 1 and go to the website (Fichter and Whitmeyer, 2018). There are several links that explore the Wilson Cycle model including: (1) a link to a website that describes the model stage by stage, (2) a link to a document describing extensively the events and rocks generated in each stage of the cycle, and (3) links to introductory lecture PowerPoint presentations that describe the model.
2. If you are familiar with the Wilson Cycle model, go to Fig. 6. Cover the lower cross-section so you can't see it (it is the key). The upper cross-section consists of several tectonic terranes labeled A through P, not labeled in any particular order. Presented here are three different ways to probe your understanding of the Wilson Cycle.
   A. Based on your knowledge of the Wilson Cycle, for each of the tectonic terranes, identify the plate tectonic regime in which it formed. Tectonic regime examples include: forearc, backarc, divergent (passive) margin, craton, rift system, arc-continent collision, etc. See Fig. 5 for examples. Solutions to these problems are in Appendix One

Tectonic Terranes	**Generated in Which Type of Plate Tectonic Regime?**
A	Continental craton
B	Passive (divergent) margin sedimentary wedge
C	Melange belt (accretionary prism) associated with a subduction zone
D	Foreland basin
…	*continue likewise*

   B. The Wilson Cycle model has nine stages: A through I. Stages A through D are the rifting phase. Stages E through I are the closing phase; see Fig. 1. For each of the tectonic terranes in the upper cross-section of Fig. 6, identify the Wilson Cycle stage it formed in, as in the examples that follow. The lower cross- section in Fig. 6 is a key you can use to check your identifications. There is also a key linked at Fichter and Whitmeyer (2018).

Tectonic Terrane	**Formed During Which Wilson Cycle Stage(s)?**
M	Stages E and F—Volcanic Arc
D	Stages H and I—Foreland basin
…	*continue likewise*

   C. Arrange the tectonic terranes A through P in order of their formation. They will not be in alphabetical order. Some of the letters may represent different parts of the same tectonic terrane that may now be separated from each other, in which case you should bracket them together. You can check your analysis with Fig. 1.

Arrange the tectonic terranes in sequential order of formation		
Listed oldest to youngest	Wilson Cycle Stage(s)	Tectonic Regime and Description
First	(I+P)	Original continental craton composed of plutonic felsic igneous rocks (e.g., granites, granodiorites, plagiogranites) or their metamorphic equivalents

Second	J	Continental rift system creating west and east continental fragments. Extensional horsts and graben with subareal proximal sediments and mafic and felsic volcanics.
Third	(K+B)	Divergent continental margins created by rifting event. Mostly shallow shelf and coastal sedimentary environments (climate controlled) forming a wedge thickening toward the ocean basin.
Fourth	*continue like wise*	

Exercise 2

Mastering Wilson Cycle Theory: Rock Genesis

We cannot see tectonic terranes, except conceptually in the mind's eye. A foreland basin, for example, is just too big. We construct a model of the foreland basin from many field observations across a wide area, aided by theoretical models. Rocks, on the other hand, we can hold in our hand. Rocks may just be "stones" to the uninformed, but for geologists rocks are like books, waiting to be read. This is what the study of petrology is all about.

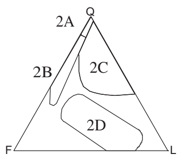
If "No Rock is Accidental" is true, then we need to analytically specify in a theoretical model, like the Wilson Cycle, which rocks will form where, under what conditions, and from what protoliths (if applicable). It is a deductive process based on theoretical models of how each rock forms.

The work of a field geologist is to reverse engineer theoretical models. In the process of mapping, we note not only the kinds of rocks found, but also their spatial relationships. And based on our theoretical training, we reconstruct the conditions that must have existed at that spot at the time each rock formed and, from that we deduce, the tectonic terrane or regime in which they must have formed. In this way, we inductively construct a model from fragmentary field evidence. The level of confidence with which you can do this is the degree to which you have mastered the theoretical model.

The field is also where we test theoretical models, for it is quite possible that the model we build inductively in the field does not match the theoretical (conceptual) model we have been using. The mismatches may be small or large, but they constitute anomalies in Kuhn's sense. The world may, in fact, be more complicated than our theoretical model suggests. Or, our theoretical model may be missing processes completely. One way or the other, discovering anomalies is the way we improve our theories.

Instructions: choose one of these two options

(1) Fig. 7 is Stage I of the Wilson cycle with locations identified by letters "1" through "25". For each of the locations, identify the rock type that would most typically form there. This analysis can be done at any level of rock classification from introductory to advanced. The table below uses broad-brush divisions and lists igneous and metamorphic rock suites in alphabetical order. If these rock categories are unfamiliar use a similar list of rock names/classifications with which you are familiar. There is a link in Fichter and Whitmeyer (2018) that describes typical rocks for each location in Fig. 7. Feel free to consult any resources you have to answer the questions below. Appendix two contains representative rock descriptions for each locality

Choose from Among these Choices Listed Alphabetically							
Igneous rocks		**Sedimentary rocks**		**Metamorphic rocks**			
1A	Alkaline suite	2A		3A	Amphibolite	4A	Migmatite
1B	Calcalkaline suite	2B		3B	Blueschist [melange]	4B	Quartzite
1C	Tholeiite suite	2C		3C	Eclogite	4C	Schist/Gneiss
1D	Komatüte suite	2D		3D	Granulite	4D	Slate/Phyllite
1E	Ophiolite Suite	2E	Carbonates	3E	Greenschist		

Location 1. Choose the one rock type most likely to form or be found at this location	
• 1A, 1B, 1C, 1D, 1E • 2A, 2B, 2C, 2D, 2E	• 3A, 3B, 3C, 3D, 3E • 4A, 4B, 4C, 4D,

Location 2. Choose the one rock type most likely to form or be found at this location	
• 1A, 1B, 1C, 1D, 1E • 2A, 2B, 2C, 2D, 2E	• 3A, 3B, 3C, 3D, 3E • 4A, 4B, 4C, 4D,
Location… Continue likewise	
• 1A, 1B, 1C, 1D, 1E • 2A, 2B, 2C, 2D, 2E	• 3A, 3B, 3C, 3D, 3E • 4A, 4B, 4C, 4D,

(2) Create a table like this one for each rock specimen and analyze each of the numbered rocks in Fig. 7. If necessary, refer back to the individual Wilson cycle stages (Fig. 1) to understand the processes operating. You may also draw on any other knowledge you have, such as a metamorphic rock phase diagram. Fichter and Whitmeyer (2018) has a link to a description of the rocks present at each location. (this option necessitates a more open-ended strategy)

Rock # and name:

Wilson Cycle stage
Tectonic regime
Processes/conditions of genesis,
Protolith (if altered from some other rock)

7 DISCUSSION AND CONCLUSIONS

The No Rock is Accidental lab exercises are designed to function as either summative exercises for an introductory historical geology course or as early refresher exercises for an upper-level course, such as SST (Stratigraphy, Structure, Tectonics). The main goal of these exercises is to remind students of characteristic rock types that they have likely discussed in previous geology courses, but then add in a tectonic framework for evaluating how and where the rocks likely formed. As such, the hand samples are no longer “rocks in a box” without any relevant context but rather key specimens that provide important information about a geologic region, such as the Mid-Atlantic Appalachians.

When rock samples are tied to a specific geologic region, and are subsequently followed up by field trips to the source locations of the rock specimens, the No Rock is Accidental exercises take on added value as effective examples of place-based geoscience education (e.g., Semken and Butler Freeman, 2008). We have found this to be an effective pedagogic strategy for helping students make the transition from introductory geoscience concepts to more advanced models that link abstract theories to integrated models of tectonics and Earth systems. In effect, these bridging exercises set the stage for more complex, multidisciplinary synthesis tasks that students will be asked to master in later projects (e.g., Whitmeyer and Fichter, this volume). We suggest that the approaches outlined in these exercises would be applicable to other tectonic settings, as long as the rock samples featured in the exercises are changed to better reflect the local geology.

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