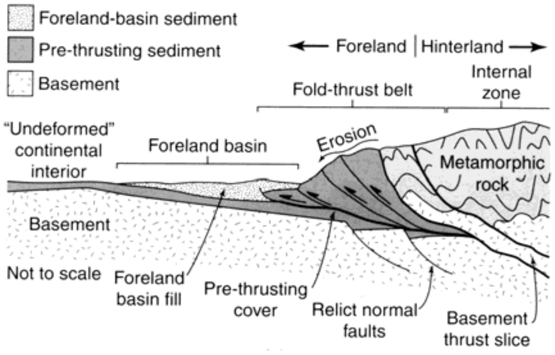
Tectonics, Stratigraphy and the Ordovician Taconic Orogeny in Northwestern Virginia

A Royal Rockhounds Field Trip

Lynn S. Fichter
Department of Geology and Environmental Science
James Madison University
August 5, 2017

Introduction:

There are only a few basic mechanisms by which mountain uplifts (orogenies) occur, and they are always accompanied by an adjacent downwarping that creates a depositional basin. One of the more common orogenic types occurs when two earth blocks collide, such as a continent-continent collision, or a volcanic arc-continent collision. In a collisional orogeny one block - the hinterland - overrides and builds a fold-thrust belt whose weight depresses an adjacent foreland depositional basin. Sediment eroding from the mountain fills the foreland basin (figure to right).



During the Ordovician Taconic orogeny a terrane called Carolina, composed of numerous amalgamated volcanic arcs, collided with a jagged zig-zag-shaped Ordovician east coast building a mountain in what is now the piedmont, and a complex of corresponding foreland basins in Pennsylvania, Virginia, and West Virginia (map on page 9). Eventually, of course, mountains erode and disappear, meaning the only record we often have of ancient mountain building events is the sediment eroded from them and deposited in the foreland basin. This field trip analyzes how we reconstruct the Taconic mountain building event from the sedimentary record it left in the Page and Shenandoah Valleys of Virginia. Figure 1 at back is a stratigraphic column of all the formations in northwest Virginia and eastern West Virginia and shows the specific formations we will analyze.

The Different Expressions of Tectonic Energy:

Tectonics is the study of earth movements, and the structures that result from those movements. Tectonic energy drives everything in the geosphere from plate tectonic processes, through specific depositional environments, down to the smallest mineral. Ultimately everything must be explained in terms of the energy that created it.

Geologic analysis is based on two principles. First: ***no rock is accidental*** - all rocks form in specific places for specific tectonic reasons. Knowing how each rock forms allows us to reconstruct the conditions that existed at the time of its formation.

Second principle: ***follow the energy***. Every mineral, every rock, every structure, every depositional basin, etc. is the result of specific and unique energy dissipation. But the effects of energy dissipation are not equally obvious. For example, structural features that appear on the outcrop - e.g. joints, folds, faults - are readily observed and subject to immediate rheological analysis from data measurable on the outcrop. For example, all the rocks seen on this field trip have been tilted, folded, and faulted during the Alleghenian orogeny, as we will see on the field trip.

Correspondingly, the stratigraphic record also responds to tectonics, but the evidence is much less direct, does not feed back directly to the responsible stresses, and usually requires interpretations within interpretations. For example, ancient water depth—driven in part by tectonics—can be interpreted from the color, texture, flow regime, etc. preserved in the rock, but each of these lies within a theoretical framework of its own (geochemistry for color; and hydraulics for texture and flow regime).

Complicating the issue, water depth—a.k.a. accommodation space: the space available for sediment to fill—is controlled by more than one variable—including subsidence, eustasy (world wide sea level changes), sediment influx rates, compaction, loading (subsidence due to an overlying weight), and climate—each of which may be operating largely independent of the others, and in different time scales. Yet, the results can easily look the same regardless of the mechanism—*sediment responds to depth, not how the depth is created.*

Also, larger tectonic processes—such as foreland basin development—that control the evolution of the stratigraphic record cannot be seen in outcrop. The study of sedimentary tectonics[1] deduces foreland basins 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, as trying to teach this stuff to undergraduates demonstrates, while observing any particular outcrop it is very difficult to imagine what is happening in the larger vertical, horizontal, and temporal contexts. We cannot ‘see’ foreland basins but have to imagine them outcrop by outcrop.

The result is, sedimentary-tectonic interpretations from stratigraphic outcrops are almost always inferences based on deductive arguments from a diversity of indirect data that must be synthesized from evidence gathered from accumulated specific outcrops. This field trip explores how these interpretations are made.

The SAATS or Tectonic-Accommodation Theoretical Model:

Sedimentary tectonic interpretations require a theoretical predictive model of how (plate) tectonic energies and sedimentary energies are related so we can use stratigraphic observations to deduce the tectonic conditions that produced them. Figure 2-top at back is a theoretical SAATS model (**S**ubsidence–**A**ccommodation–**A**ccumulation **T**ime–**S**eries) model. It is based on the plate tectonic concept that during a collision orogeny the over thrusting hinterland places a load on the foreland resulting in relatively rapid foreland basin subsidence and accommodation increase, followed by basin filling that reduces accommodation space.

A heads-up: do not confuse the SAATS models in Figure 2 with a cross section. A cross section shows the size and shape of a basin *horizontally* from one location to another. The SAATS model shows the *vertical* history of a foreland basin through time *at a single geographic location*, as preserved in the stacked sequence of formations. The model typically is located at the theoretical point of deepest basin subsidence. The time series in Figure 2-top begins with:

- Tectonically quiet conditions—upper left of model: slow subsidence, small accommodation space . .
- . . . interrupted by the sudden onset of tectonic activity and exponential subsidence into a deep water basin; depth increases more rapidly than sedimentation can keep up.
- Through time—toward the right on the SAATS diagram—the subsidence rate decays exponentially (curve flattens).
- But, at the same time, sediment flowing into the basin from the eroding mountain increases exponentially (accommodation/volume curve curves upward) results in the water shallowing (accommodation decreases). That is, subsidence rates slow while sedimentation rates increase.

---

[1] Sedimentary tectonics uses the properties of a rock—grain size, composition, color, sedimentary structures, etc.—to deduce the conditions under which the rock formed. For example, quartz sandstones and carbonates point to tectonic stability and shallow water deposition, while immature sediments (arkoses and lithic rich rocks) point to tectonic instability—mountain uplift and deep-water basin formation.

- At the end—top right of diagram—we have a completely full basin, and have returned to tectonically stable conditions.

An historical aside, during the 19th and 20th century development of the geosynclinal theory of mountain building—which took place with these very rocks—both Hall and Dana argued that subsidence and sedimentation took place at the same time and rate, and the miogeosyncline to exogeosyncline (platform to foreland basin) transformation filled completely with shallow water deposits. They would have categorically rejected this Tectonic/Accommodation model.

A SAATS Model for the Ordovician Taconic Sequence of Page and Shenandoah Valleys

Figure 2-bottom shows a SAATS model for the evolution of the Middle and Upper Ordovician strata of Page Valley developed by Diecchio and Fichter (2015). It is based on known stratigraphic thicknesses and ages, interpreted changes in relative sea-level and depths of sedimentation, and calculated isostatic response. It illustrates the total subsidence necessary over time to deposit the strata between the top of the Beekmantown Formation and the base of the Massanutten Formation, both of which are interpreted to have been deposited at or near sea-level.

The model depicts an evolving basin that fills with a predictable vertical stacking of carbonate and clastic sediment. The ideal stacked facies sequence might look like this (Figure 2-bottom):

1. Pre-tectonic, stable, shallow water (carbonate) deposits—Tumbling Run: Beekmantown, New Market, Lincolnshire (part)—driven primarily by sediment load-induced isostatic subsidence (slow subsidence rate, small accommodation space, slow sediment accumulation).
2. Followed by rapid subsidence into deep, quiet water, fine-grained, anoxic (carbonate to clastic) deposits—Lincolnshire to Edinburg Formations.
3. Slowing subsidence countered by mass transport of clastic deposits (e.g. debris flows, turbidity flows, etc.) down an underwater slope, resulting in a coarsening, shallowing upward sequence as the accommodation space fills—Martinsburg Formation.
4. Final basin filling, with distal to proximal shelf environments, grading into shoreface and coastal environments. Generally a coarsening, shallowing upward sequence—represented in part by the “Cub” Sandstone.

Nota Bene

About the actual trip.

The field trip stops described below explore the rocks representing each stage of the SAATS model, and the theoretical tools we use to make these interpretations for the Taconic orogeny. Some times the descriptions get technical, and I am not expecting that all of it will make sense just by reading it, although I want this field guide to stand alone if someone wants to follow it. But we can look at the Taconic orogeny as a story that the rocks are telling us. On the field trip I will develop this story while we are looking at the rocks that contain the evidence. When we approach it like this it does all make sense. But, absorb this at what ever depth feels comfortable for you. One of my goals is to illustrate how geologists think, how we solve problems, but not to turn you into a geologist.

And I encourage questions. Some of this stuff is not easy, but I will answer any and all questions until everyone is satisfied.

And, of course, debate and talk about this among yourselves. This is an interactive field trip!

Field Trip Itinerary

Figure 0 (first page after field trip description) is a map showing the location of the stops

Stop One: Tumbling Run Section.

BEEKMANTOWN, NEW MARKET, LINCOLNSHIRE, EDINBURG FORMATIONS

Location: Outcrop first appears along Rt 601 (Fishers Hill road) about a hundred meter west of the junction of Rt 601 and Rt 11. The Rt 11-Rt 601 junction is about a mile south of Strasburg Virginia.

Exposure: a several hundred meter long, low outcrop along the northeast side of the highway (Figure 3 at back). Road is commonly traveled and there is little shoulder so use caution. We begin on the east side of the bridge.

Formation Descriptions:

Tumbling Run is one of the more important stratigraphic sections in the region since it contains an almost complete transition from the tectonically stable Iapetan Ocean passive margin through the beginning of the Taconic Orogeny.

We examine 4 formations here: Beekmantown, New Market, Lincolnshire, and the beginning of the Edinburg (also seen at Stop 3). Each formation has distinctive lithofacies[2]. Most of these rocks were formally described more than a half century ago, and since they were originally defined as map units, their descriptions are often tedious and only marginally informative for interpretations. Plus, the study of modern carbonate environments and interpretations took place in the 1960's-1990's after these units were described, and that is what we are interested in. For each formation below the first is the formal, mapping, description, followed my pithier descriptions that lead to interpretations.

Beekmantown Formation (Clarke and Schuchert, 1899). Dominantly dolostone and chert-bearing dolostone with lesser limestone. Dolostone, light- to very-dark-gray, fine- to coarse grained, mottled light- and dark-gray, with crystalline beds locally contains nodular, dark-brown or black chert and thick, hill forming, lenticular chert beds in lower part. Limestone, very-light- to medium-gray, fine-grained, medium- to thick bedded, locally dolomitic and locally fossiliferous.

Interpretive Description: dolomite is associated with high evaporative, arid, tropical environments. Occasional "leopard" rock facies (vugs filled with white dolomite rhombs in a gray sugary dolomite) is also evaporitic. The pervasive algal laminated rocks (micrites and dolomites) are formed on super and upper intertidal environments. Occasional fossiliferous ribbon rock is subtidal.

New Market Limestone (Cooper and Cooper, 1946). Limestone, medium- to dark-gray, aphanic to fine-grained. The upper portion of the New Market, the major quarry rock of northern Virginia, is massive micrite that weathers to fluted ledges. The lower portion is dolomitic with scattered lenticular, black, pyritic limestone, locally conglomeratic at the base. Upper contact is disconformable and the lower contact is a locally angular unconformity.

Interpretive Description: a very pure, clean, light gray limestone (fresh and weathered colors are almost identical); associated with well oxygenated intertidal lakes. Rare fossils, including the coral *Tetradium*. Common mm scale "birds eyes" (small calcite crystals, sometimes replacing fossils) interpreted as vugs created by dessication. Occasional algal laminates and small stromatolites are tidal features.

Lincolnshire Limestone (Cooper and Prouty, 1943). Limestone, light- to dark-gray, fine- to coarse-grained, with black chert nodules. Light-gray, coarse-grained limestone probably represents carbonate mounds (Murat limestone). Upper contact is gradational

Interpretive Description: At Tumbling Run the Lincolnshire starts off with a several dm thick rough textured, coarse biosparite (note the numerous shiny calcite cleavage faces of broken crinoid skeletons and spar cement)—beach facies. Above is a meter of so of cm thick beds of black micrite, even blacker (anoxic) on a broken surface—lagoon. Followed by several meters of, again, coarse grained, rough biosparite often with beds of black chert nodules and calcareous algae—reef/bioherm facies. Above this are 10's of meters of thick interbedded biosparite and micrite/siltite; color tends to darken up section—deepening shelf facies.

---

[2] A lithofacies is the sum total of all the physical, chemical, and biological properties of a rock, and that distinguish it from other lithofacies.. Essentially the rock's description, but are also the basis of interpretations.

Edinburg Formation (Cooper and Cooper, 1946): ***Liberty Hall lithofacies***: Limestone and shale. Limestone, dark-gray to black, aphanic, thin-bedded with thin, black shale partings, locally contorted limestone beds, intraformational limestone breccias, and olistoliths interstratified with typical planar bedded limestone. ***Lantz Mills lithofacies:*** Limestone, medium- to light-gray, fine- to coarse-grained, nodular with very thin, black shale partings. ***St Luke Limestone Member***: Limestone, light-gray, medium- to coarse-grained, thick-bedded). Shale, black, graptolites common, basal unit in Augusta, eastern Rockingham, and southern Page counties. Thickness ranges from 400 feet at Strasburg . . . with a maximum of nearly 1500 feet near Harrisonburg.

Interpretive Description: massive beds of black micrite often interbedded with thin black shale units—basin facies. Slumps common indicating down slope movement. Note also that the volume of shale increases to the SW, and in SW Virginia turns into immature sandstones and conglomerates. Clastic sourceland was to the SW.

Sedimentary Tectonic Interpretations:

Principle: sediment responds to water depth[3], not how the depth is created.

On a broad scale the top of the Beekmantown Group displays evidence of deposition in a shallow, tidal evaporitic/dolomitic system, the New Market Limestone is convincingly a carbonate tidal system, and the Lincolnshire Limestone is a deepening carbonate shelf (Fichter and Diecchio, 1986).

The upper half of the Lincolnshire is considered the transition from a stable platform to the beginning of a subsiding basin (Rader and Henika, 1978; Read, 1980). Carbonate deposition continues to fine up-section through the Edinburg Formation and get darker and more anoxic before transitioning into the clastic dominated Martinsburg Formation composed of clastic, lithic-feldspathic rich turbidity currents (Bouma sequences) deposited in a submarine fan.

The problem:

The transition from the tectonically stable passive margin to the tectonically driven foreland basin subsidence is represented by deepening water, but what is the evidence? Changes in water depth can result from several distinct mechanisms: eustatic (world-wide) sea level changes, tectonics (sinking or rising of the basin floor), changes in the volume of sediment filling the accommodation space, and others. The two most important for us are sea level fluctuations and tectonic subsidence.

The problem is, all these water depth controls can go on at the same time. The sedimentary tectonic question is, where exactly in the section does tectonic subsidence supersede eustatic controls on water depth, and what is the evidence for it. The sediments tell us the water is getting deeper, but exactly where do these transitions from eustacy to tectonics take place?

Sea Level Changes:

Sea level changes go on continuously, at five different scales. First order changes take on the order of a couple of hundred million years, and sea level changes ± 250 meters. These cannot be seen in outcrop. Fifth order changes take about 10,000 years with sea level changes of about 20 meters. Fourth and fifth order changes are easy to detect in outcrop as coarsening or fining upward sequences that run from a meter to several meters thick. The study of how sea level changes affect the stratigraphic record is called *sequence stratigraphy* and will be studied in more detail at Stop 4 where the evidence is more obvious.


Load structures in the upper part of the Lincolnshire formation used to interpret the transition from passive margin sedimentation driven by sea level changes, to foreland basin subsidence.

---

[3] We can with confidence deduce the depth any particular sediment was deposited in. Implication is, any rock can tell us how deep the water was when it was deposited. We just don't always know *why* the water was that particular depth at that point in time.

The transition from eustasy to tectonic subsidence at the Tumbling Run Section

The evidence used at Tumbling Run to identify the transition from water depth changes driven by eustasy to tectonic foreland basin subsidence is a sedimentary feature called load structures. The argument will be developed on the outcrop, but below is a summary of it.

Load structures are common in the stratigraphic record, and typically form when an overlying unit rapidly deposits on an underlying hydroplastic unit, leading to instability, sinking (loading), and upward injection of the underlying unit (figure on previous page). It is commonly seen in sandstone-shale couplets with the sand, rapidly transported in by a high-energy event, doing the loading. However, loading can occur when any sediment is rapidly deposited over mobile, unlithified sediment. Loading is not depth or environment dependent.

Haynes et al. (1998) suggested that the shales at Tumbling Run have a high percentage of volcanic ash, which would enhance their mobility. Support that these units are volcanic ash is the very high gamma radiation they emit (McGary, personal communication). A possible mechanism for loading is an underwater mass flow (debris, fluidized, turbidity, etc. flows) of micrite flowing downslope. There is no reason carbonates—including fine grained ones—cannot form turbidites, as the conditions that set up and control energy dissipation down a slope are not dependent on sediment size.

So, the argument is, shelves do not typically have slopes; their gradients are on the order of a degree or so, and turbidity currents do not form under these conditions. Everything previous in the Tumbling Run section points to these low gradients. To transition from a low gradient shelf to one with enough slope to generate turbidity currents requires subsidence, and a subsiding foreland basin would create one. Thus, these load structures in the Edinburg Formation reflects the point of transition from a eustatic shelf to a subsiding basin.

Stop Two:

MIDDLE MARTINSBURG FORMATION

Location: Location: lat 38.38.00 long -78.34.44 to 78.34.34. At juncture of Rts 211 and 340, Page County.

Exposure: Roadcut on the north side of US 211. Overall outcrop is about half a mile long, but we are interested only in the 100 meters on the west end, 40-50 meters tall; well exposed.

Formation Description:

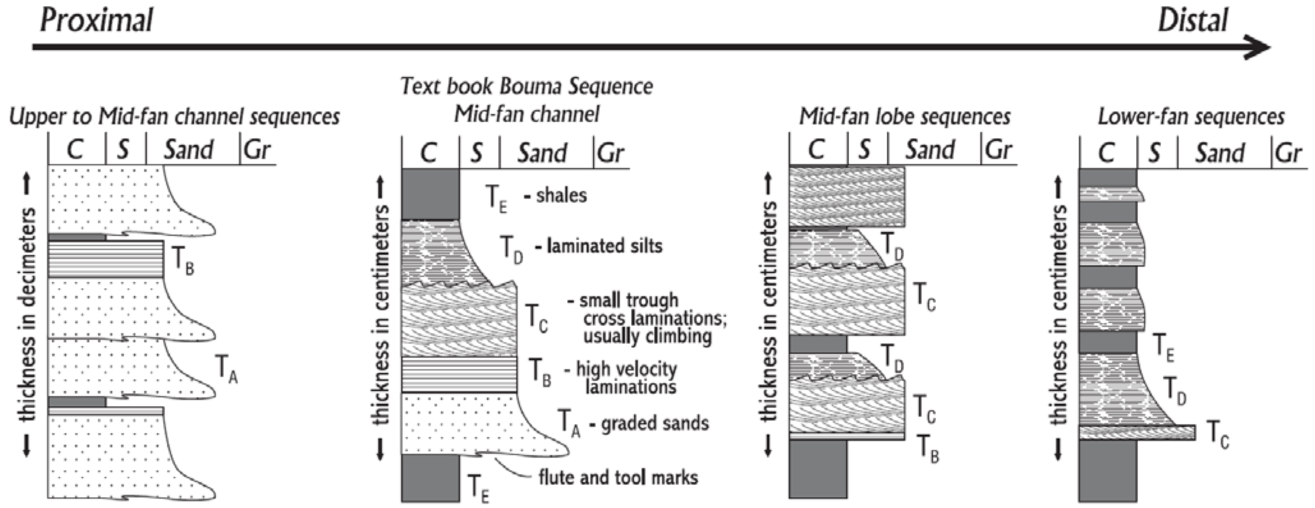
This outcrop is typical of the middle portion of the Martinsburg Formation, with turbidity-current-generated Bouma sequences (figure next page) with well developed T_A (graded beds), T_B (high velocity laminations), capped by T_{DE} (laminated silts/shales) deposited by turbidity currents during filling of the Taconic foreland basin. Sands are very immature lithic-feldspathic-quartz wackes.

Detail of the Middle Martinsburg formation. Overall they appear as interbedded sandstones and shales, but are actually Fining Upward Bouma sequences that result from turbidity currents.

***Principle: every depositional environment dissipates energy in specific ways, that result in unique sedimentary deposits that record the energy and conditions at the time of deposition; these deposits unique to each environment are called* signatures**.

A turbidity current is an underwater avalanche flowing down a slope. The energy starts off high, and steadily decays from proximal to distal, as well as vertically (Figure 4 at back). Note the following on the outcrop:

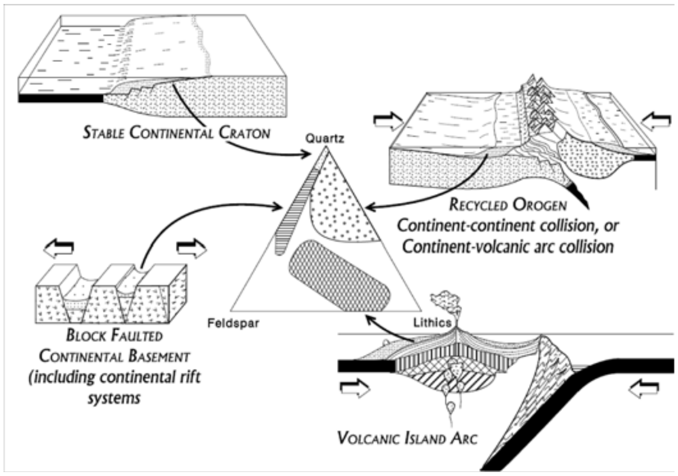
1. Bouma sequences and variations: the ideal Bouma sequence (T_{ABCDE}; T stands for turbidite; ${}_{ABCDE}$ subscripts are the specific units in the sequence) is shown in the figure below (2nd from left), but the ideal is rarely



Bouma sequence variations typical of different parts of a submarine fan. The ideal sequence (second from left) is rarely found in outcrop, but is most typical of mid-fan channels. More proximally, thick, amalgamated T_{A} and T_{AB} sequences dominate. More distally T_{A} and T_{B} units drop out and T_{C} units increase in importance. Distal sequences contain rare, thin T_{C} units, but mostly T_{DE} units. At this location the units are mostly T_{ABDE} which are relatively proximal.

found in outcrop. Instead variations such as T_{AE}, T_{ABDE}, T_{BCDE}, $_{TCDE}$, etc. are common, each formed in different portions of a submarine fan (figure above).

2. Note that the Bouma sandstone-shale couplets maintain thickness for long distances along the outcrop; this is typical of turbidite deposits (and not, for example, of storm shelf hummocky sandstones, Stop 4).



3. The composition of the sandstones at the base of each Bouma sequence. Highly lithic sandstone with lesser feldspar (feldspathic litharenites) indicate a tectonically active (volcanic arc) sourceland (figure below).

Sedimentary Tectonic Interpretations:

In the SAATS model the Martinsburg is the rapid filling of the foreland basin and was responsible for filling a significant proportion of the accommodation space created by tectonic subsidence and sediment loading. The Martinsburg basin was likely narrow and elongate (trapped between the volcanic arc to the east and the Little North Mountain arch to the west). In this case these turbidites may have been flowing long distances along the basin floor from SW to NE, parallel to the trend of the present-day mountain ridges (McBride, 1962).

At Stop 3 we will explore the plate tectonic mechanisms and paleogeography of the Taconic orogeny.

Stop Three:

EDINBURG FORMATION

Outcrop of Edinburg Formation along Rt 340Bus south of Alma Virginia on the south side of the bridge across the Shenandoah River.

Location: Route 340 Business ~9.5 miles north of Shenandoah, Virginia (~ 1.1 miles south of Alma, Virginia) at the junction of 340Bus and Shuler Lane on the south side of the bridge over the South Fork of the Shenandoah River.

Exposure: Road cut on both sides of Rt 340Bus about 50 yards long, 20 meters high, dipping west. Interbedded black micrites and shales dipping to the west about 30^o (figure to right). (Traffic is heavy here, and goes fast; keep alert!).

Formation Description:

Observe the following[4]:

1. Interbedded fine grained limestones (micrites) that weather blocky, interbedded with fissile, smudgy shales.
2. Shales and micrites are deep black on a fresh surface (gray color micrites in photo above is weathering).
3. Parasequences: about 5 meter thick fining upward sequences (FUS) (figure above) that begin with a relatively thick micrite that transitions upward into thinner micrites interbedded with black shales.
4. Base of thick micrites sometimes irregular (loaded or scoured into underlying units).

These features point to deposition in deep, anoxic, generally quiet water—interrupted by the occasional turbidity current. In the SAATS model this is consistent with deposition on top of the subsiding Beekmantown⇨New Market⇨Lincolnshire formations as seen at the Tumbling Run section.

Sedimentary Tectonic Interpretations—A Paradox:

These rocks present a paradox, whose solution leads to regional understanding of the evolution of the basin. Note the following:

1. Modern and ancient limestones form in warm, clear, shallow water (e.g. Bahama Banks), which are usually highly agitated (tides or storms) and well oxygenated. The micrites at this outcrop are deposited in deep, quiet water and could not have formed here. They had to form somewhere else and been transported in.
2. Shales and limestone cannot come from the same source. Thus, the shales represent appearance of a new sourceland.

Only in context of what is stratigraphically below and above can we understand the Edinburg as the initiation of foreland basin subsidence that corresponds with the beginning of the Taconic orogeny. This is where the SAATS model becomes useful (Figures 2) since it establishes from a theoretical viewpoint predictions of what a foreland basin stratigraphic sequence filling should look like, and when we examine what appears up section (the clastic Martinsburg), what these black micrites/shales of the Edinburg represents becomes clear.

The Edinburg is interpreted to have been deposited in a deep-water anoxic environment by mass transport processes (turbidity or debris flows), during maximum subsidence of the Taconic foreland basin. The carbonates were generated on a tectonically stable, shallow carbonate platform which existed to the west. It had the same environmental conditions that resulted in the Beekmantown, New Market, and Lincolnshire formations.

It is not fully obvious from this stop alone that the Edinburg was deposited by mass flows down a slope into a deep-water anoxic basin. In other locations there are good examples of scours, slump, and soft sediment

---

[4] Note that at the river end of the outcrop the rocks are shot through with white calcite veins, slickensides, and are deformed. There is a fault here created during the Alleghenian orogeny. From a stratigraphic viewpoint this is all noise; it just gets in the way of interpretations. For a structural geologist this is information. We want the undeformed rocks further down the highway.

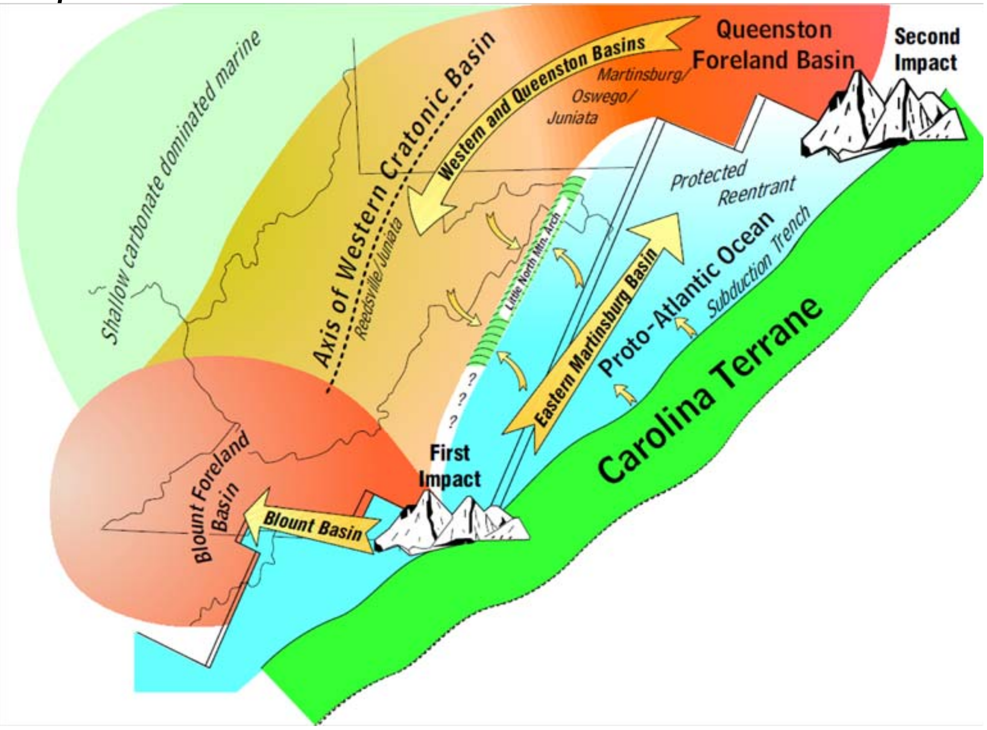
deformation features (e.g. Lowry and Cooper, 1970; Pritchard, 1980; Read, 1980) that point to down-slope mass movement.

In addition, since shales and limestones cannot have the same source we deduce the shales have a different clastic source, most likely to the south.

Paleogeographic Reconstruction of Taconic Foreland Basin:

Until now we have been examining evidence for the subsidence of the foreland basin using the SAATS model. But the paradoxes above (evidence of rapid deepening, and a new clastic sourceland) lead to paleogeographic questions.

The Taconic orogeny affected the east coast from New England down to the Carolinas so it is complicated (map to right). But, the map is a composite of many events that developed in stages. On the trip I will develop the Taconic orogeny stage by stage, and it *will* make sense because it tells a story; Figures 4 through 7 at back.



Paleogeography of the Mid to Late Ordovician Taconic orogeny in the Mid-Atlantic region. The paleogeography is not palinspastically restored but based on the present location of the rocks.

Stop Four: Catherine Furnace Section

UPPER MARTINSBURG ("CUB" SANDSTONE), MASSANUTTEN FORMATIONS

Location: 38.557595 N, 78.635510 W. Catherine Furnace and Cub Run Road; north of Shenandoah, Virginia. (From Shenandoah Virginia head north of US 340 North about 7 miles to Rt. 685/Newport Road. Turn left onto Rt. 685 and continue to the stop sign, approximately 1.2 miles. Turn left onto Katherine Furnace Road and enter the George Washington and Jefferson National Forest. Continue down this gravel road approximately 0.4 miles to Catherine Furnace on the right.)

Exposure: The outcrop extends most of the way along Catherine Furnace Road down to the furnace, with occasional covered zones. The rocks are mostly vertical with the "Cub" being highly weathered.

Formation Descriptions:

We examine two formations here, the Late Ordovician Middle/Upper Martinsburg ("Cub" Sandstone), and Early Silurian Massanutten Sandstone. The "Cub" represents the final filling stages of the Taconic foreland basin, and the Massanutten the post-orogenic stage. Each is described and discussed individually below:

"Cub" Sandstone Description and Interpretations

Principle: the world is fractal: patterns, within patterns, within patterns

Upper Martinsburg Formation ("Cub" Sandstone): an extensive (120 meters thick), badly weathered roadcut of sub-vertical shale and sandstone beds that comprise the middle to upper sections of the Martinsburg Formation.

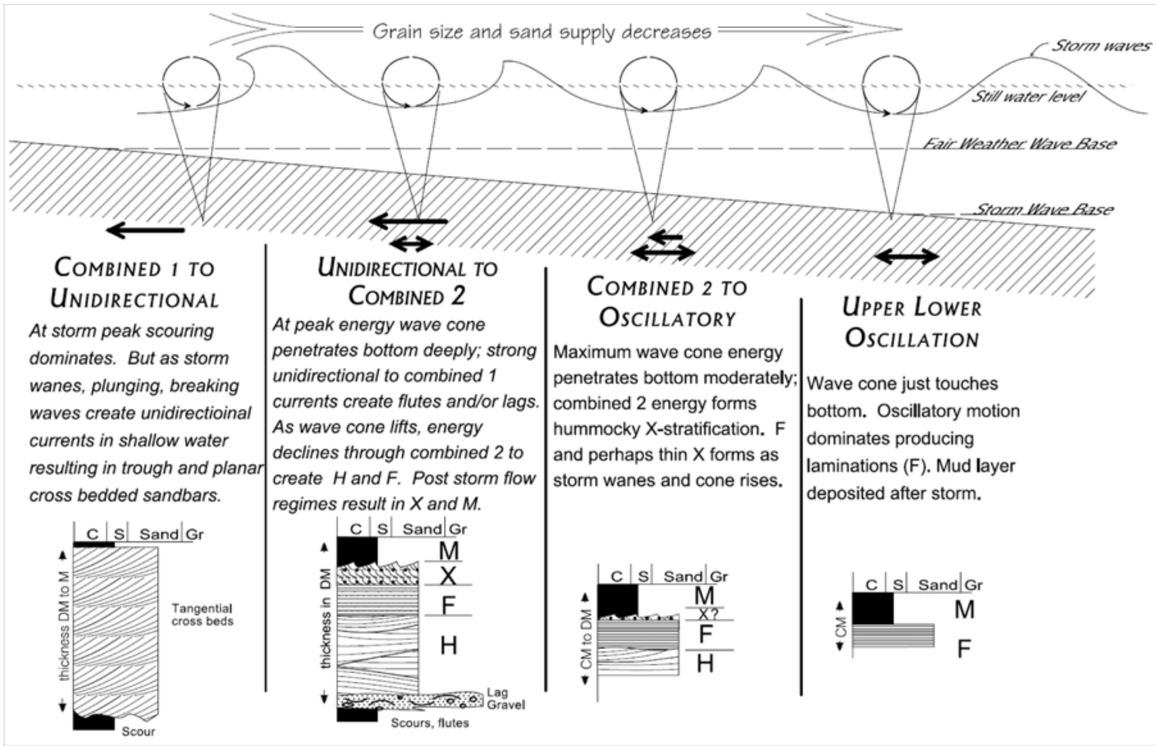
Superficially the outcrop looks noisy, the sandstones almost random. But, if you squint your eyes you will notice that from bottom to top (right to left down the road) the sandstones become thicker and more prominent—an overall coarsening upward sequence.

But, within the overall CUS there are other smaller coarsening upward parasequences, and within those even smaller fining upward hummocky sequences—that is, patterns, within patterns, within patterns. We need to understand each of these, beginning with the smallest.

First (smallest) pattern: Fining Upward Hummocky Sequences:

The "Cub" Sandstone was deposited on a storm shelf (similar to the Virginia coast today) representing the final shallowing and filling stages of the Taconic foreland basin, Figure 8 at back and next page. The energies on storm shelves are strong waves that produce an oscillatory to unidirectional current as the waves move shoreward.

Storm shelf energies create hummocky cross-stratification that is the basal unit in a hummocky sequence that represents the individual storm event from peak energy back to fair weather energies. The figure below models a storm wave traveling across a shallowing shelf toward the shore. As the storm wave touches bottom its energy is translated into oscillatory flow (double headed arrow; far right). But, as the wave moves closer to the shore into shallower water (moving left), the wave cone begins to drag along the bottom, and adds a small unidirectional storm surge component to the oscillatory component, etc. From deep to shallow shelf the translating wave energy generates different sedimentary units that compose the hummocky sequence. By the time the waves wash onto the shoreface (far left) most of the energy has been translated into unidirectional currents that result in near shore unidirectional planar and trough cross bedding (e.g. off shore sandbars) and finally the beach swash zone. Thus, a single storm wave produces a diversity of bedforms as it travels into shallower water. The actual sedimentation sequences will depend on the size of the storm waves, whether there are also storm surges, and position relative to the coast.



COMBINED 1 TO UNIDIRECTIONAL

At storm peak scouring dominates. But as storm wanes, plunging, breaking waves create unidirectioinal currents in shallow water resulting in trough and planar cross bedded sandbars.

UNIDIRECTIONAL TO COMBINED 2

At peak energy wave cone penetrates bottom deeply; strong unidirectional to combined 1 currents create flutes and/or lags. As wave cone lifts, energy declines through combined 2 to create H and F. Post storm flow regimes result in X and M.

COMBINED 2 TO OSCILLATORY

Maximum wave cone energy penetrates bottom moderately; combined 2 energy forms hummocky X-stratification. F and perhaps thin X forms as storm wanes and cone rises.

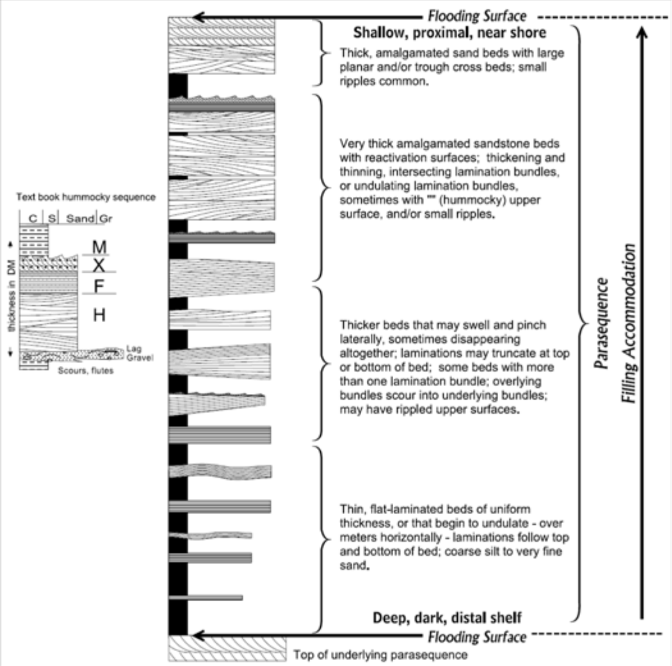
UPPER LOWER OSCILLATION

Wave cone just touches bottom. Oscillatory motion dominates producing laminations (F). Mud layer deposited after storm.

Model of changing energy of storm waves across a shallowing shelf. As moving waves touch down more and more of the energy translates from oscillatory to combined 2 (oscillatory > unidirectional), to combined 1 (unidirectional > oscillatory), to unidirectional on the shoreface. The result is that a single storm wave can produce different bedforms in different places as the water shallows.

In the figure previous page the ideal hummocky sequence is second from the left, but one rarely sees the ideal sequence since they vary as the storm waves migrate into shallower water. The ideal model is useful for predicting what might be expected but natural variations occur both horizontally across a shallow shelf and vertically within a shallowing parasequence.

The figure to the right shows the range of bedding from bottom to top as seen in the "Cub" parasequences. Notice that in a parasequence the sandstones thicken up section, and vary from flat laminated sands, to undulating laminated sands that commonly thicken and thin parallel to bedding, to cross bedded sands. In the lower part of the section each sand represents an individual storm event, but toward the top they begin to amalgamate, that is any one sandstone bed represents more than one storm event.



A coarsening upward parasequence showing the kinds of (cross) stratification found in the "Cub sandstone." Note the coarsening/thickening/amalgamating upward trends and changes in bed shapes.

Second (intermediate) pattern: Coarsening Upward Parasequences:

Sea level rises in pulses, followed by a still stand (Figure 9 at back). During the rise the water gets quickly deeper, and the environments at a specific outcrop shift off shore. Or in the big picture the shoreline transgresses onto the land (moves inland).

During the still stand sediment continues to be deposited and fills in the new accommodation space. Or as we say, the sediment progrades (accumulates out, fills in, or builds out) into the basin causing the water to become more shallow as more proximal environments appear up section from bottom to top.

Parasequences represent intervals of progradation—coarsening upward sequences—punctuated by abrupt sea level rises (called flooding surfaces). The figure above represents such a parasequence. Sandstones thicken, become coarser, and may amalgamate. With the next sea level rise the shore transgresses again, and the water at the section gets deeper and more distal from the shore. In a section this appears as a rapid transition to relatively thick shale-thin sand units.

Third (largest) pattern: Coarsening Upward Composite Sequences made of many Parasequences:

Figures 10 through 14 are a 5 page striplog of the "Cub" Sandstone at Catherine Furnace to guide us. Essentially, from bottom to top of the outcrop the environments become shallower and closer to shore. They are punctuated by abrupt sea level rises that take us into deeper water, but each parasequence is closer to shore.

Observe the following as we walk down the outcrop.

- Notice that the whole section, all 120 meters of it, even though we cannot see it all at once, is an overall coarsening upward (sandstones overall become thicker and more abundant as we walk down the road). This is because we are moving into shallower water and closer to shore from bottom to top.

- Near the bottom (beginning) of the section there are six relatively obvious 8 to 12 meter thick parasequences, each coarsening upward, and each coarser than the one below. Each new coarsening upward brings the shoreline closer to the section we are looking at. Strip logs on pages 10-14 show where we think the parasequence boundaries are.

- The top of each parasequence is a "flooding surface" (a rapid sea level rise that results in an abrupt transition to relatively thick shales). A rapid rise in sea level pushes the coast farther away from where we are; that is, we go farther off shore. Flooding surfaces become less clear near the top of the section as overall sand increases and amalgamates.

- Note the section is “noisy.” Commonly within each parasequence there are anomalous sandstones that seem out of place—too thick or two thin compared to surrounding sands. This reflects the fact that the storms that produce hummocky sequences range from frequent small storms that produce thin beds to very infrequent massive storms that produce thick sands. Abnormally thicker sand units may appear anywhere in a section and represent truly massive storms; (a “Perfect Storm; category 4, 5, or above) and they can appear randomly.

Sedimentary Tectonics Interpretations: Taconic foreland basin - final filling stages:

The “Cub” SS represents the end of the Taconic foreland basin filling when it has shallowed upward enough for storm wave to touch bottom and generate hummocky sequences (See SAATS model). However, in an ideal prograding system we would expect the shelf facies (i.e. “Cub” Sandstone) to be overlain by a beach deposit, and that in turn overlain by a meandering river as the sediment progrades into the basin. The beach and meandering river are absent here; we will discuss why with the Massanutten below.

Depending on the preferences of the group we can continue down the road toward Catherine Furnace to see the Massanutten Sandstone, or move on to Bonus Stop 5 where it is better exposed. One way or another, the Massanutten will be described and interpreted under Stop 5.

* * *

Bonus Stop (Five)

MASSANUTTEN FORMATION

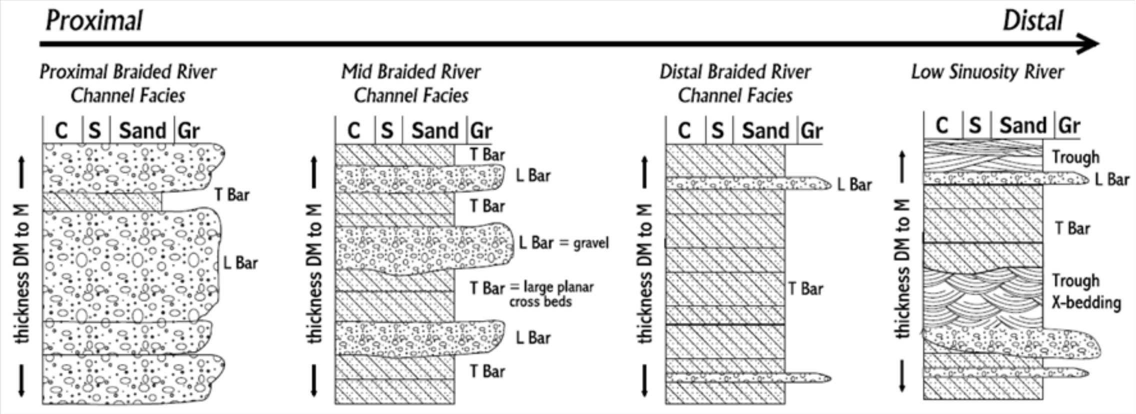
Location: This outcrop is a bit difficult to locate but has a fantastic view over Page Valley and the Blue Ridge to the east, not to mention the Massanutten Sandstone outcrop behind you. From the junction of Rt 11 Bus and North Hawksbill Street in downtown Luray, take North Hawksbill Street north until it T’s at Mechanic Street (< a mile). Turn left onto Mechanic Street which will eventually turn into Rt. 675 as it leaves town. Follow Rt 675 for 2 to 3 miles until it crosses the South Fork of the Shenandoah River. Turn left on 675 for less than half a mile where it turns sharp right and starts to climb the mountain. It will meander around for a while but eventually begin a long, straight climb up the side of the mountain. When you start to see blocky quartz sandstone beds on the left, that is the Massanutten Sandstone.

Formation Description: Indurated (Catherine Furnace) to friable (Massanutten Mtn.), medium to coarse grained quartz sand beds with occasional gravel beds and planar and trough cross bedding (Figure 15 through 17 at the back).

The Catherine Furnace section of the Massanutten Sandstone does not give a lot of sedimentologic information and our description/interpretation is based on better exposures along Rt. 675 (Fort Valley Road) on the east flank of Massanutten Mountain near Luray. There, we find a nearly complete Massanutten section. The sandstone beds are friable and virtually every one has well-expressed large planar and trough cross bedding, often in 3 dimensions. Rare granule beds in the cm range are also present.

Braided River Interpretations: Pratt et al. (1978) and Pratt (1979) proposed that the Massanutten Sandstone represents a braided river system (example in Figure 18 at back). This is supported by the abundant sand and gravel, and cross bedding, as well as the absence of shale beds.

But, depending on the reference you read there are 5 or 6 different kinds of braided rivers (figure below shows striplogs of 4 of them). Even though each is based on a modern river, they can more or less be arranged in a proximal to distal sequence, from gravel-dominated L-Bar systems, to coarse-sand-dominated T-bar systems.



In Massanutten Mountain the L-Bar system is predominant at the northern, Front Royal, end, while cross bedded sands become more prominent toward the south. That is, the rivers were flowing from northeast to southwest down the axis of the mountain.

Along Fort Valley road gravel is very rare, and mostly granule sized, implying this was a distal braided river. But, cross bedding is common. Identifying the different kinds of cross beds on the outcrop takes practice. Figures 15 through 17 illustrates the different kinds, and criteria for distinguishing among them, and this stop is an ideal place to learn to recognize them.

At this locality, both large planar and large trough cross beds are present. For a braided river interpretation trough cross beds are a problem; they are not normal in classical braided river systems. But trough cross beds are common in meandering rivers, the next system down stream (and not present here), where trough cross beds and abundant shales prevail.

The solution is, between the pure braided and pure meandering river systems there must be a transition system, sharing features of both. This transition river is the Low Sinuosity River (far right above, and Figure 18 - the South Saskatchewan Model). Trough and planar cross beds are common, but shales have not yet appeared.

Opps! But, there is one big opps to this neat little story. Braided rivers are always proximal to the sourceland and their sediments tend to be feldspar or lithic rich—that is, very immature. No modern braided rivers are known to be quartz rich. The Massanutten Sandstone, however, is pure quartz—an enigma.

Sedimentary Tectonic Interpretations:

The Martinsburg shelf facies (“Cub” sandstone) is directly overlain by the Massanutten braided river facies. Bretsky (1970) and Kreisa (1980) recognized that the beach and meandering river facies were missing, and suggested that a disconformity may exist between the Martinsburg and Massanutten. The Martinsburg-Massanutten contact is not exposed here. East of here where the contact is exposed, it is abrupt and definitely not gradational. In New York this contact is a slight angular unconformity[5].

The conclusion is, the Massanutten Sandstone represents a post-Taconic tectonic regime and must be interpreted independently from the underlying Taconic sequence.

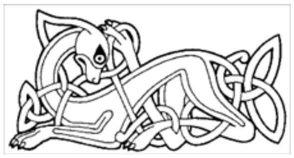
Lower Silurian quartz arenites are widespread (Dorsch and Driese, 1995), but discontinuous and isolated from each other (e.g. Massanutten Sandstone, Tuscarora Formation, Shawangunk Conglomerate, Clinch Formation). Lithologic variations among these units suggests different sourcelands, perhaps from both foreland and hinterland regions. It is also possible that these quartz arenites were derived from a sourceland that only generated

---

[5] It is common in an orogenic cycle for the initial foreland basin subsidence/filling stages to end with an isostatic rebound stage when the region rises back up and is partially eroded. The rebound is because as the weight of the mountain thrust stack is removed by erosion the foreland basin isostatically rebounds back up. Imagine holding a piece of water down in the water, and then letting go; it will float back up.

quartz-rich sediment (a first-cycle quartz arenite, e.g. Johnsson et al., 1988). Overall, the sourceland(s) for the abundant quartz in the lower Silurian is an interesting problem, ripe for discussion, but the Massanutten may represent deposition in a post-Taconic elongate, but isolated, narrow valley.

Thus Endith the Field Trip



Some Useful References:

Bretsky, P.W. 1970. Late Ordovician ecology of the central Appalachians: Peabody Museum of Natural History Bulletin 34, 150 p.

Diecchio, R.J. 1985. Post-Martinsburg Ordovician stratigraphy of Virginia and West Virginia: Virginia Division of Mineral Resources Publication 57, 77 p.

Diecchio, R.J. 1993. Stratigraphic interpretation of the Ordovician of the Appalachian Basin and implications for Taconian flexural modeling: Tectonics, v. 12, p. 1410-1419, doi: 10.1029/93TC01791.

Diecchio, Richard J., and Fichter, L.S., 2015: A Theoretical Foreland Basin Subsidence-Accommodation Time-Series (SATS) Model with Applications to the Taconic Sequence of Northern Virginia; GSA Poster Session, Baltimore Annual Meeting.

Dorsch, J., and Driese, S.G. 1995. The Taconic Foredeep as sediment sink and sediment exporter; implications for the origin of the White Quartzarenite blanket (Upper Ordovician-Lower Silurian) of the Central and Southern Appalachians: American Journal of Science, v. 295, p. 201-243.

Evans, M.A 1989. The structural geometry and evolution of foreland thrust systems, northern Virginia: Geological Society of America Bulletin 10, p. 339-354.

Fichter, L.S., and Diecchio, R. 1986. The Taconic sequence in the northern Shenandoah Valley, Virginia: In: Geological Society of American Centennial Field Guide - Southeastern Section, p. 73-78.

Haynes, J.T., Melson, W.G., O-Hearn, T., Goggin, K.E., and Hubbell, R. 1998. High potassium mid-Ordovician shale of the central Appalachian foredeep: implications for reconstructing Taconian explosive volcanism: in Schieber, J., ed., Shales and Mudstones, v. 2: Stuttgart, E. Schweizerbart'sche, p. 129-141.

Johnsson, M.J., Stallard, R.F., and Meade, R.H. 1988. First-cycle quartz arenites in the Orinoco River basin, Venezuela and Colombia: Journal of Geology, v. 96, p. 263-277.

Kreisa, R.D. 1980. The Martinsburg Formation (Middle and Upper Ordovician) and related facies in southwestern Virginia [Ph. D. dissertation]: Virginia Polytechnic Institute, Blacksburg, 355 p.

Lowry, WD. and Cooper, B.N., 1970. Penecontemporaneous down dip slump structures in Middle Ordovician limestone, Harrisonburg, Virginia: AAPG Bulletin, v. 54, p. 1938-1945.

McBride, E.E 1962. Flysch and associated beds of the Martinsburg Formation (Ordovician), central Appalachians: Journal of Sedimentary Petrology, v. 32, p. 39-91.

Perry, WJ. 1977. The Massanutten Sandstone in Rockingham, Page, Shenandoah, and Warren counties, Virginia: U.S. Geological Survey Bulletin 1435-A, p. A140-A142.

Pratt, L.M. 1979. Stratigraphic framework and depositional environment of the lower to middle Silurian Massanutten Sandstone: University of North Carolina, M.S. Thesis, 76 p.

Pratt, L.M., Phillips, T.L., and Dennison, J.M. 1978. Evidence of nonvascular land plants from the Early Silurian (Llandoverian) of Virginia, U.S.A.: Review of Palaeobotany and Palynology, v. 25, p. 121-149.

Pritchard, E.V. 1980. Soft-sediment deformation within clasts of the Liberty Hall Formation: Virginia Minerals, v. 26, p. 37-39.

Rader, E.K., and Henika, WS. 1978. Ordovician shelf-to-basin transition, Shenandoah valley, Virginia: in Contributions to Virginia Geology - III, Virginia Division of Mineral Resources, Publication 7, p. 51-65.

Read, J.E 1980. Carbonate ramp-to-basin transitions and foreland basin evolution, Middle Ordovician, Virginia Appalachians: AAPG Bulletin, v. 64, p. 1575-1612.

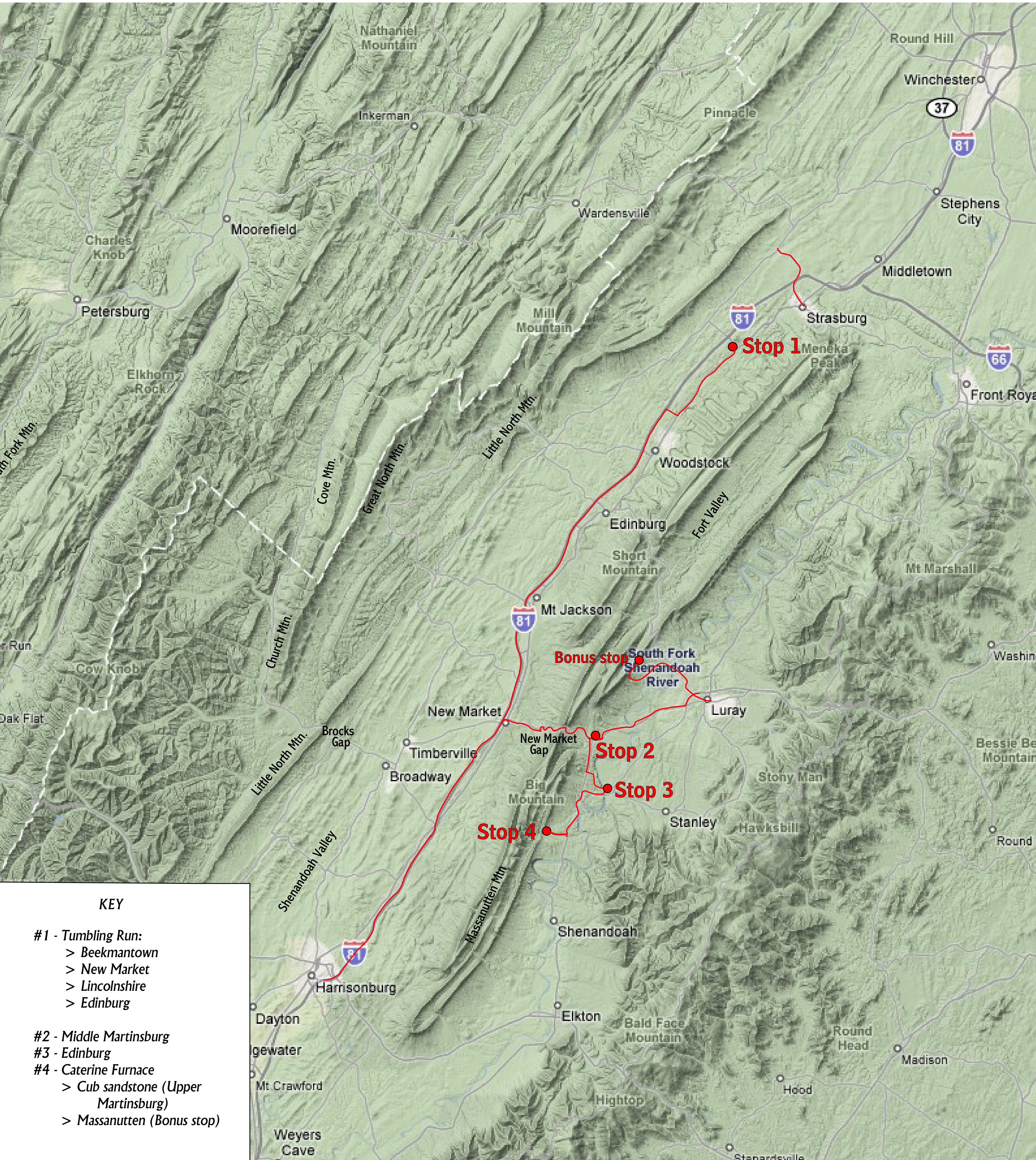
Whitmeyer, S.J., Fichter, L.S., Diecchio, R. Heller, M.J., Eaton, L.S., Cross, A., Coiner, L., Biggs, T.H., Patterson, C.R.: Geology of Page Valley: Stratigraphy, Structure, and Landscape Evolution, 42nd Annual Virginia Geological field Conference, September 28-29, 2012.

Figure 0

Field Trip Base Map

Tectonics, Stratigraphy and the Ordovician Taconic Orogeny in Northwestern Virginia

Dept. of Geology and Environmental Science - James Madison University - Lynn S. Fichter- 2017



KEY

#1 - Tumbling Run:
  > Beekmantown
  > New Market
  > Lincolnshire
  > Edinburg

#2 - Middle Martinsburg
#3 - Edinburg
#4 - Caterine Furnace
  > Cub sandstone (Upper Martinsburg)
  > Massanutten (Bonus stop)

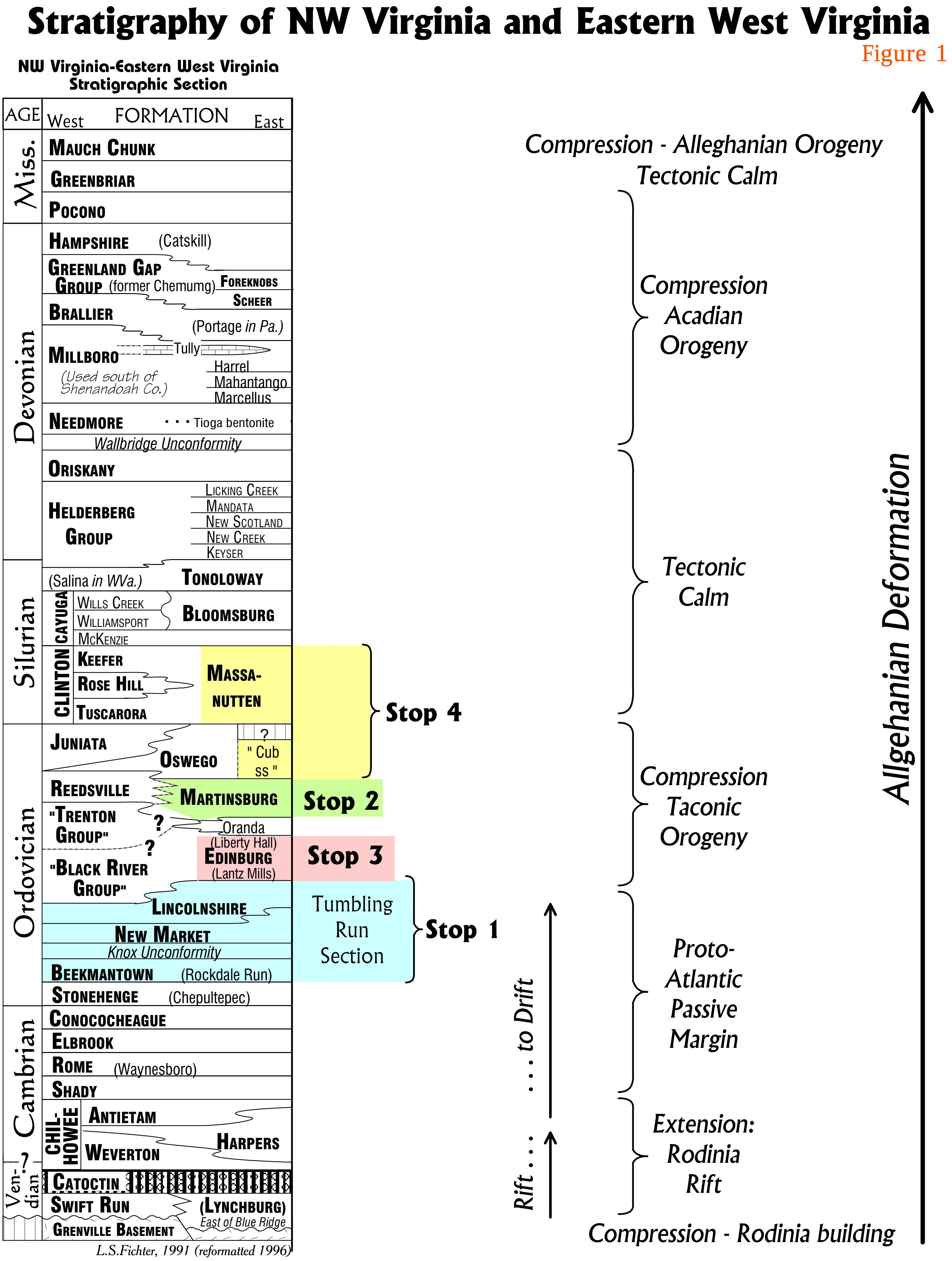
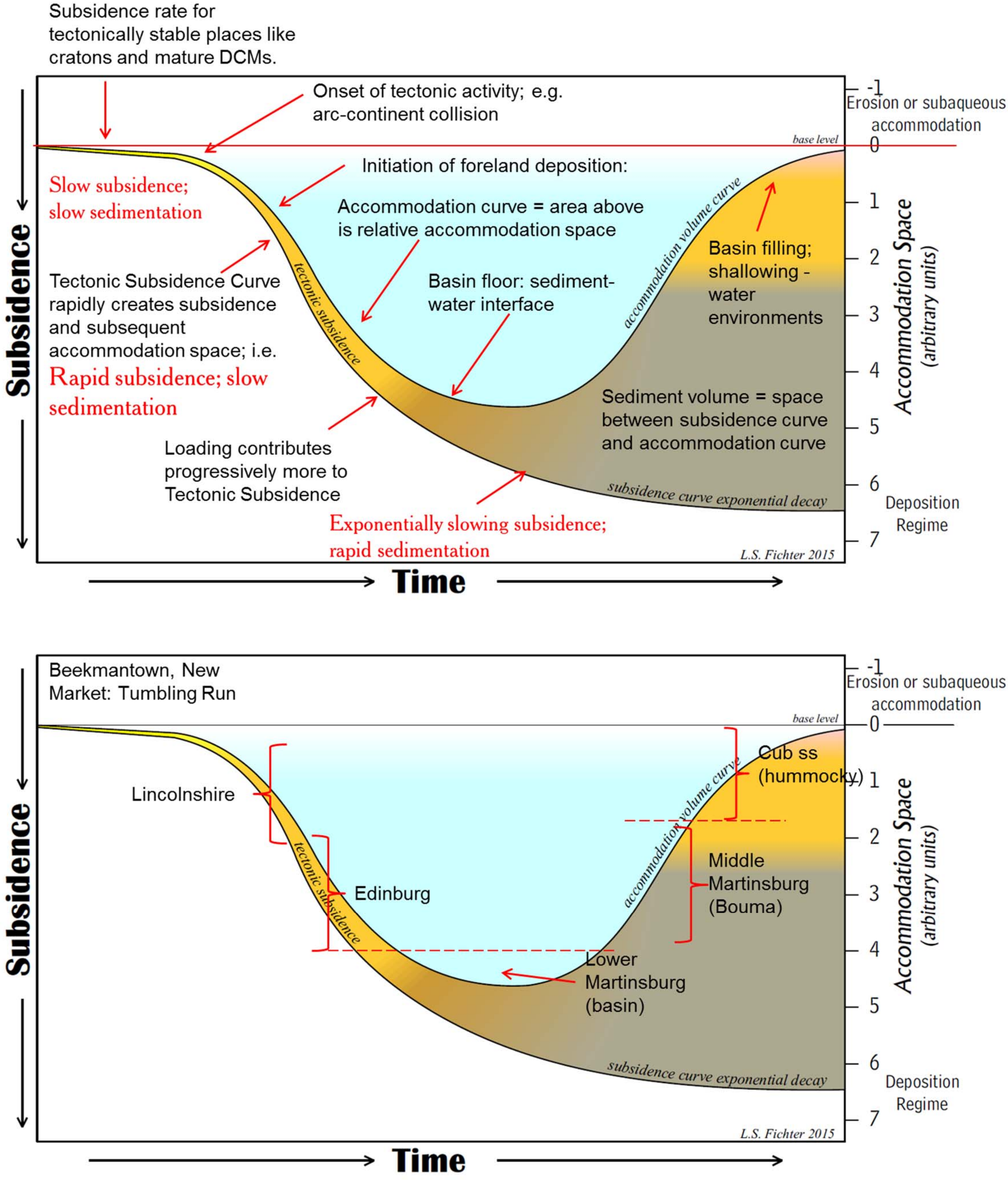


Figure 4. Regional stratigraphic column showing the stratigraphy, location of field trip stops, and tectonic interpretations.

Subsidence-Accommodation-Accumulation Time Series Diagram For the Taconic Foreland Basin in Northwestern Virginia

Figure 2



Stratigraphy and Interpretation of the Tumbling Run Section, Strausburg, Virginia

Route 601, Fisher's Hill Road, North Side Outcrop Profile

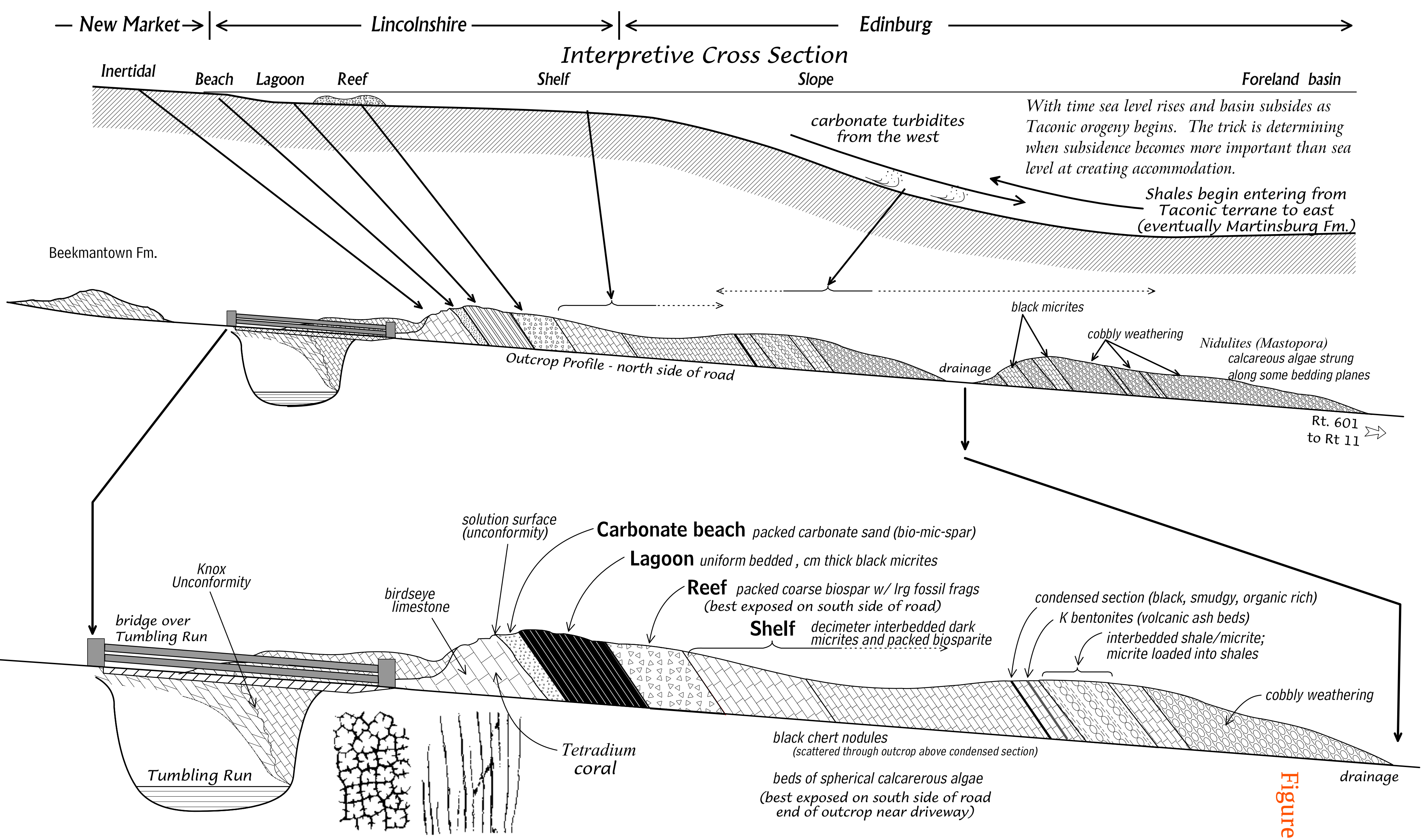


Figure 3

Figure 4

Paleogeography of the early Ordovician, Pre-Taconic, Virginia and Surrounding Areas

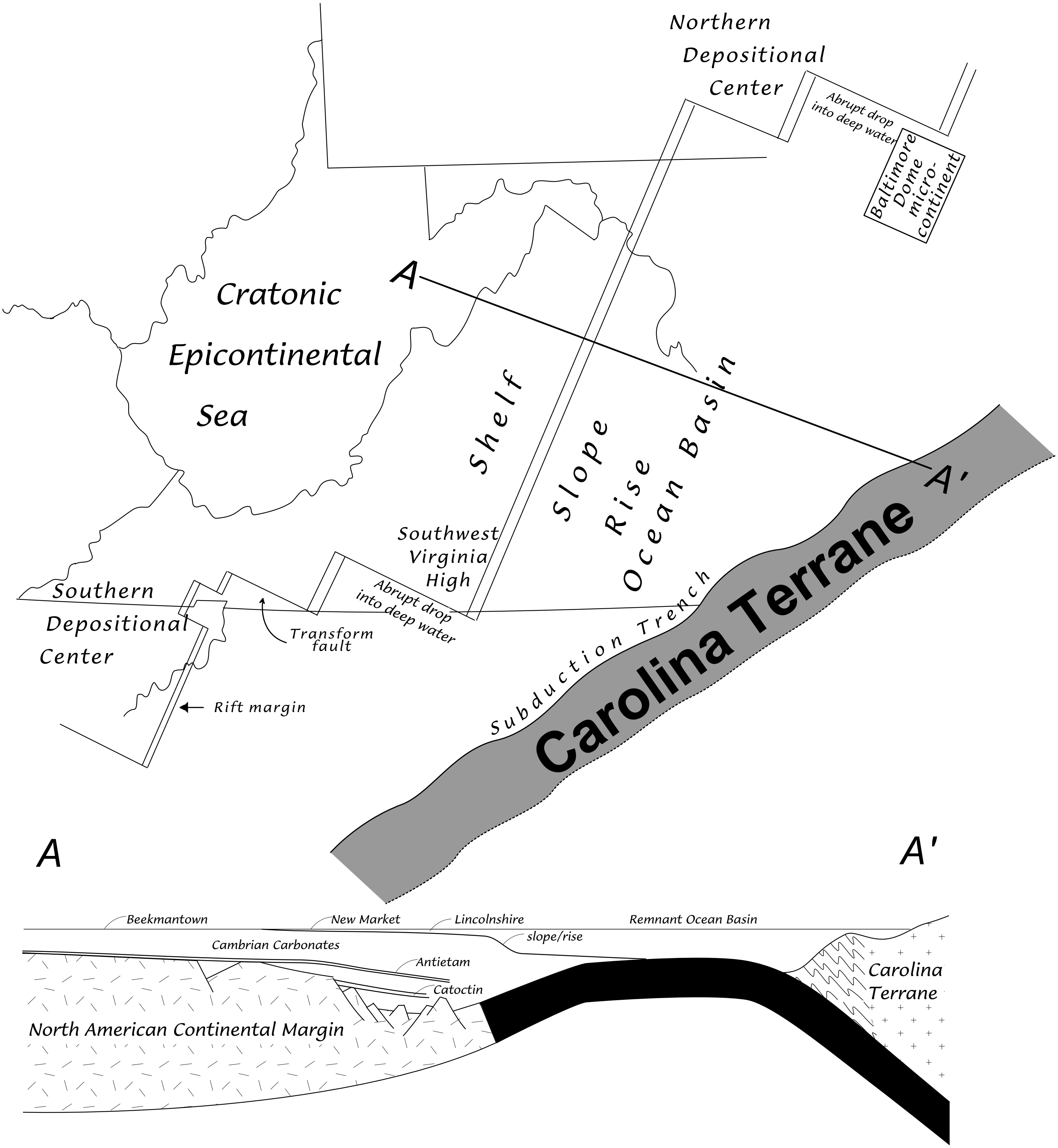
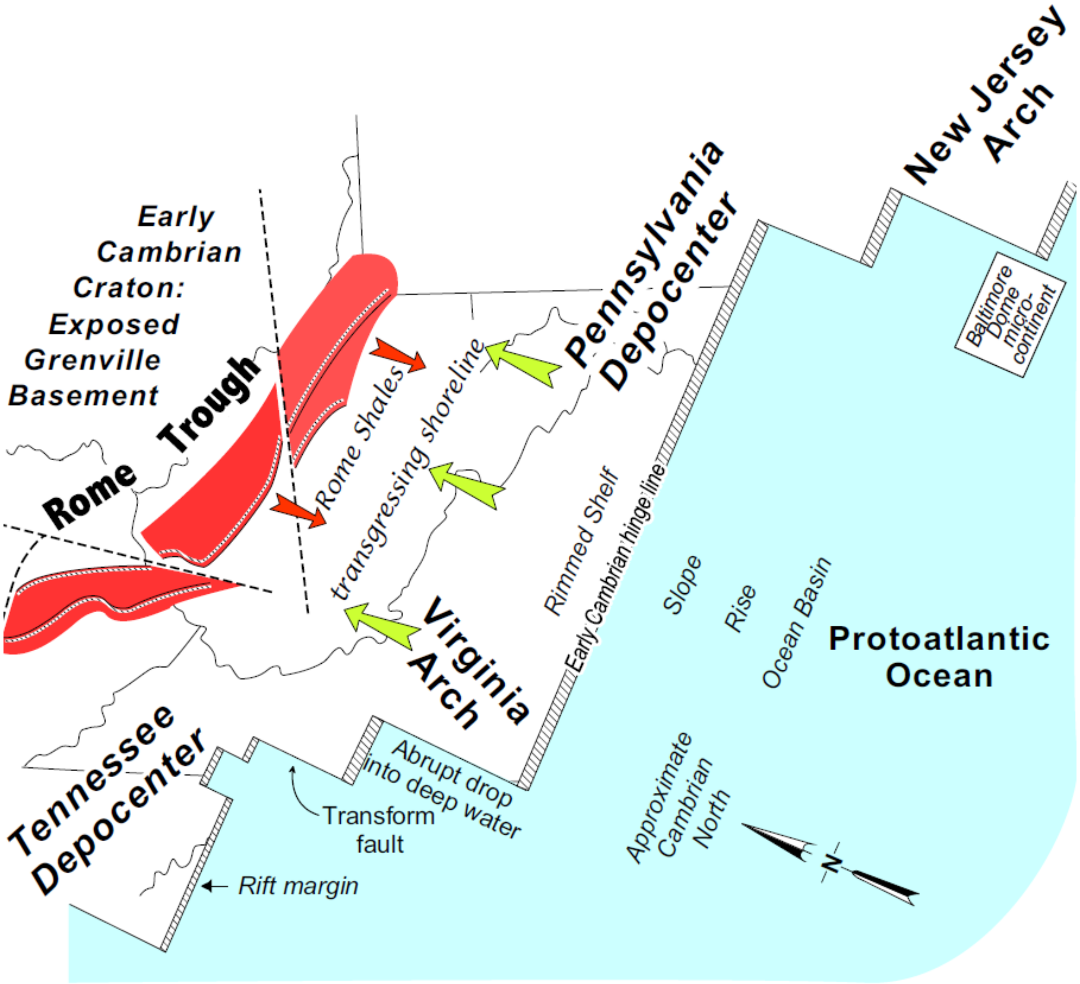


Figure 5



Cambrian Continental Margin

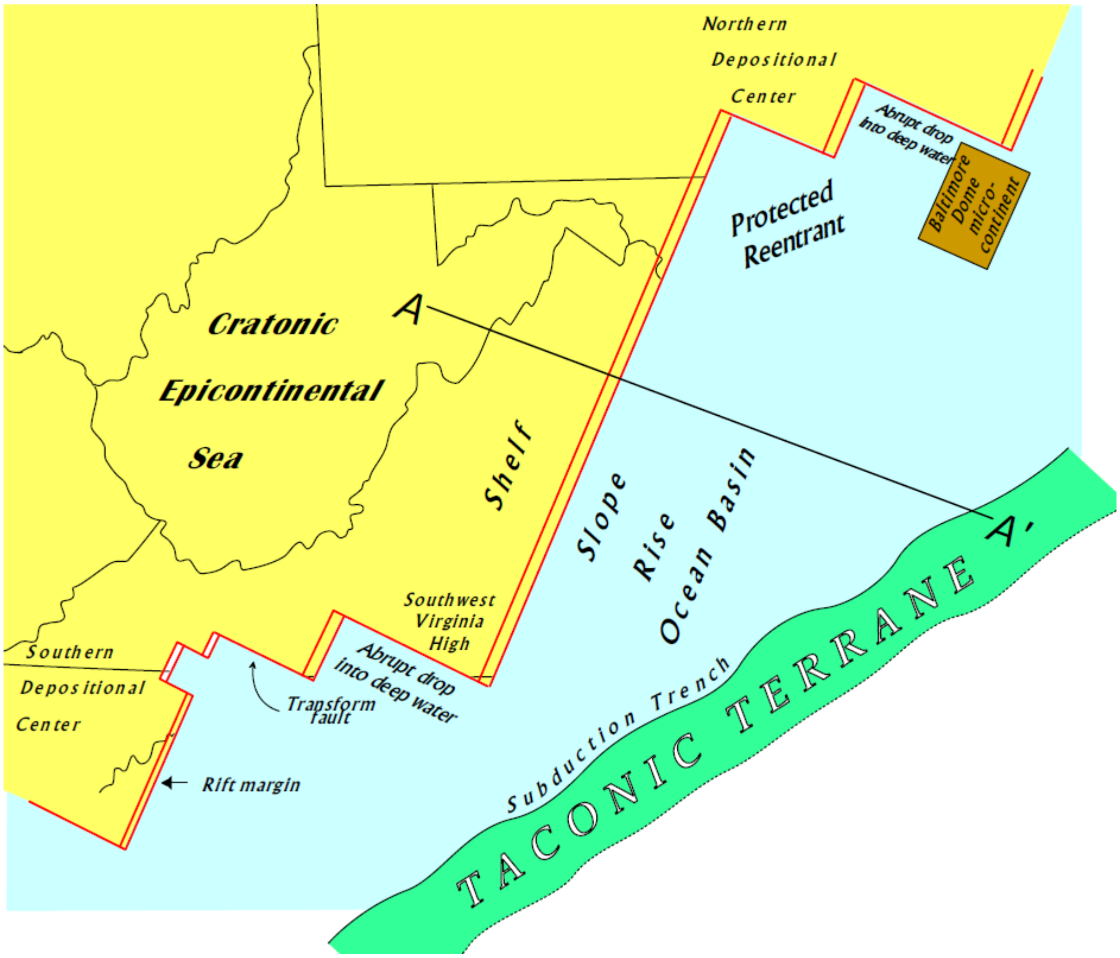


Figure 6

Paleogeography Associated with the middle Ordovician Taconic Orogeny in Virginia and Surrounding Areas

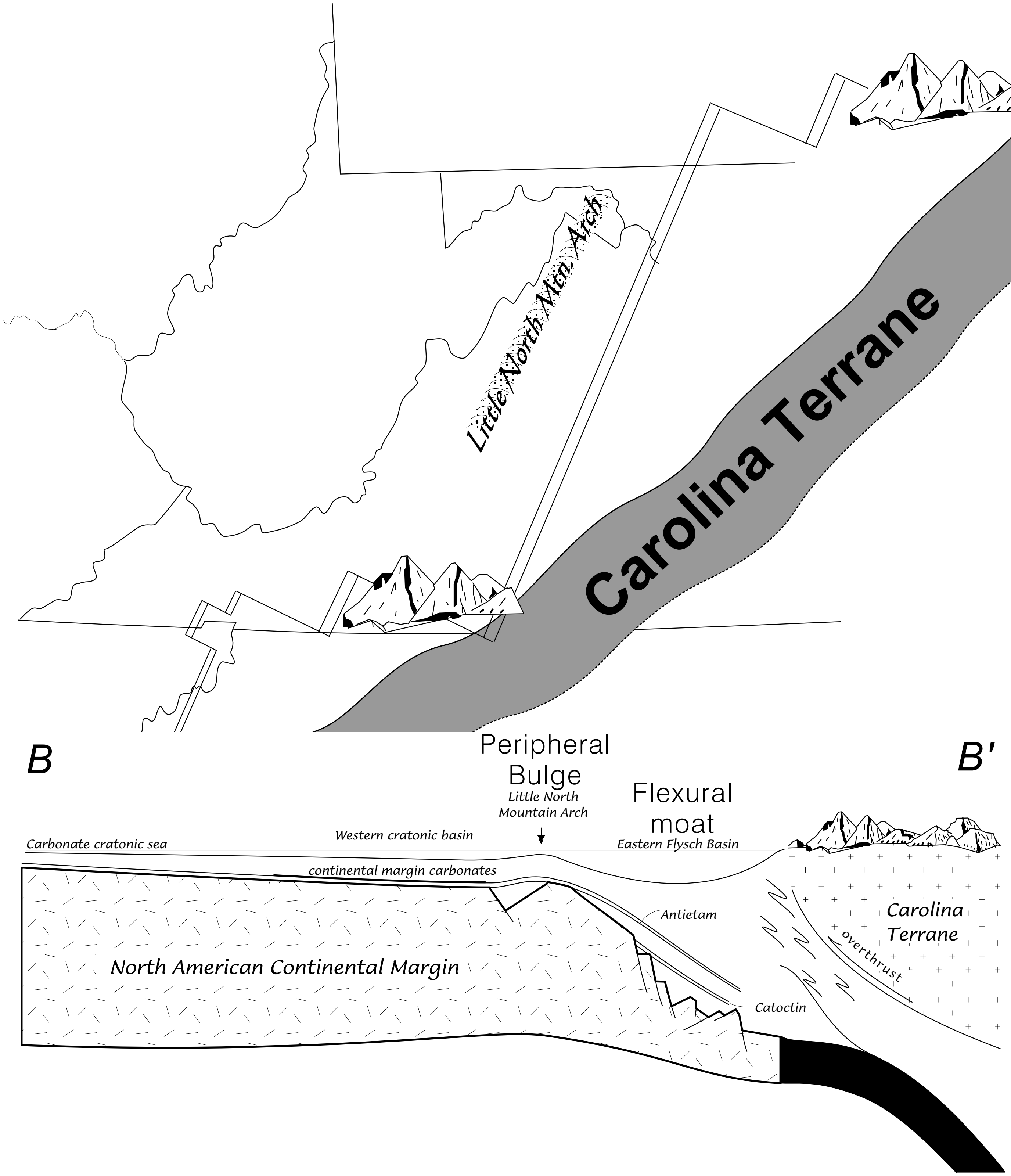
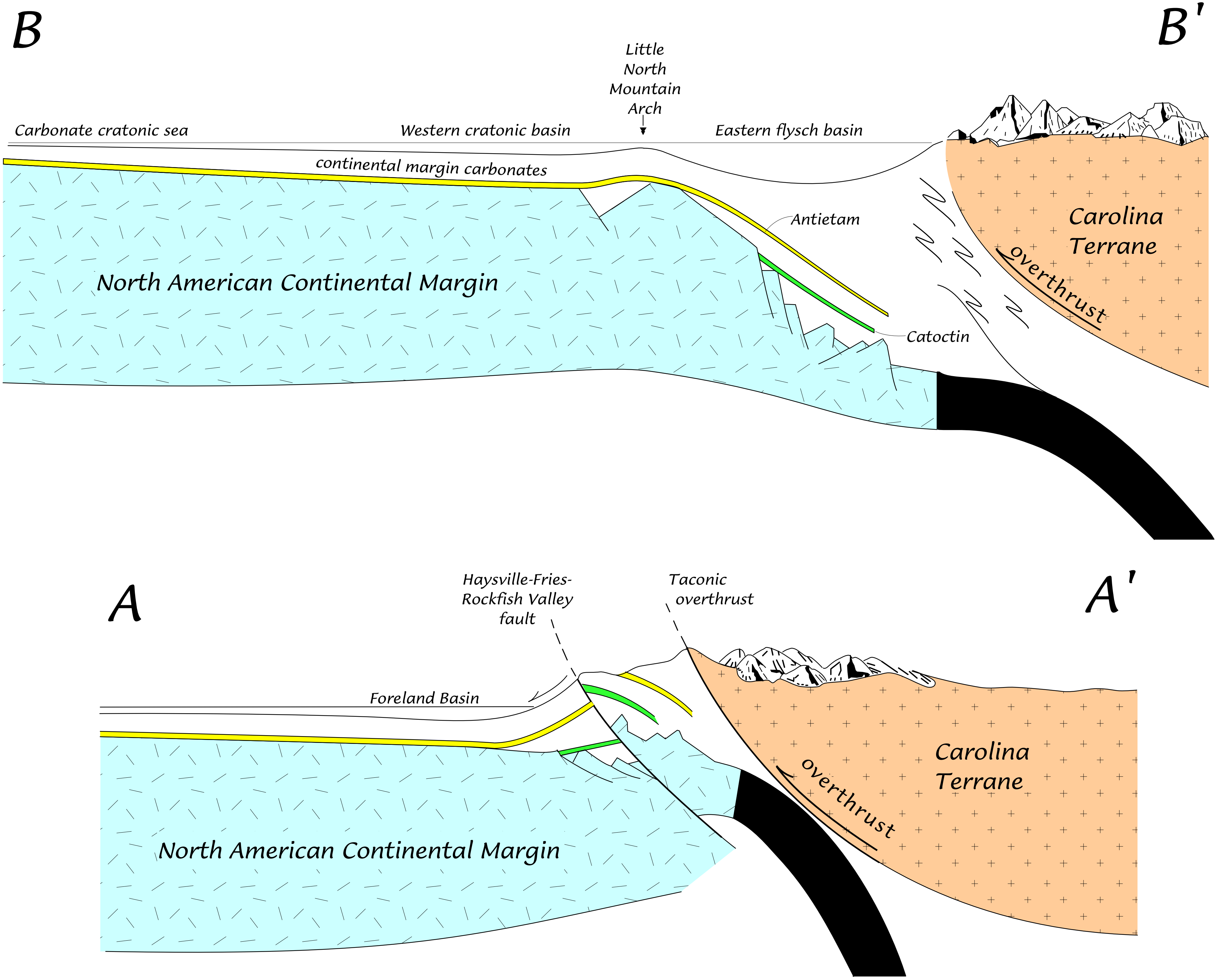


Figure 7


B
B'
Little
North
Mountain
Arch
Carbonate cratonic sea
Western cratonic basin
Eastern flysch basin
continental margin carbonates
Antietam
Carolina
Terrane
overthrust
North American Continental Margin
Catoctin
A
A'
Haysville-Fries-
Rockfish Valley
fault
Taconic
overthrust
Foreland Basin
Carolina
Terrane
overthrust
North American Continental Margin

Wave Translation Across a Shallowing Shelf and Typical Structures

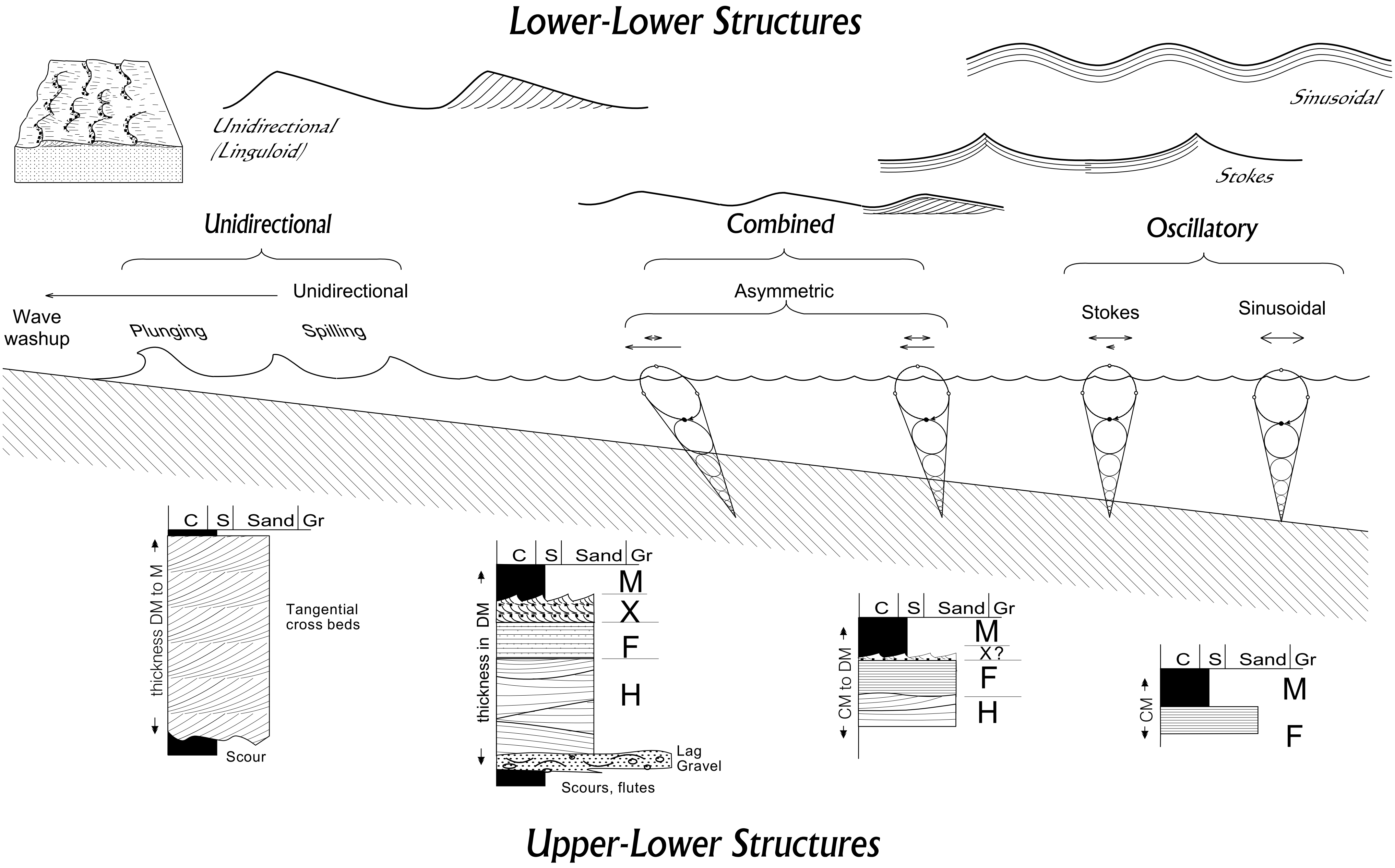
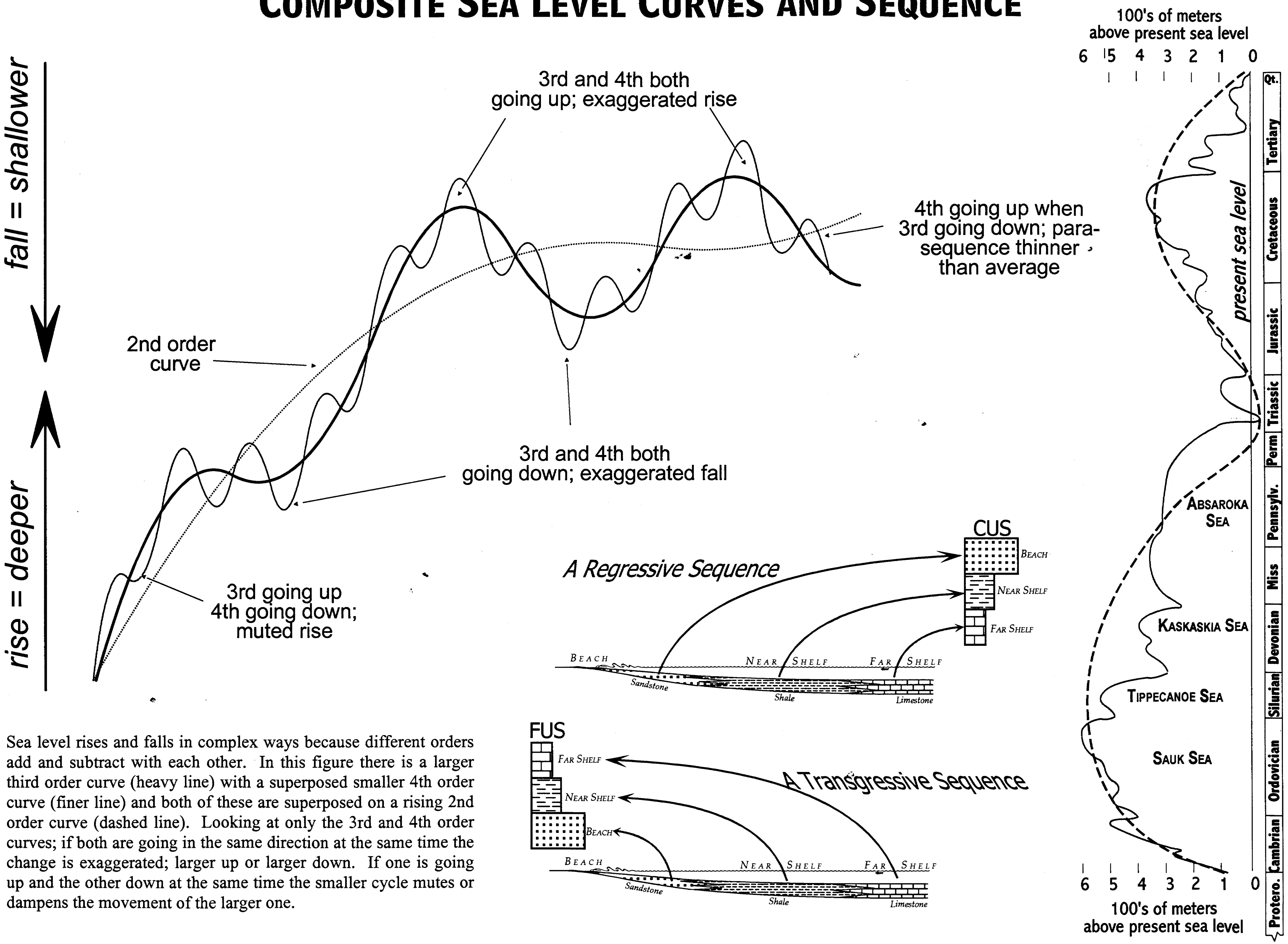


Figure 8

Figure 9

COMPOSITE SEA LEVEL CURVES AND SEQUENCE



Sea level rises and falls in complex ways because different orders add and subtract with each other. In this figure there is a larger third order curve (heavy line) with a superposed smaller 4th order curve (finer line) and both of these are superposed on a rising 2nd order curve (dashed line). Looking at only the 3rd and 4th order curves; if both are going in the same direction at the same time the change is exaggerated; larger up or larger down. If one is going up and the other down at the same time the smaller cycle mutes or dampens the movement of the larger one.

Figure 10

Upper Martinsburg (Cub Sandstone), Catherine Furnace.
Measured by Rick Diecchio and Lynn Fichter, August, 2012

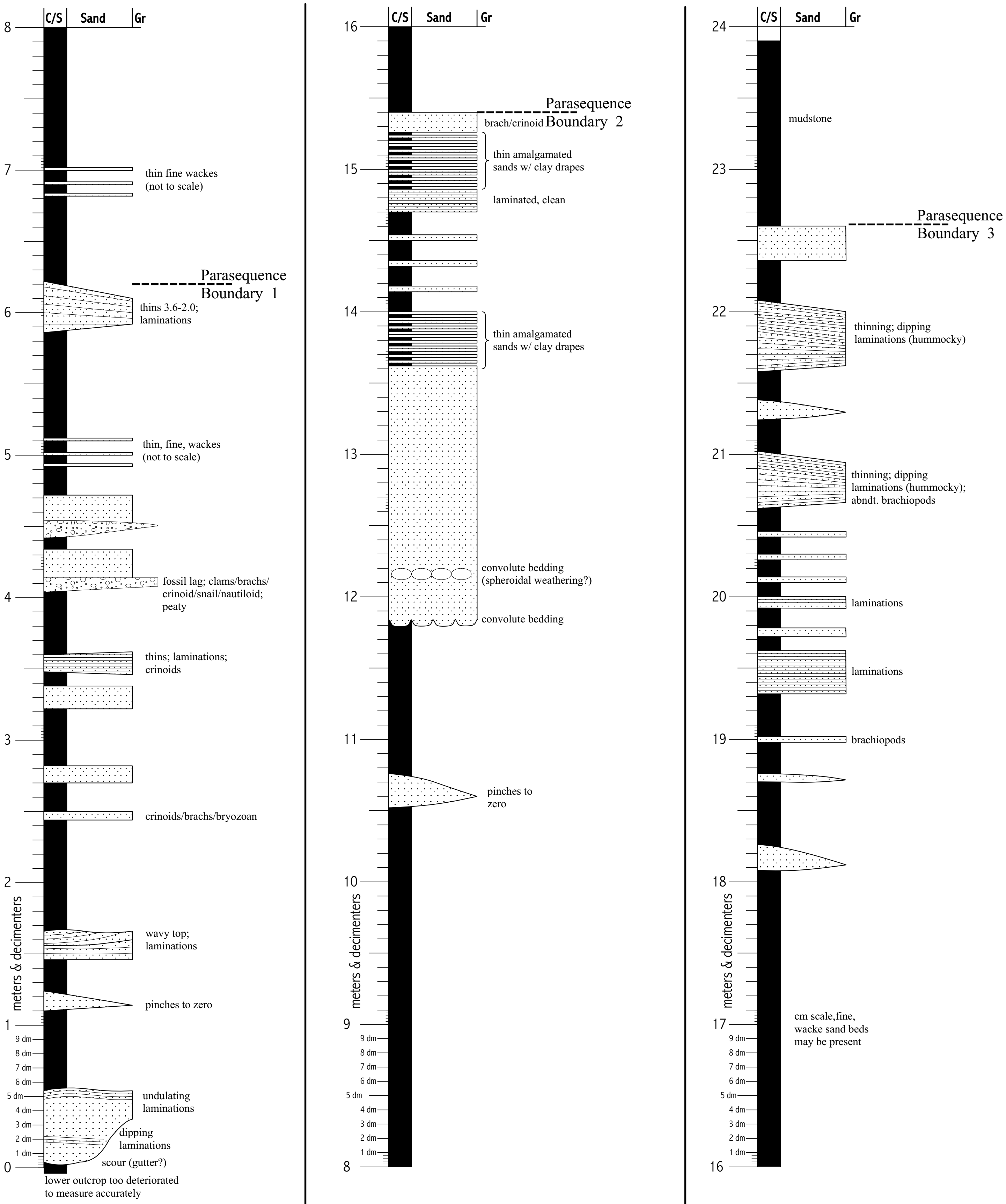


Figure 11

Upper Martinsburg (Cub Sandstone), Catherine Furnace.
Measured by Rick Diecchio and Lynn Fichter, August, 2012

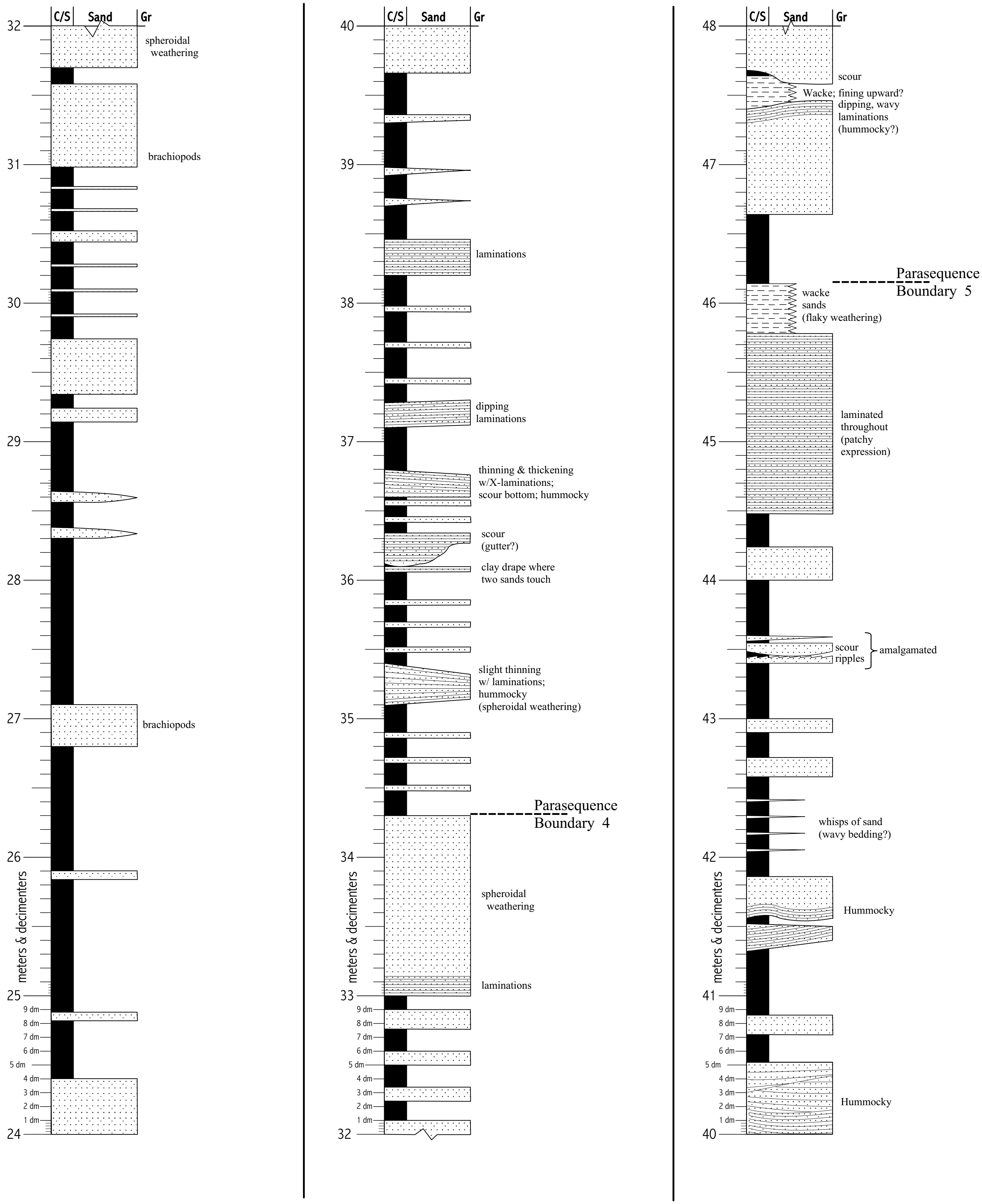


Figure 12

Upper Martinsburg (Cub Sandstone), Catherine Furnace.
Measured by Rick Diecchio and Lynn Fichter, August, 2012

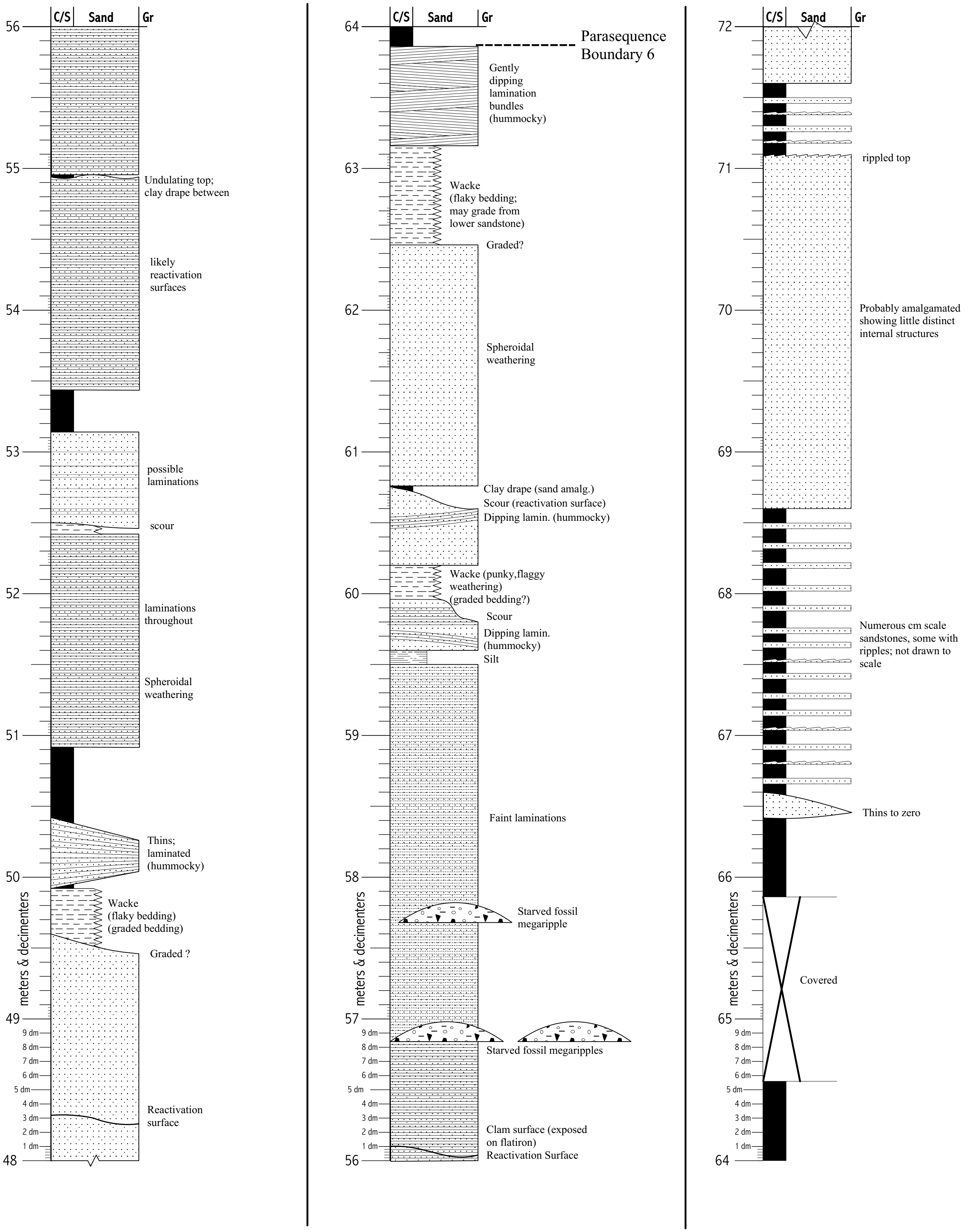


Figure 13

Upper Martinsburg (Cub Sandstone), Catherine Furnace.
Measured by Rick Diecchio and Lynn Fichter, August, 2012

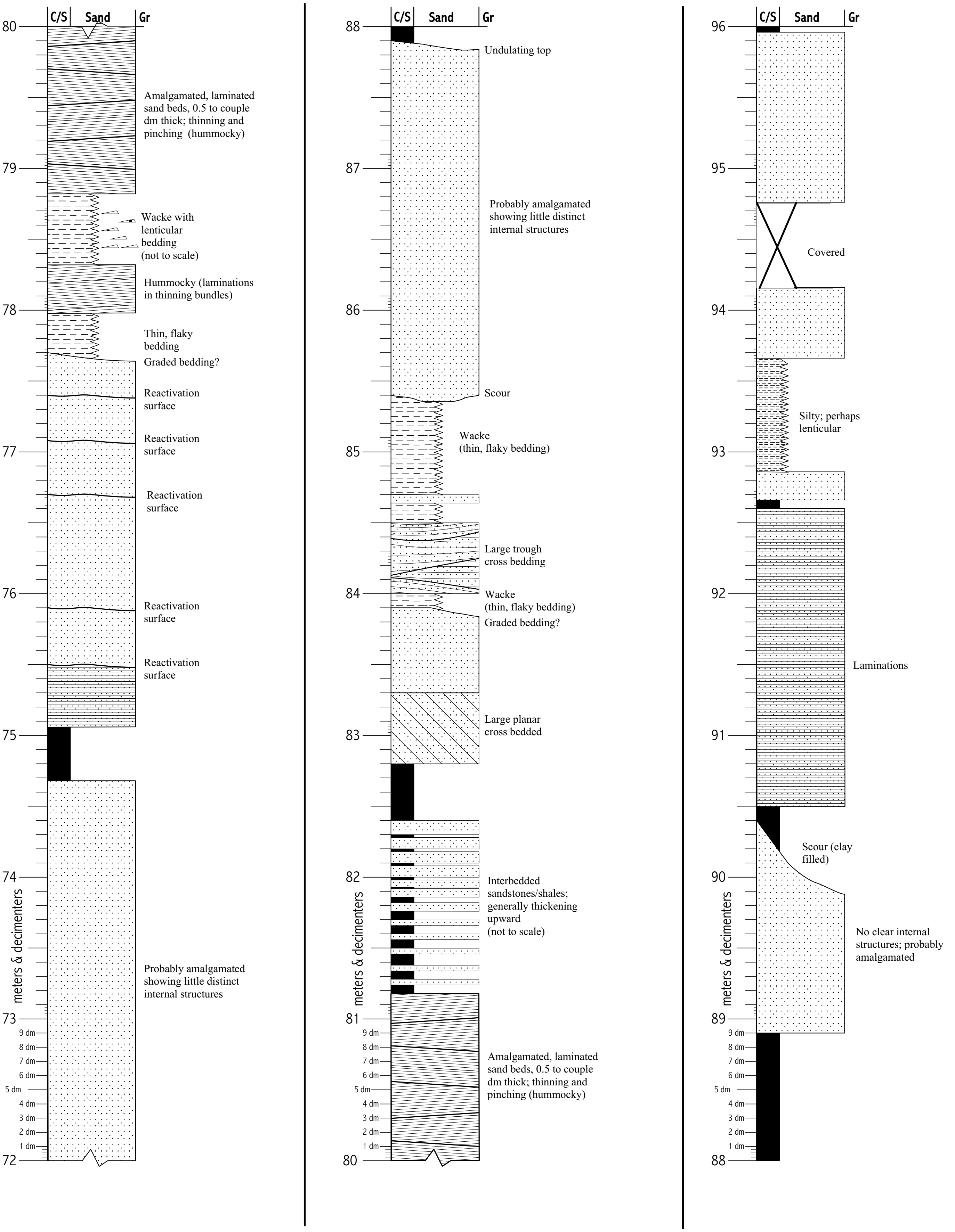
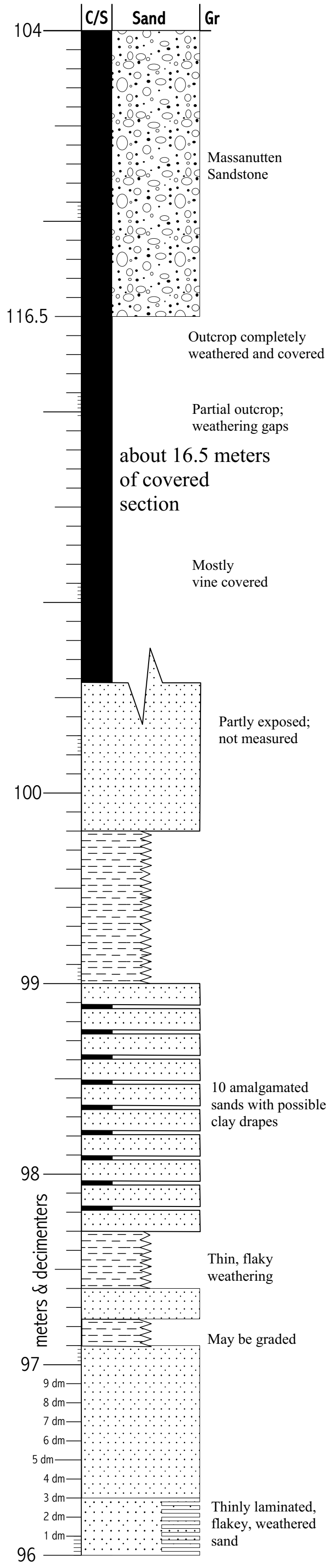


Figure 14

Upper Martinsburg (Cub Sandstone), Catherine Furnace.
Measured by Rick Diecchio and Lynn Fichter, August, 2012



State of the Outcrop and Measured Section

The Catherine's Furnace section of the "Cub sandstone" or upper Martinsburg is badly deteriorated by weathering, masking many of the sedimentologic and stratigraphic signatures. Some relatively clean arenite beds do stand out, but wacke beds are more common and often have diffuse boundaries, especially at the top where they may grade or fine upward into flaky weathered units looking superficially like weathered silt or shale but on close examination are sand rich. Many parts of the outcrop that look to be dominated by weathered shale/silt have sand rich zones that may be lenticular, wavy, or flaser-type bedding, but without distinct bed contacts to identify them. Sand rich zones were not mapped as beds unless distinct contacts were visible. We frequently used the cleavage to distinguish shale layers because the shale cleavage differs by a few degrees from the bedding fissility of weathered wacke or silt beds.

Many of the sand beds change thickness laterally, thickening and/or thinning, or pinching to zero, but it is easy to miss these changes. The thickening/thinning may occur on both the top and bottom of the bed; or on one or the other; often it is not possible to tell. Some sandstones shows internal layering (laminations or cross bedding), and were indicated as such, but many do not, or have only a faint hint of internal layering. We assume that all the sandstone beds were deposited by flow regime conditions that would result in laminations, beds, or bedsets (as opposed to mass transport mechanisms), consistent with the beds for which we do have flow regime structures

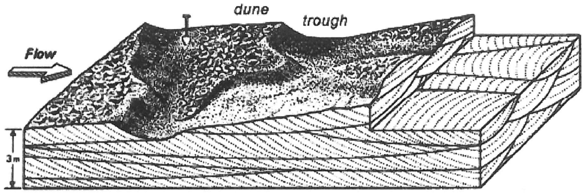
Many of the thicker sandstone beds are almost certainly amalgamated (composed of more than one deposition event separated by reactivation surfaces, such as scours, clay drapes, or pebble lags). In some cases the reactivation surfaces were visible, but often they were not. Flow regime and environmental interpretations are based on a composite of all the information in the section and extrapolated to parts of the section where evidence was sketchy or missing. Our interpretation is most consistent with storm shelf parasequence models.

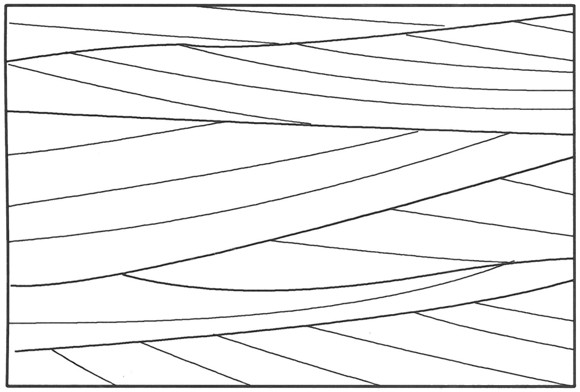
It is difficult to be entirely objective when measure a section like this. We strove to be consistent in the accuracy and precision of the data collected, especially across the coarsening/thickening upward changes in the section, but someone else might make different judgements about what is significant or not, and therefore what patterns are present. We welcome discussion and debate on these differences of observation and opinion.

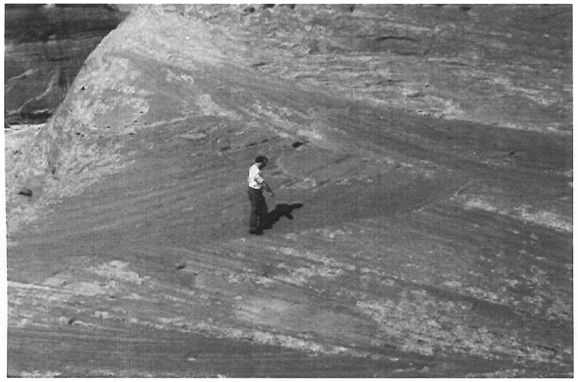
Figure 15

Trough, Planar, and Hummocky Cross Stratification

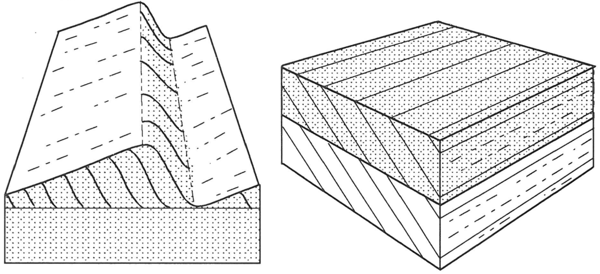
Large Trough Cross Stratification

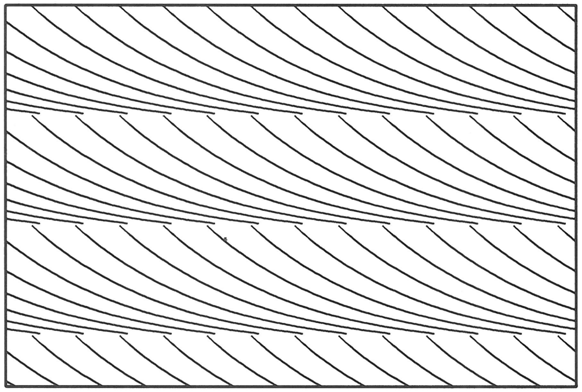


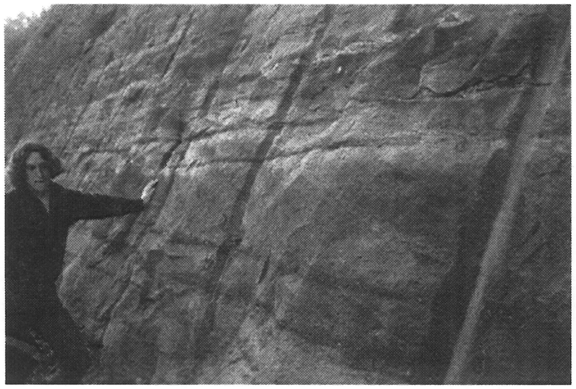




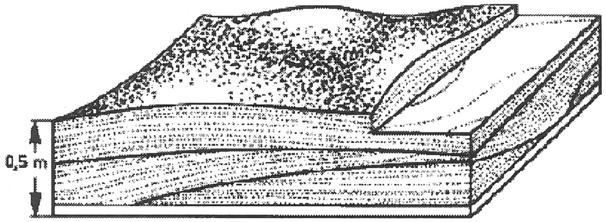
Large Planar Cross Stratification







Hummocky Cross Stratification



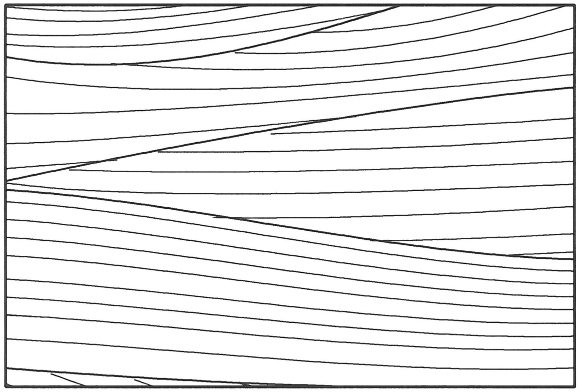


Figure 16

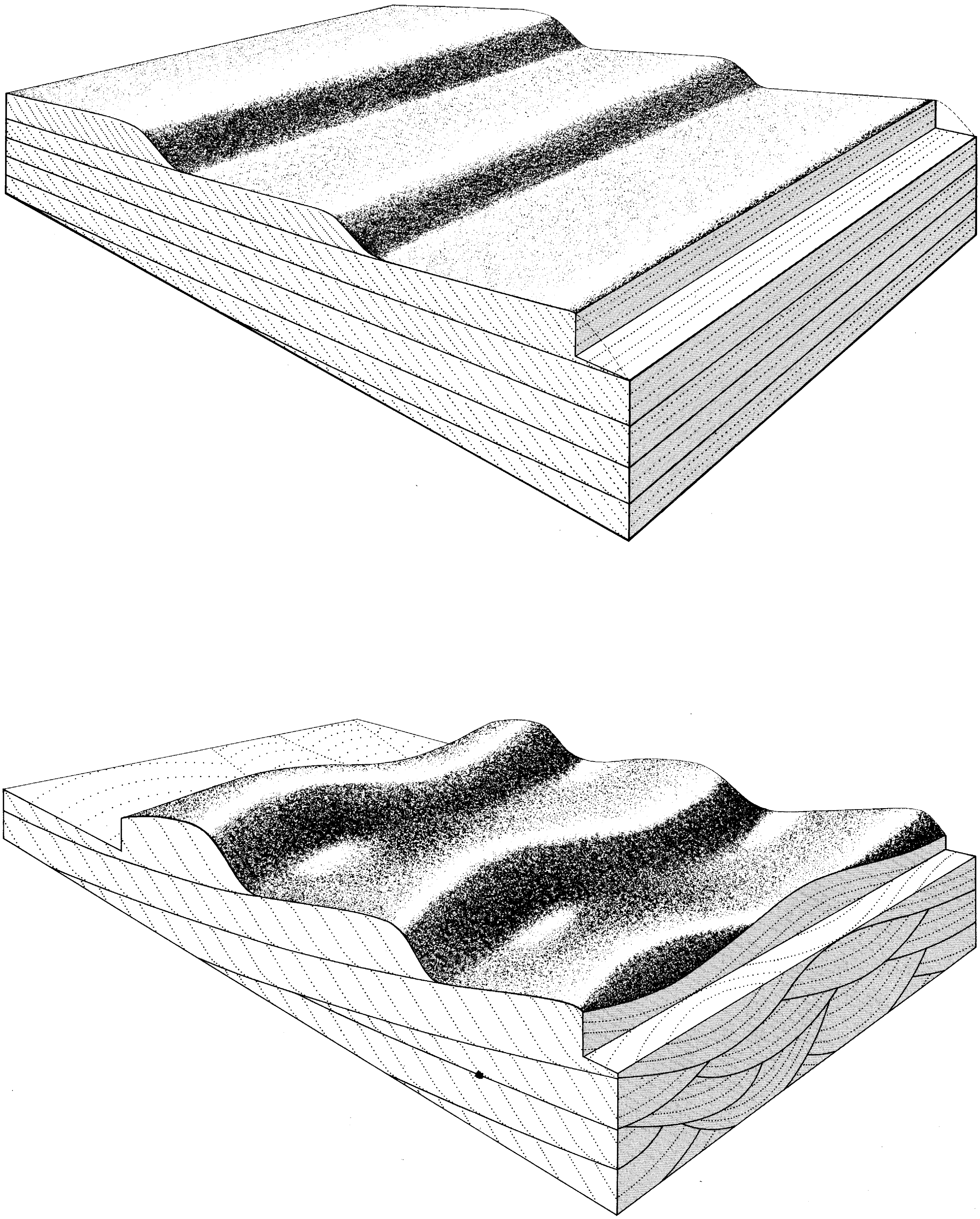
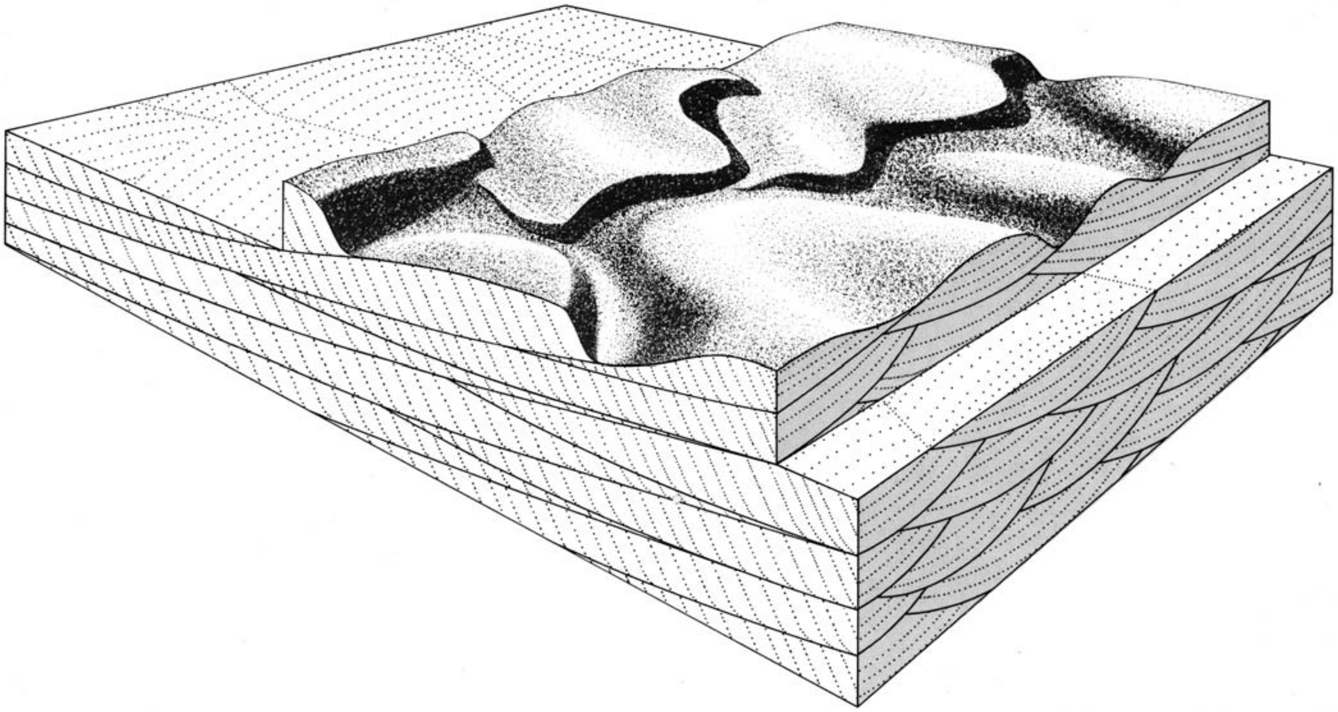
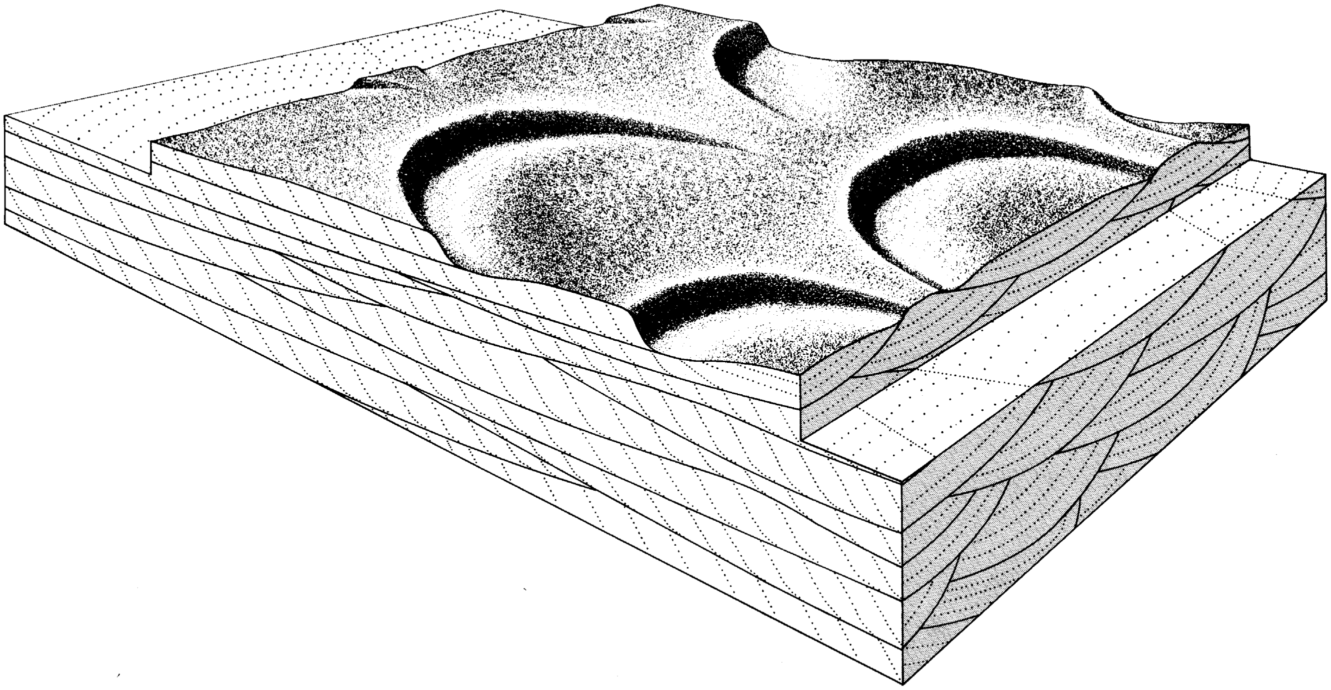


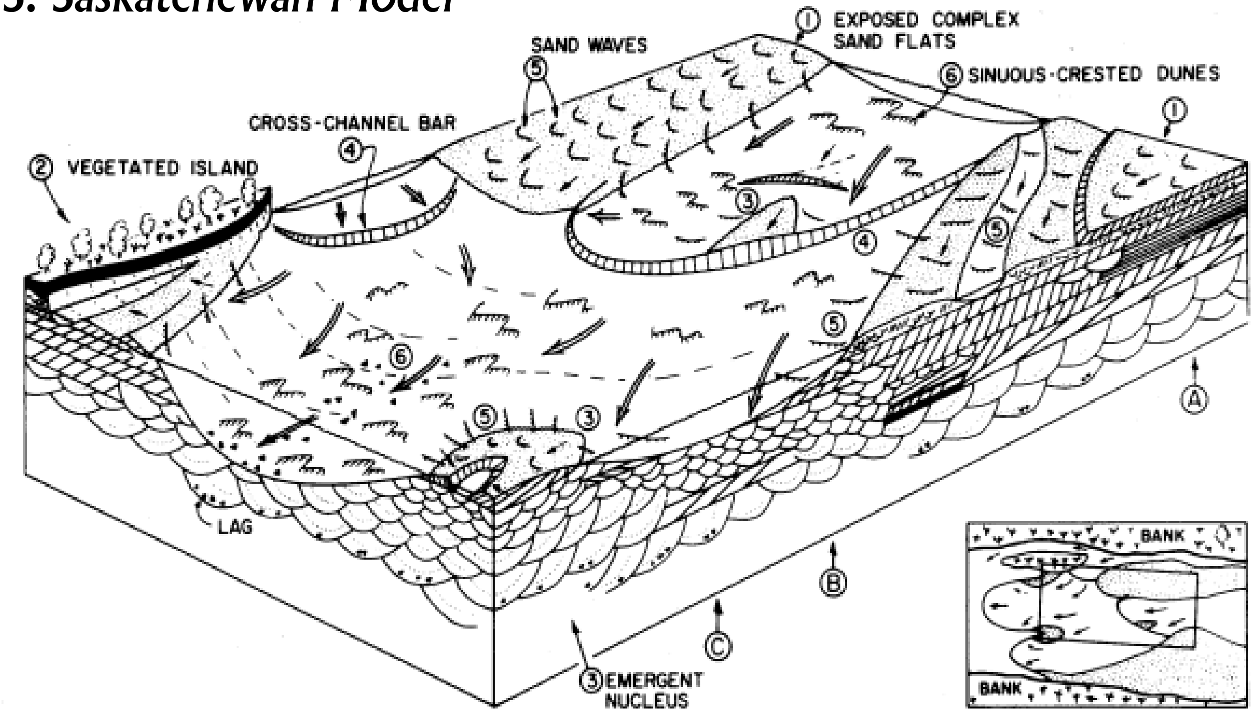
Figure 17





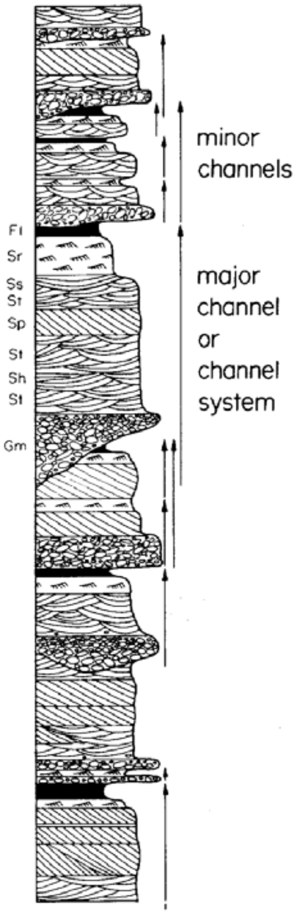
Braided River Spectrum

S. Saskatchewan Model

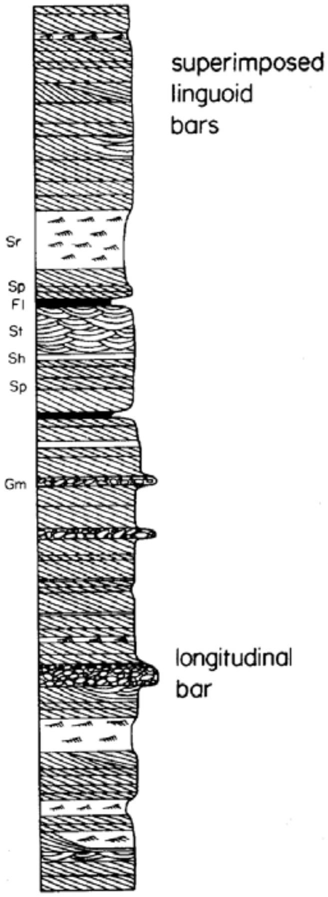


Proximal → **Distal**

DONJEK TYPE



PLATTE TYPE



S. SASKATCHEWAN TYPE