CHAPTER

13

Integrating Structural and Stratigraphic Field Data to Build a Tectonic Model for the Mid-Atlantic Appalachian Orogenic Cycle

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OUTLINE

1 INTRODUCTION

Stratigraphy, structural geology, and tectonics are all common core components of undergraduate geoscience curricula. However, though both stratigraphy and structural geology are often presented in a tectonics framework, they are commonly taught as separate, stand-alone courses, at least within undergraduate curricula of geoscience departments in the United States. Within these courses, there typically is little overlap of subject, field data, techniques, or tools, and thus structural geologists have little common terminology with stratigraphers. Yet, structural and stratigraphic signatures in an outcrop are clearly related because these fabrics are the products of tectonic energies, and often both stratigraphic and structural features are found in the same outcrop. This is particularly apparent in regions like the Mid-Atlantic Appalachians of the eastern United States, where stratigraphic sequences record evidence from the Taconic and Acadian orogenies, and structural deformation fabrics predominantly were produced during the Alleghanian orogeny (Fichter et al., 2010; Whitmeyer et al., 2015). Collectively, these stratigraphic and structural signatures document much of the Appalachian orogenic cycle (comprising the Taconic, Acadian, and Alleghanian orogenies), and thus provide an excellent natural laboratory for integrated, cross-disciplinary, field-based investigations.

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In 2007 the Department of Geology and Environmental Science at James Madison University introduced an upper-level course entitled Stratigraphy, Structure, and Tectonics (SST) for a newly-revised Bachelor of Arts (BA) curriculum. The course has subsequently been incorporated into the Bachelor of Science (BS) curriculum, replacing stand-along Stratigraphy and Structural Geology courses. The SST course was designed to incorporate stratigraphic and structural concepts and analyses under the grand, unifying umbrella of tectonics. Two organizing motifs drove the development of the course. The first of which is “No Rock is Accidental” (Fichter and Whitmeyer, Chapter 10, this volume), where geoscientists must be prepared to gather all lithologic, stratigraphic, and structural information available in an outcrop, without discipline blinders. The second organizing motif is “follow the energy”, connoting that practically every observable feature in an outcrop is the result of tectonic energies, with the goal of deducing energy transfer from the many signatures apparent in the rocks (Fichter et al., 2010; Whitmeyer et al., 2012).

1.1 The Different Expressions of Tectonic Energies

Tectonic energies drive much of the geosphere, but the effects are not equally conspicuous. Structural features (joints, folds, faults, etc.) resulting from tectonic deformation allow rich interpretations that are either apparent as fabrics or features in the rocks, or can be extrapolated from outcrop measurements. In foreland fold-thrust belts, deformation fabrics occur at multiple scales, exhibiting fractal behavior, such that parasitic folds at the outcrop scale can be used to model the geometry of folds at the kilometer or regional scale. Faults with limited displacement have an orientation and sense of movement replicated by a few regional scale faults with significant transport. Dynamic analyses of these structural features can provide information about principal stress orientations during tectonic events, whereas kinematic analyses can suggest the magnitude and amount of transport during a tectonic event. Occasionally, deformation fabrics can also provide geochronologic information that can constrain the timing of tectonic events.

For the Blue Ridge and Valley and Ridge provinces of the Mid-Atlantic Appalachians, we can use aspects of foreland fold and thrust belt models (Fig. 1A) to organize and constrain field data and interpretations. Prior to, and concurrently with, field trips students are presented with models for how deformation features and fabrics develop, such as the formation of duplex structures and the development of antiformal stacks and imbricate thrust systems. These theoretical models, though never perfectly rendered in the field, provide a framework for students as they make observations from individual outcrops or hand samples. Ultimately, students will need to extrapolate beyond disparate elements of field data to synthesize their observations by making use of one or more of these tectonic models to assemble a regional-scale structural depictions (e.g., cross-sections) of the area.

The stratigraphic record also responds to tectonics, however the evidence is much less direct, does not feed back directly to the responsible stresses, and usually requires a theoretical framework for analyses. For example, relative water depth can be interpreted with color, texture, flow regime, etc., but each of these lies within a theoretical framework of its own (geochemistry for color; hydraulics for texture and flow regime). Complicating the issue, water depth, AKA accommodation space, is controlled by more than one variable (subsidence, eustasy, sediment influx rates, compaction, loading, and climate), each of which may be operating largely independent of the others, and in different time scales. Yet, the results can look the same regardless of the mechanism—water responds to depth, not how the depth is created.

Large tectonic processes that control the evolution of the stratigraphic record, such as foreland basin development, cannot be seen in individual outcrops. We deduce they exist, that they represent subsidence from shallow into deep water, and that they influence the stratigraphic record, but we do not have direct outcrop evidence of the subsidence, or its rates, or the size and shape of the basin. Indeed, while observing any particular outcrop it is difficult to imagine what is happening in the larger vertical, horizontal, and temporal contexts. Thus sedimentary-tectonic interpretations from field evidence are almost always inferences based on deductive arguments from a diversity of indirect data that must be synthesized from individual outcrops.

Stratigraphy-focused interpretations of tectonics require a predictive model that correlates tectonic energies with sedimentary energies. For SST we use a tectonic-accommodation model that focuses on the investigation and classification of basins (basin analysis) based on how they form and evolve, and their resultant geologic records. The records occur in a nested hierarchy of signatures, from individual laminations through beds, bedsets, parasequences, systems tracts, and basin-filling sequences. The filling sequence of any basin results from multiple energy sources. The initial driving energy is tectonic, influencing the rate and degree of subsidence, followed by dip-fed and strike-fed processes

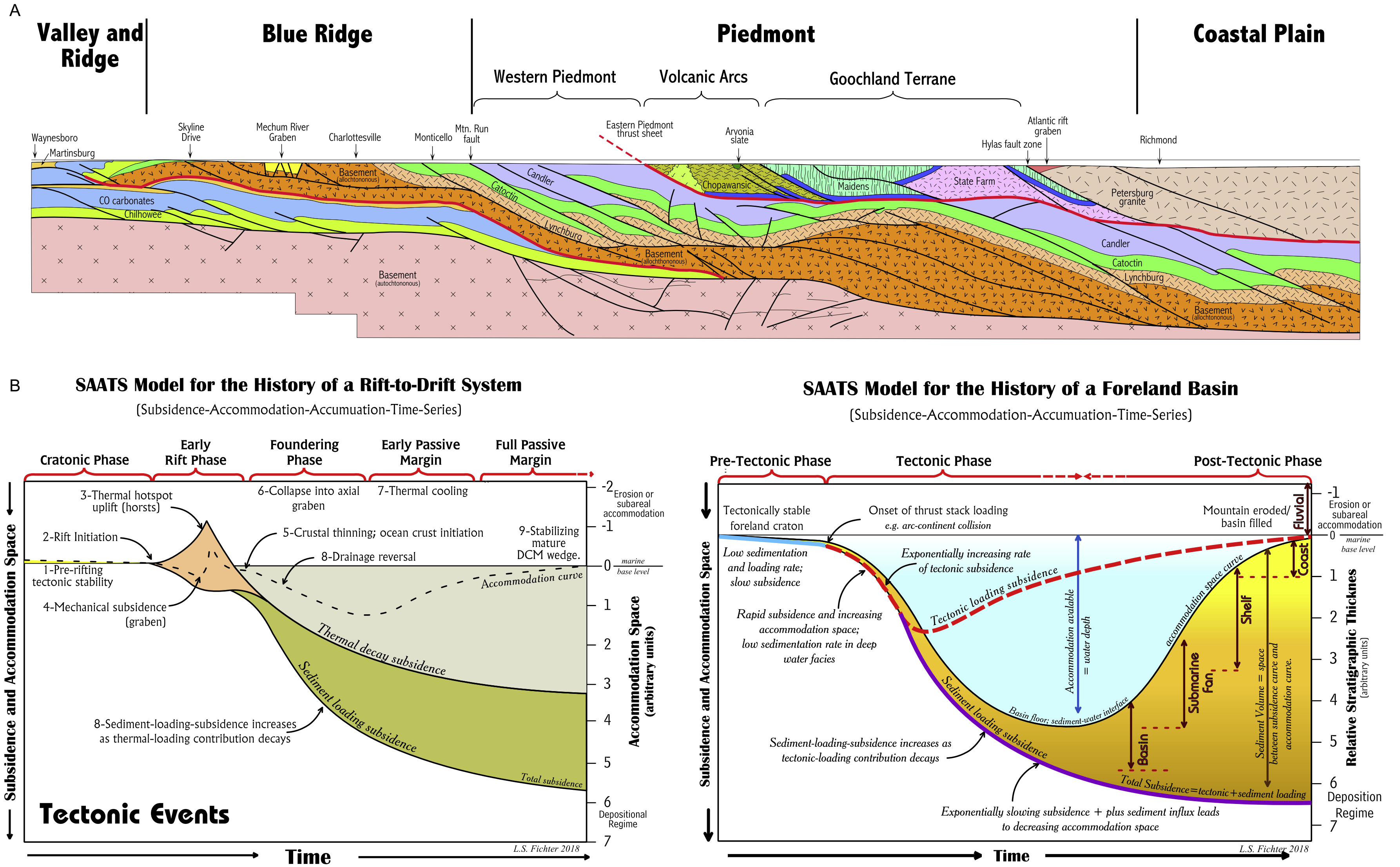


FIG. 1 Theoretical models relevant to the field transect areas. (A) Model of the Mid-Atlantic foreland fold-thrust belt (after Harris et al., 1982). (B) Example of tectonic-accommodation models for the investigation and classification of basins (Diecchio and Fichter, 2015; Fichter and Diecchio, 2015).

that fill the accommodation space and are influenced by sediment supply and sea level changes (Fig. 1B; Diecchio and Fichter, 2015; Fichter and Diecchio, 2015). See Fichter et al. (2010) for more details on stratigraphic models used for basin analysis.

1.2 The Importance of Field-focused Tectonic Investigations

It is now well-established that field investigations produce important cognitive gains for students (Boyle et al., 2007; Butler, 2008). Through fieldwork, students develop a deeper understanding of spatial and temporal relations (Kastens et al., 2009), which enhances their ability to draw conclusions or inferences from incomplete data. Students also learn to integrate field observations with knowledge previously gained from other geoscience coursework. Field experiences inculcate students into the methods, techniques, and intellectual mindset of the geosciences. Discussions that ensue among students as they evaluate group data encourage higher-order thinking skills and often provide transformative experiences (Whitmeyer and Mogk, 2009; Mogk and Goodwin, 2012).

Exploring the stratigraphic, structural, and tectonic evidence in an outcrop requires a deliberate and systematic strategy. It is important to keep evidence organized: what is apparent in each outcrop (e.g., petrologic, structural, and stratigraphic data), at what scales of observation, and how can the observed features be explained by tectonic models? This approach requires the examination of a rock or outcrop through more than one lens: a stratigraphic lens, a structural lens, and several tectonic lenses. Fieldwork begins with empirical data: what can be seen in an outcrop, and what is a plausible interpretation. Only when basic data collection is completed at an outcrop do students start incorporating regional contexts and ultimately construct tectonic histories from syntheses of all of the outcrops.

2 THE PROJECT

The "Tectonic Synthesis and Interpretation of the Mid-Atlantic" project is organized as an interplay between classroom-developed, top-down deductive theoretical models, and bottom-up inductive field experiences and data collection. These two approaches are woven together in a semester-long project whose goal is an examination of how stratigraphic, structural, and tectonic principles have produced the regional geology of western Virginia and eastern West Virginia. Across four field trips, we visited ~60 outcrops along two transects running from the Blue Ridge Province in the east, across the Valley and Ridge province, to the Allegheny Front in the west. Each outcrop is examined through multiple disciplinary lenses, with continuous discussions on how the regional tectonics of the Mid-Atlantic (Grenville orogeny and Rodinia rifting events; Taconic, Acadian, Alleghanian orogenies and intervening semiquiescent periods; rifting of Pangaea) progressed through time based on evidence in the rocks.

On each field trip, students work in two or three person teams to collect stratigraphic and structural data that provide information about regional tectonics. Students use their field data to draft multiple cross-sections that, in combination, highlight plutonic, volcanic, metamorphic, and in particular the stratigraphic sequence and structural deformation that characterize the Grenville and Appalachian orogenic cycles. Students summarize the geologic history of the region in a tectonic synthesis that interprets the depositional and deformation features within the context of theoretical models developed throughout the rest of the course.

The project is summarized in the following excerpt from a recent SST course syllabus:

> "To be a well-educated Earth scientist means possessing the knowledge, skills, and ability to do several things. First, the ability to visit a locality anywhere in the world, and by examining its geological, hydrological, biological, climate, and land use features deduce the sequence of geological and environmental conditions that have existed there throughout the region's history. Second, being able to compile and summarize all of that information into a scientific, written document. And, third, being able to use that knowledge to analyze and solve an anthropogenic problem, or series of problems, based on that knowledge. In one course, we are not able to do this entire sequence of activities. However, because this course encompasses structure, stratigraphy, and tectonics, and because we will also need to incorporate petrologic data, one of our major goals is to do a semester project that synthesizes and integrates all of this structural, stratigraphic, and petrologic information.
>
> Your tectonic syntheses will be based on lab and fieldwork in our local region. The project consists of constructing a structural/stratigraphic profile across West Virginia and Virginia from the Allegheny Front, through the Valley and Ridge, and into the Blue Ridge.

> The fieldwork consists of visiting dozens of outcrops across the region, gathering structural, stratigraphic, and petrologic data from each outcrop, plotting that data on a topographic profile, and then using that to interpolate and construct a structural profile. This will be followed by a synthesis report that takes that information and uses it to write a complete structural, stratigraphic, and tectonic description and history of the region. There are a lot of technical details that you will master in doing this project, and we will provide more detailed and individual instruction as the semester progresses.”

In the following, we highlight two exercises incorporated within the project, as examples of the field data collection strategies employed by students and tectonic synthesis components that they produce.

EXAMPLE EXERCISE 1

This exercise involves building a cross-section from lithologic and orientation data that students collect in the field. Students will already have completed an introductory cross-section exercise earlier in the semester, during which they learned how to take a simple geologic map with orientation and lithologic data and construct a geologically valid cross-section interpretation. For further background and examples of cross-section construction, see Lopez-Mir, Chapter 3, this volume. For this Example Exercise 1, students’ collect field data along a transect that extends from the western end of the Blue Ridge province through the eastern part of the Valley and Ridge province in central-western Virginia (Figs. 2 and 3A). Progressing from east to west, it incorporates Grenville-age charnokite gneisses and greenschist-facies cover sequences related to the breakup of Rodinia, which have been transported tens of kilometers to the west along a major structural boundary - the cryptic Blue Ridge thrust (Bailey et al., 2006a; Fichter et al., 2010; Whitmeyer et al., 2015). Footwall rocks include Cambrian-Silurian sedimentary rocks that have been deformed into a predominantly west-vergent sequence of meters-to-kilometers wavelength folds, occasionally dissected by west-directed thrust faults (Fig. 4).

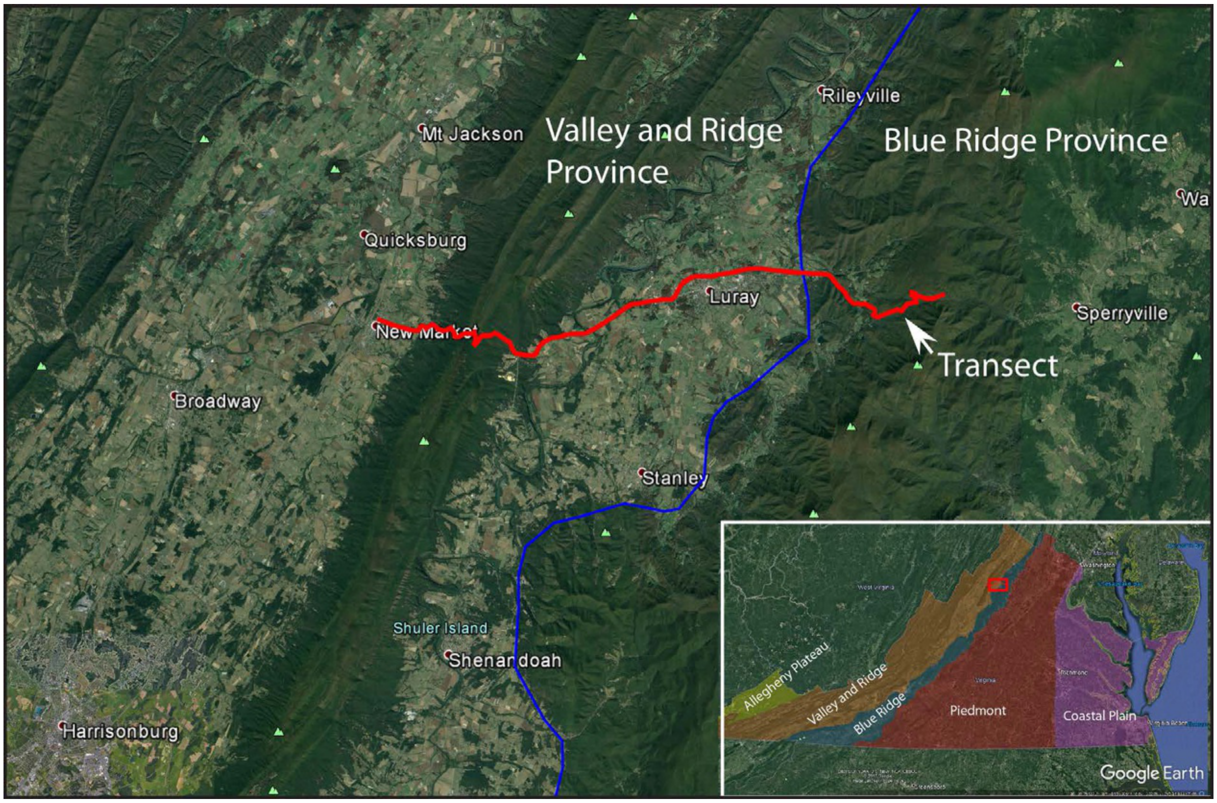


FIG. 2 Location of the field transect (red line) discussed in the text. The inset map shows the general field location (red box) in the context of the five geologic provinces of Virginia.

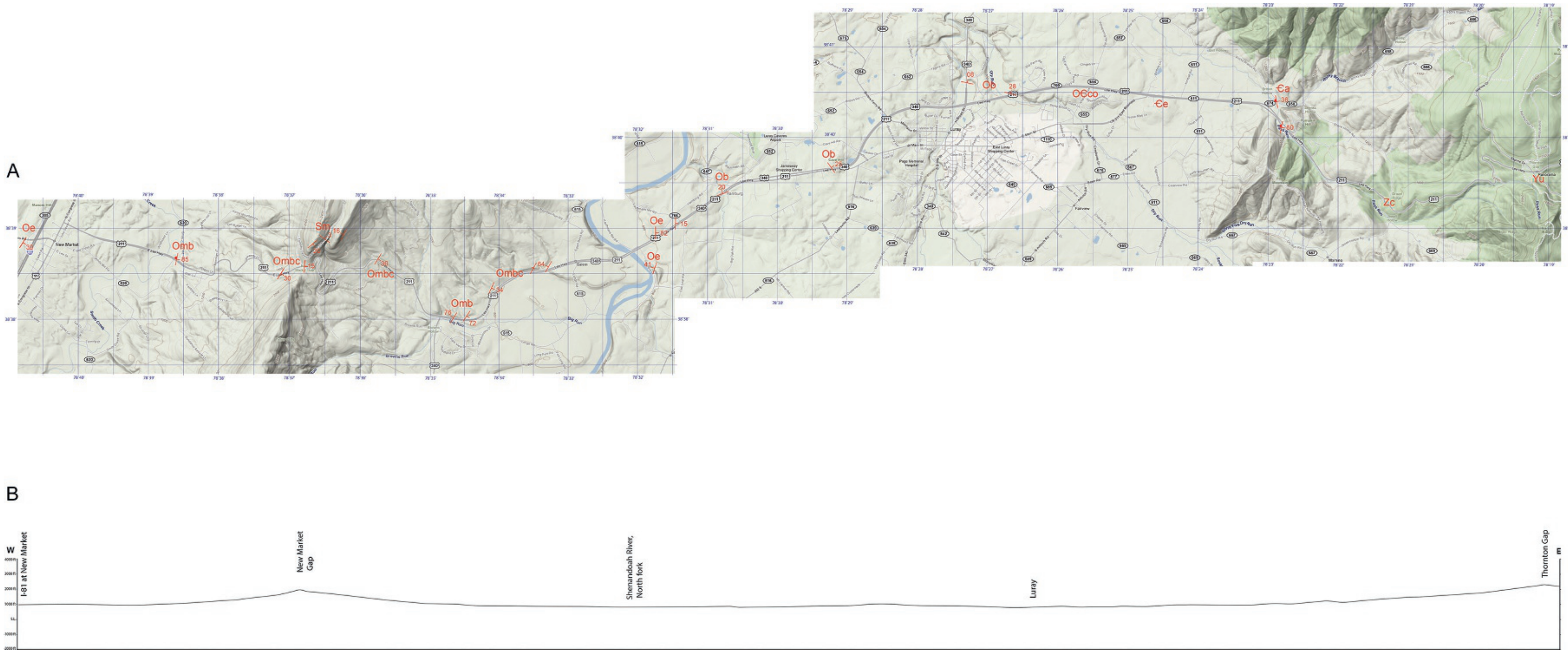


FIG. 3 (A) Topographic map of the proximal areas along Rts. 211 and 259, from Luray in the east to New Market in the west (assembled from Google Maps), with field data collected by students (orientation symbols and lithologic units) in red. (B) A blank cross-section box similar to what is used by students to build their structural interpretation.

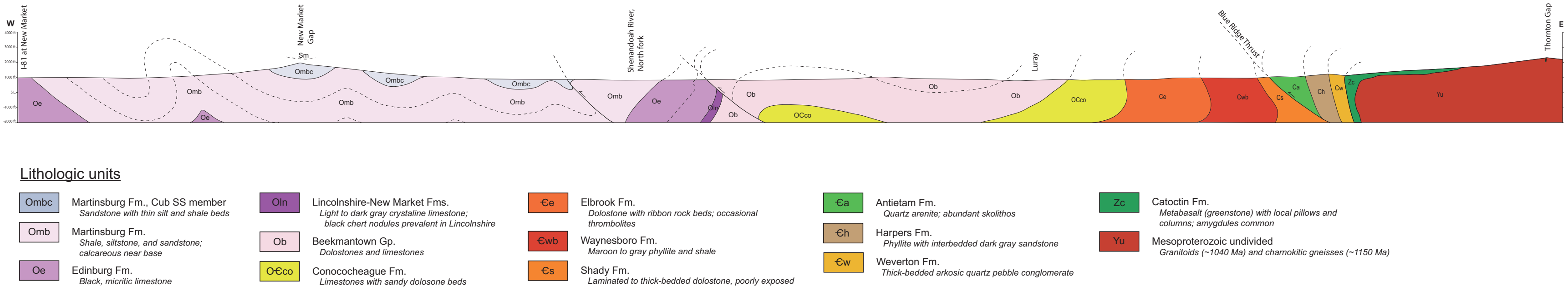


FIG. 4 An example cross-sectional interpretation of the geology along the Rt. 211-Rt. 259 transect shown in Fig. 3A. *Modified from Whitmeyer, S.J., Fichter, L.S., Diecchio, R.J., Heller, M.J., Eaton, L.S., Cross, A., Coiner, L., Biggs, T., Patterson, C.R., 2012. Geology of Page Valley: stratigraphy, structure, and landscape evolution. 42nd Annual Virginia Geological Field Conference Guidebook, 63 p.*

2.1 Field Data Collection

Students work in groups of two or three on the project and collect field data during full-day Saturday field trips. Each field trip consists of 10–15 stops, typically at roadcuts along roads oriented east–west, basically perpendicular to regional strike (Fig. 2). Students record their field data on custom field data sheets (Appendix A), recording general information (observer, date, location) as well as detailed data on stratigraphic and lithologic features, orientations and structural features, and information about tectonic models/interpretations that are relevant to the specific outcrop. The goals of the data collection component of the exercise are for students to develop skills in lithologic characterization, measuring the orientations of planar and linear features with a Brunton compass, and fitting stratigraphic and structural outcrop information into a tectonic framework through time (e.g., Appendix B).

2.2 Constructing the Cross-Sections

At each outcrop visited, students collect latitude and longitude from a handheld GPS unit, identify the rock unit, and measure orientations of planar features – typically bedding (and occasionally foliations), where available. Students then plot their field data as strike and dip symbols on topographic maps (red symbols on Fig. 3A) that cover the transect in question.

Question 1

You are provided with a cross-section box that parallels the transect where you collected field data. Your goal is to transfer the orientation and lithologic data from the topographic map (red symbols, top of Fig. 3A) to the cross-section box below (Fig. 3B). Dip directions and angles from measurements taken at each outcrop should be transferred straight down to the corresponding spot on the cross-section topographic surface.

Remember that lithologic contacts were rarely observed in the field, and thus the contacts between your units will need to be inferred as you construct your cross-section interpretations.

Guiding principles for building your cross-section include:

(a) Maintain consistent thicknesses for sedimentary units, except where they are truncated or offset by faults,
(b) Include all units in the stratigraphic sequence (e.g., Appendix B) in your cross-section, even if you did not see them in the field,
(c) Match interpreted fold patterns and geometry to dip data collected in the field,
(d) Use the principle of parsimony (Occam's Razor; Sober, 2015) to keep your interpretations as simple as possible, while working within the constraints provided by your field data.

Question 2

Once you have your cross-section constructed, consider whether it reflects the outcrop evidence you saw in the field. The questions below will help guide your interpretations.

(a) What major structure brought the Proterozoic Blue Ridge basement rocks and Cambrian cover sequence up and to the west over the Ordovician sedimentary rocks? Where else in your cross-section are similar structures in evidence?
(b) What is the overall geometry (e.g., the vergence) of the fold sequence in your cross-section? What does this suggest about the direction of the principal collisional force (sigma 1)?
(c) Do you have field evidence that these structural features continue to be replicated father to the west (beyond this cross-section)?

2.3 Interpretation

Fig. 4 shows an example cross-section interpretation of field data collected along the transect highlighted in Fig. 3A, making use of the blank cross-section box in Fig. 3B. Key elements of the interpreted geology include the western limb of the Blue Ridge anticlinorium at the right side of the cross-section, which constitutes the hangingwall of the cryptic Blue Ridge thrust. Unfortunately, the Blue Ridge thrust is nowhere seen in outcrop, but is necessarily inferred by the significantly higher elevation of the older Precambrian rocks of the Blue Ridge massif and the overturned, east-dipping Cambrian Chilhowee Group rocks (Antietam, Harpers, Weverton Fms.) that represent a drag fold in the proximal hanging wall. Cambrian-Silurian carbonate and clastic rocks in the footwall west of the Blue Ridge thrust exhibit asymmetric, west-vergent folds that are periodically cross-cut by smaller, west-directed, low angle thrusts. A second major thrust occurs at the western end of the transect (not included on the cross-section in Fig. 4), where the Little North Mountain thrust transported Cambrian-Ordovician carbonate rocks several kilometers to the west over

Silurian-Devonian clastic rocks (Rader and Perry, 1976; Orndorff, 2012). Fig. 4 is certainly a simplified depiction of the regional geology, but it summarizes the major elements of this part of the Mid-Atlantic foreland fold-thrust belt. Note that students submit drafts of their cross-sections to instructors in iterative stages, so that abundant feedback can be provided by the instructors at each stage of development.

EXAMPLE EXERCISE 2

Detailed outcrop sketches of important geologic features are encouraged at all field locations and required at a few key outcrops. Students complete a drawing/sketching exercise at the beginning of the semester, which encourages them to examine features critically and translate those features to an accurate sketch. Encouraging sketching in the field lengthens the time spent at outcrops, but it is an important skill for effective field data collection (Compton, 1985; Coe, 2010). An example of a key outcrop is shown in Fig. 5A, where a small, west-directed thrust fault dissects a package of quartz arenite beds of variable

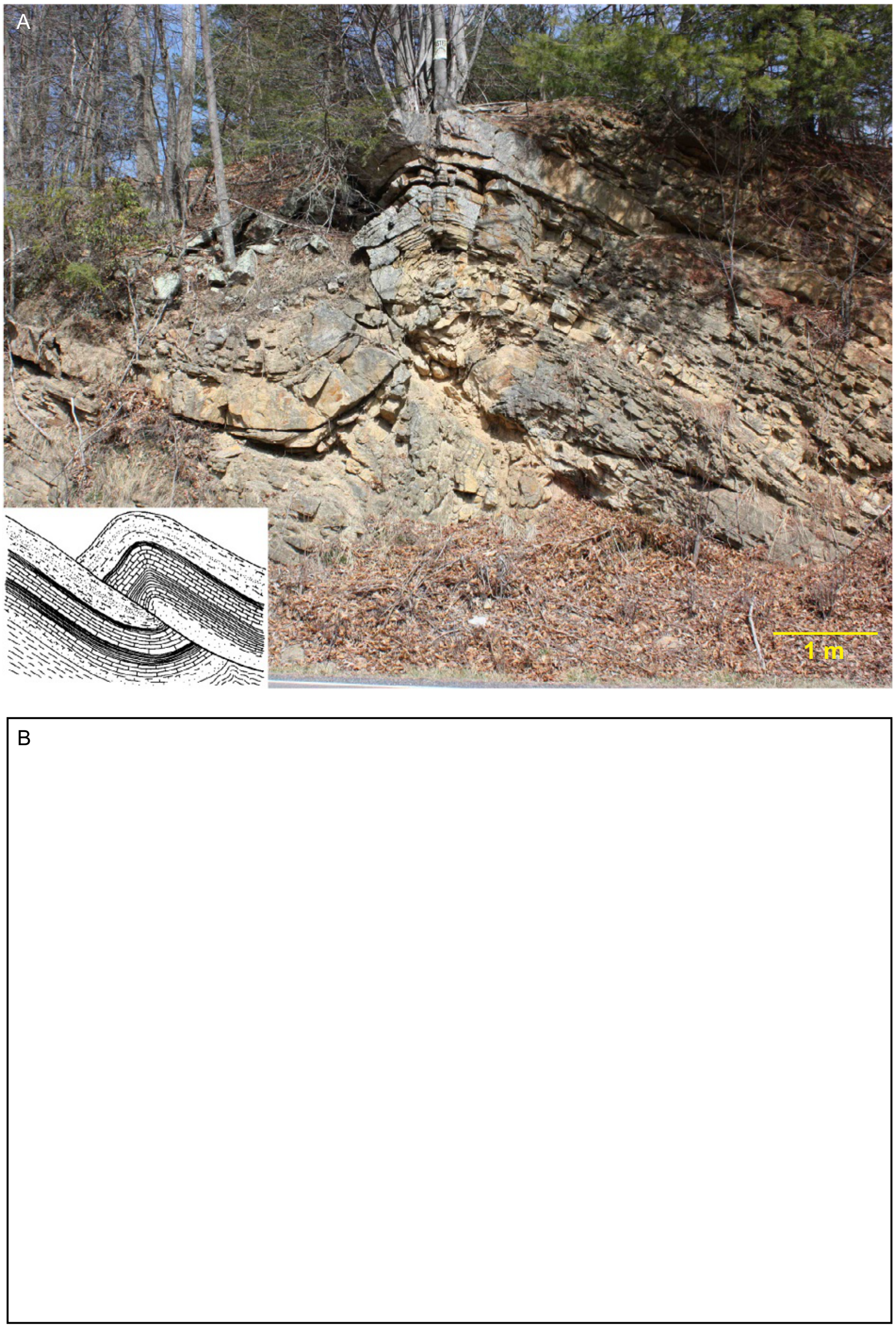


FIG. 5 (A) Photo of an outcrop highlighting a break-thrust fold, with lower left inset showing the classic sketch of a similar feature by Bailey Willis (1893). (B) Empty box for students to sketch the geologic features of the outcrop shown in (A).

thickness. This is an ideal outcrop for students to sketch as it contains bedding layers that can easily be traced on each side of the fault, enabling students to examine the kinematics (direction and amount of movement) of the thrust by determining the offset of matching beds. In addition, this outcrop shows a footwall syncline and a hanging wall anticline on opposing sides of the fault, and is therefore a classic example of a break-thrust fold (see inset in Fig. 5A; Willis, 1893).

Question 1

Fig. 5A is a photo of a roadcut that shows quartz arenite layers that have been folded and cross-cut. Sketch the outcrop in the empty box (Fig. 5B), and make sure to include the following features and annotations:

(a) Highlight the key beds that are offset, and indicate where they occur on both the left and right sides of the outcrop
(b) Sketch the feature that is offsetting the beds and approximate its location
(c) Don't forget to include a scale bar and the facing direction of the outcrop

Question 2

Once you have your sketch drawn, interpret the outcrop in the context of the regional geology and relevant cross-section. The questions below will help guide your interpretations.

(a) What is the feature that cross-cuts the quartz arenite beds? How much movement occurred along this feature and in what direction?
(b) What is the scale of this outcrop, and how does it compare to the scale of other structural features in this region?
(c) How might this outcrop provide an indication of the regional structures that predominate in the Valley and Ridge Province of the Mid-Atlantic?

2.4 Interpretation

An example of a well-drawn student field sketch is shown in Fig. 6. The sketch does a nice job of capturing the geometry of the folds and fault, including a marker bed that shows the offset along the thrust surface. From this, students can determine the direction of movement (hanging wall up and to the west) and the amount of movement along the thrust surface (about 1.5 m). In Fig. 6 the student includes a scale (important!) but fails to indicate the facing direction of the outcrop (e.g., are we looking north or south?) Also, as shown with the red ellipse and comment, the student fails to extrapolate the trace of the fault though the lower part of the sketch (covered by leaves in the photo). Students are encouraged to use some of their field sketches as "blow-up" diagrams to accompany their deliverable cross-sections, in order to highlight important features that are at a more detailed scale than the regional cross-sections (Fig. 7).

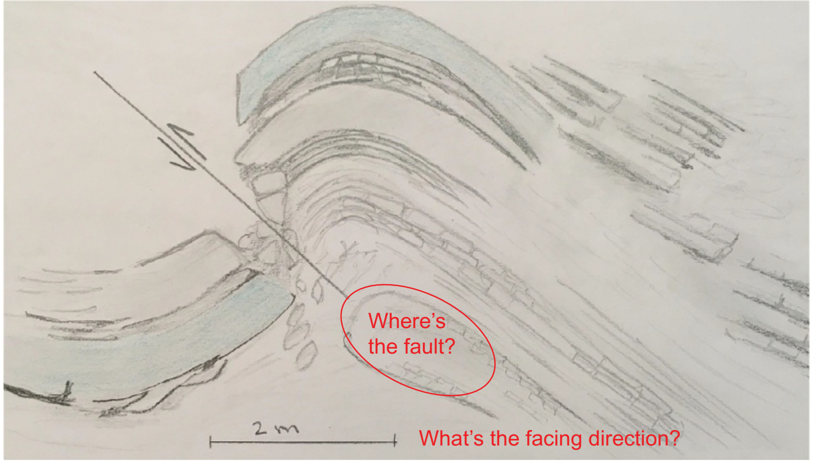


FIG. 6 Example of a student's detailed outcrop sketch of the feature in Fig. 5A; instructor's comments in red.

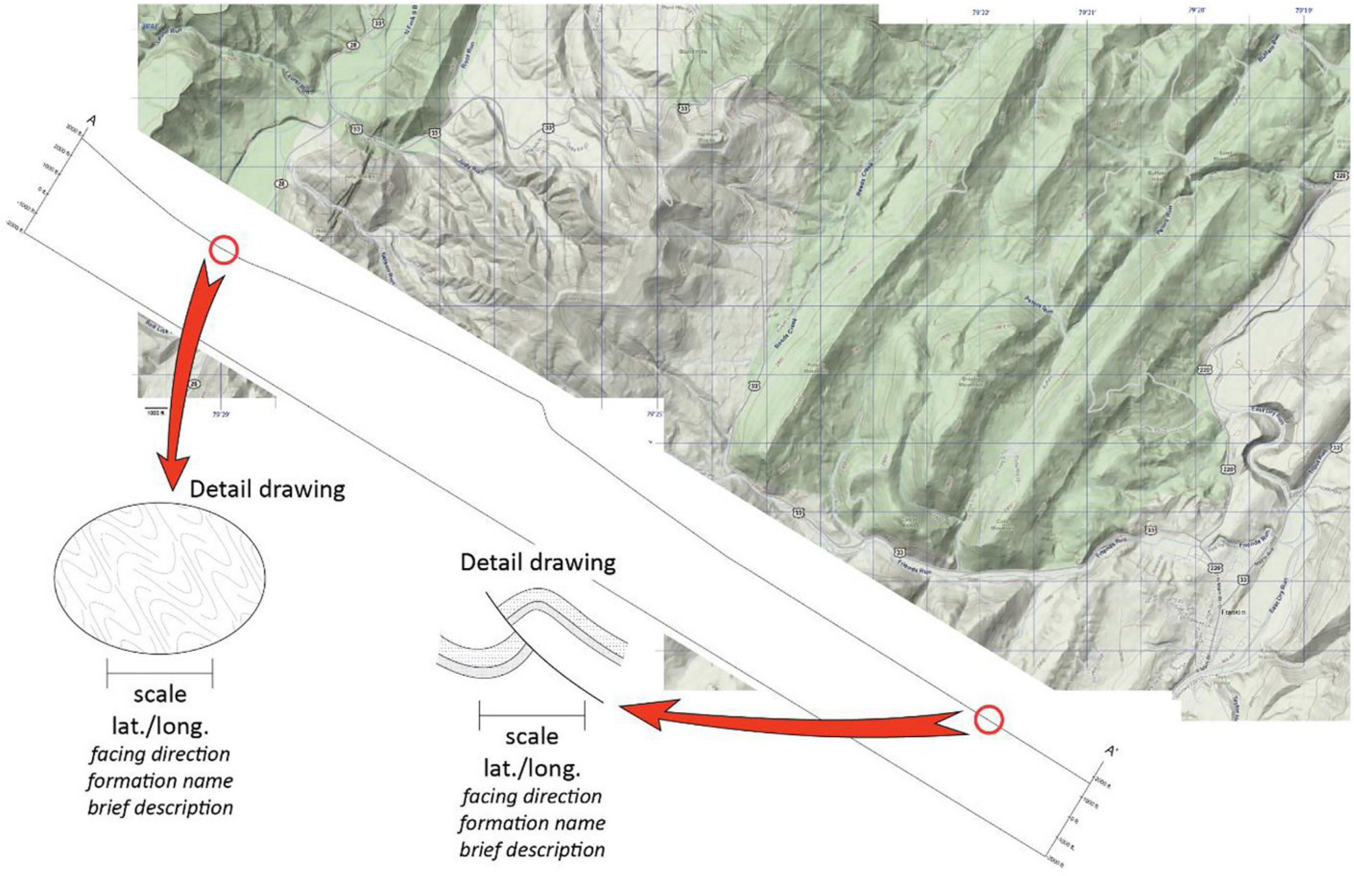
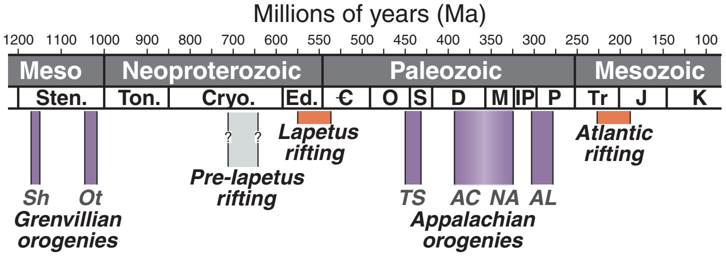


FIG. 7 Excerpt from the instruction packet given to students, which highlights how to include detailed outcrop sketches (e.g., Fig. 3B) as components of the overall structural cross-sections.

FIG. 8 Temporal summary of tectonic events in the Blue Ridge and Valley and Ridge provinces in the Mid-Atlantic region. Orogenic events indicated: Sh—Shawingian & Ot—Ottawan (Grenville); TS—Taconic-Salinic; AC—Acadian; NA—Neo-Acadian; AL—Alleghanian. *After Whitmeyer, S.J., Bailey, C.M., Spears, D.B., 2015. A billion years of deformation in the central Appalachians: Orogenic processes and products. In: Brezinski, D.K., Halka, J.P., Ortt, R.A. Jr. (eEds.) Tripping from the Fall Line: Field Excursions for the GSA Annual Meeting, Baltimore, 2015: Geological Society of America Field Guide 40, p. 11–34, https://doi.org/10.1130/2015.0040(02).*



This concept is especially important for this outcrop, as the west-vergent fold package cut by a west-directed fault is a nice example of Pumpelly's rule (Pumpelly et al., 1894) that small outcrop-scale structures often mimic larger regional-scale structures, as long as the features were formed during the same orogenic event.

2.4.1 *Assembling the Tectonic Synthesis*

Once students have completed the cross-sections they compose a tectonic synthesis that explains intrusive, volcanic, metamorphic, depositional, and structural features in the context of Mid-Atlantic geologic events (Fig. 8), from the assembly of Rodinia (ca. 1180–1080 Ma; Bailey et al., 2006a) through Mesozoic extension related to the breakup of

Pangaea (Hatcher, 1989). The synthesis is written chronologically, explaining each tectonic event or geologic environment, with reference to the student team's field data where appropriate.

The chronology begins with the assembly of the Rodinia supercontinent during the Grenville orogeny, evidence for which is seen in charnokitic gneisses in the Blue Ridge province (Bailey et al., 2006a). The two-stage breakup of Rodinia (failed rifting following by the successful opening of the Iapetus ocean; Whitmeyer and Karlstrom, 2007) is seen in Neoproterozoic volcanic rocks and arkosic graben-fill deposits. The subsequent rift-to-drift sequence is documented in the Chilhowee group, followed by Cambrian-Ordovician carbonate and clastic rocks that predate the Taconic orogeny (Rader and Henika, 1978; Read, 1980). Deformation fabrics related to the Taconic orogeny are not obvious in the Blue Ridge or Valley and Ridge provinces, with the exception of stratigraphic evidence for a peripheral bulge located in the middle of the Valley and Ridge province, in the vicinity of Brocks Gap and Little North Mountain (Diecchio, 1993). Evidence for the Acadian orogeny is likewise restricted to depositional evidence in a thick package of Devonian clastic rocks, derived from presumed Acadian highlands that were originally located to the east (Woodward, 1943; Shumaker and Wilson, 1996). The ubiquitous west-directed folding and faulting seen along all transects was produced during the Alleghanian orogeny (Evans, 1989; Fichter et al., 2010), during which Gondwana collided with the eastern margin of Laurentia in the culminating phase of the assembly of Pangaea (Hatcher Jr, 1989). Mesozoic graben east of the Blue Ridge preserve evidence for the breakup of Pangaea. However, Mesozoic fabrics are sparse west of the Blue Ridge, only occasionally apparent as northwest-striking normal or transverse faults (Bailey et al., 2006b).

Students include a discussion of how their field data and interpretations fit within the theoretical models previously presented. Students need to highlight key field-based observations, such as regional patterns, deformation at various scales, ductile vs. brittle fabrics, the variation in intensity of deformation among formations and locations, and the tectonic events responsible for the patterns recorded in the field. Then all of these observations and interpretations are explained in the context of foreland fold-thrust belt models (e.g., Fig. 1A) and basin analysis models (Fig. 1B). Students compare the theoretical models to their field data, applying the models where they fit, and modifying the models as needed to match their observations. Writing this synthesis is typically an iterative process for the students, in consultation with the instructors.

3 DISCUSSION

The goals for this project are threefold:

1. Introduce students to methods for collecting stratigraphic and structural data in the field, and give them enough time in the field to develop competency with these skills.
2. Provide students with abundant evidence, derived from their own experience, that a single outcrop can contain geologic data relevant to multiple subdisciplines (stratigraphy, structural geology, petrology).
3. Develop habits of mind in students to evaluate multiple datasets, from which they can deduce and explain the overall geologic and tectonic history of a region, such as the Mid-Atlantic Appalachians.

Our approach to addressing goal #1 recognizes that separate skill sets are necessary for collecting structural and stratigraphic data. For structural field data, students begin by learning how to use a geologic compass to take orientation measurements of planar (bedding, foliation) and linear (slickenlines, mineral lineations) features. Students also learn to recognize and evaluate deformation features, including ductile fabrics (mineral lineations, asymmetric or rotated porphyroclasts) and brittle fabrics (bedding-cleavage relationships, slickenlines, parasitic S, Z, and M folds). For stratigraphic data, students learn to recognize sedimentary features (scours, cross-beds, load structures, etc.) and packages of laminations/beds to deduce depositional environments. Collectively, these are all skills that students need to master to collect outcrop data.

Goal #2 is where SST deviates from traditional curricular approaches that treat stratigraphy and structural geology as separate undergraduate courses. Several years ago we realized that the same local outcrops were being used in both stratigraphy and structural geology field trips, but students were directed to examine different features in each course. For structural analyses, the stratigraphic data was ignored in favor of the deformation fabrics, and for stratigraphic analyses, the deformation overprint was "noise" to be overlooked. We recognized that that the ability to recognize and evaluate multiple types of data in a single outcrop was an important skill set for today's budding geologists, and one that we needed to explicitly develop. Students definitely find it challenging to learn to evaluate both stratigraphic and structural features at an outcrop, and often they will overlook some important features in favor of others. However, we found that providing students with outcrop data sheets that explicitly include fields for recording both stratigraphic and structural data (Appendix A) helped students remember to evaluate all features in an outcrop.

The ultimate challenge for SST students is to develop the capacity to utilize multiple datasets to address the tectonic history of a region (goal #3). In the Mid-Atlantic Appalachian region, structural data provides information about the Grenville and Alleghanian orogenies, while stratigraphic data primarily documents the rifting of Rodinia and the Taconic and Acadian orogenies (and intervening quiescent periods). Thus students cannot explain the past billion years of Mid-Atlantic tectonics (e.g., Whitmeyer et al., 2015) without utilizing both of these datasets. However, all students find it challenging to recognize that stratigraphic and structural features at a single outcrop happened at different times during different geologic events. We have found that it takes constant discussion and probing interaction with students in order for them to decipher where particular pieces of outcrop evidence fit into the overall tectonic model for the region. Recently, we have provided students with a blank timeline sheet, so that they can record outcrop data in the appropriate chronologic position. However, we are not sure yet how effective this is for students; some students were diligent in using the timeline to record events and where the evidence was seen in the field, while other students seemed to consider it yet more busywork. This is an item for future investigation.

4 CONCLUSION

The approaches to stratigraphic and structural analyses in this project highlight a multidisciplinary toolkit for outcrop-based fieldwork and tectonic analyses. Our integrated approach challenges undergraduate geoscience students to synthesize the billion-year tectonic history of the Mid-Atlantic region from field data they have collected. As such, this project functions as a type of authentic field-based research experience. Students recognize that outcrop evidence exists at several temporal scales: stratigraphic data provide information about rift-to-drift sequences and the Taconic and Acadian orogenic events, while structural data is predominantly derived from the Grenville and Alleghanian orogenies. Interpreting and synthesizing observations at a variety of spatial and temporal scales is challenging for students and experts alike, but our experience is that students cannot effectively master tectonic theory and analysis without this sort of integrated approach.

We are fortunate that the Blue Ridge and Valley and Ridge provinces of the Mid-Atlantic region are rich in outcrops/roadcuts that facilitate multidisciplinary approaches to collecting tectonics-oriented field data. For this project, the expectation is that theoretical models that were presented in class will guide students' evaluation of the preserved stratigraphic and structural record in the field. Students typically find it difficult to accept that theoretical models rarely match field observations completely. However, discrepancies between models and outcrop evidence provide an opportunity to refine the models, and provide students with a template for how geoscience research progresses. From a pedagogic perspective, what is important about this project is that students learn important stratigraphic and structural field skills within the context of synthesizing multiple datasets and interpreting the geologic history of a region in terms of integrated, multidisciplinary systems.

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APPENDICES

Appendix A. Field Data Sheets Used by Students to Collect Stratigraphic and Structural Data in the Field (Front Side), with Space for Notes on Tectonics (Back Side)

Geol 467—Stratigraphy, Structure, Tectonics ***SS&T Field Trip #***	*Formation*	*Observer:*	*Date*
	Stop #	*Thickness*	*Age*

Longitude	*Latitude*	*Elevation*	*Strike/dip*	*Dip direction*

Outcrop Location/Description:

☐ *Bedding*
☐ *Foliation*

Outcrop observations—Local interpretations

Empirical, inductive, bottom-up

Stratigraphy

Structure

Scale bar

Cl *Sand* *Gr*

tectonics on back

Formation	*Thickness*	*Trip/ stop #*	*Latitude*	*Longitude*

Tectonics

Theoretical, deductive, top- down, abstract models/Interpretations (specify those you use)

Structural tectonics

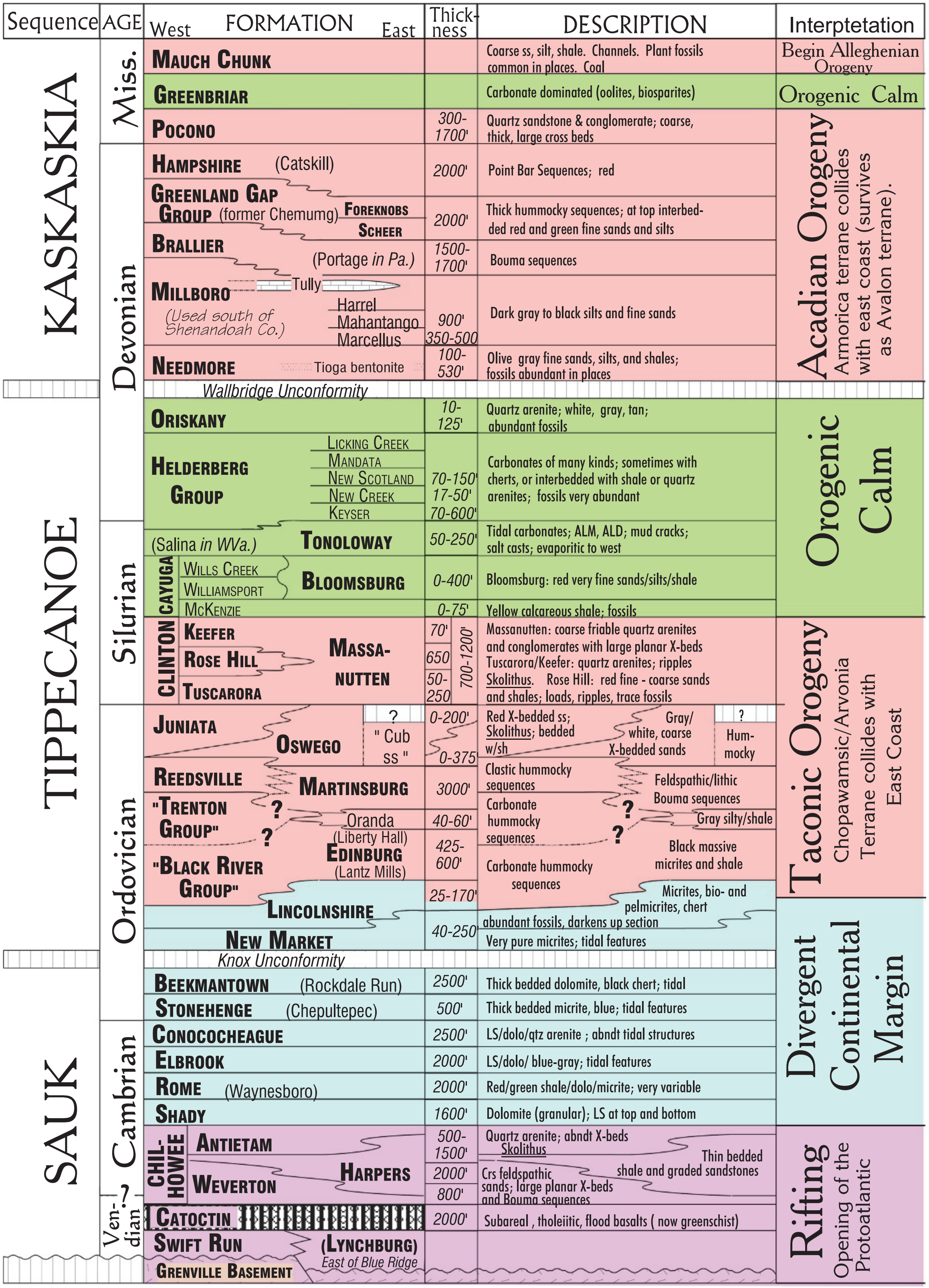
Sedimentary tectonics

Plate tectonics

Fractals

Appendix B. Generalized Stratigraphy of the Blue Ridge and Valley and Ridge Provinces of the Mid-Atlantic Region, Including Basic Tectonic Interpretations in the Rightmost Column. Students are Expected to Have this Memorized Prior to the First Field Trip

Stratigraphy of the Central and Northern Shenandoah Valley, and Eastern West Virginia



Sequence	AGE	West FORMATION East	Thickness	DESCRIPTION	Interptetation
KASKASKIA	Miss.	**Mauch Chunk**		Coarse ss, silt, shale. Channels. Plant fossils common in places. Coal	Begin Alleghenian Orogeny
		Greenbriar		Carbonate dominated (oolites, biosparites)	Orogenic Calm
		Pocono	300-1700'	Quartz sandstone & conglomerate; coarse, thick, large cross beds	Acadian Orogeny Armorica terrane collides with east coast (survives as Avalon terrane).
	Devonian	**Hampshire** (Catskill)	2000'	Point Bar Sequences; red	
		Greenland Gap Group (former Chemumg) **Foreknobs** **Scheer**	2000'	Thick hummocky sequences; at top interbedded red and green fine sands and silts	
		Brallier (Portage *in Pa.*)	1500-1700'	Bouma sequences	
		Millboro *(Used south of Shenandoah Co.)* Tully Harrel Mahantango Marcellus	900' 350-500	Dark gray to black silts and fine sands	
		Needmore Tioga bentonite	100-530'	Olive gray fine sands, silts, and shales; fossils abundant in places	
		Wallbridge Unconformity			
TIPPECANOE		**Oriskany**	10-125'	Quartz arenite; white, gray, tan; abundant fossils	Orogenic Calm
		Helderberg Group Licking Creek Mandata New Scotland New Creek Keyser	70-150' 17-50' 70-600'	Carbonates of many kinds; sometimes with cherts, or interbedded with shale or quartz arenites; fossils very abundant	
	Silurian	(Salina *in WVa.*) **Tonoloway**	50-250'	Tidal carbonates; ALM, ALD; mud cracks; salt casts; evaporitic to west	
		Cayuga Wills Creek Williamsport **Bloomsburg**	0-400'	Bloomsburg: red very fine sands/silts/shale	
		McKenzie	0-75'	Yellow calcareous shale; fossils	
		Clinton **Keefer** **Rose Hill** **Tuscarora** **Massanutten**	70' 650 50-250 700-1200'	Massanutten: coarse friable quartz arenites and conglomerates with large planar X-beds Tuscarora/Keefer: quartz arenites; ripples Skolithus. Rose Hill: red fine - coarse sands and shales; loads, ripples, trace fossils	Taconic Orogeny Chopawamsic/Arvonia Terrane collides with East Coast
	Ordovician	**Juniata** **Oswego** ? " Cub ss "	0-200' 0-375'	Red X-bedded ss; Skolithus; bedded w/sh Gray/white, coarse X-bedded sands ? Hummocky	
		Reedsville **Martinsburg**	3000'	Clastic hummocky sequences Feldspathic/lithic Bouma sequences	
		"Trenton Group" ? Oranda	40-60'	Carbonate hummocky sequences ? Gray silty/shale	
		"Black River Group" (Liberty Hall) **Edinburg** (Lantz Mills)	425-600'	Carbonate hummocky sequences Black massive micrites and shale	
		Lincolnshire	25-170'	Micrites, bio- and pelmicrites, chert abundant fossils, darkens up section	Divergent Continental Margin
		New Market	40-250'	Very pure micrites; tidal features	
		Knox Unconformity			
SAUK		**Beekmantown** (Rockdale Run)	2500'	Thick bedded dolomite, black chert; tidal	
		Stonehenge (Chepultepec)	500'	Thick bedded micrite, blue; tidal features	
	Cambrian	**Conococheague**	2500'	LS/dolo/qtz arenite ; abndt tidal structures	
		Elbrook	2000'	LS/dolo/ blue-gray; tidal features	
		Rome (Waynesboro)	2000'	Red/green shale/dolo/micrite; very variable	
		Shady	1600'	Dolomite (granular); LS at top and bottom	
		Chilhowee **Antietam** **Harpers** **Weverton**	500-1500' 2000' 800'	Quartz arenite; abndt X-beds Skolithus Thin bedded shale and graded sandstones Crs feldspathic sands; large planar X-beds and Bouma sequences	Rifting Opening of the Protoatlantic
	? Ven-dian	**Catoctin**	2000'	Subareal , tholeiitic, flood basalts (now greenschist)	
		Swift Run **(Lynchburg)** *East of Blue Ridge*			
		Grenville Basement			

L.S.Fichter, 1991 (reformatted 1996)

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