East Tennessee Geological Society

President: Tony McClain

Field Guide to the Geology of the Oak Ridge Area*

Oak Ridge, Tennessee

December 9, 2023

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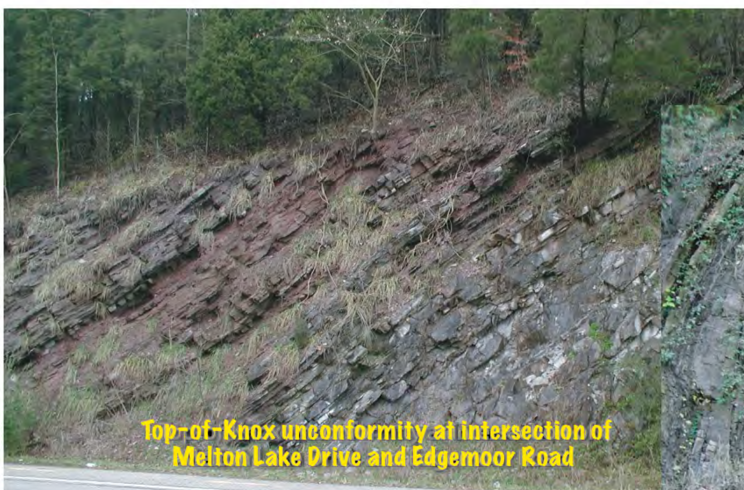


Top-of-Knox unconformity at intersection of Melton Lake Drive and Edgemoor Road

#Home address:
107 Goldengate Lane
Oak Ridge, TN 37830

Small fault in Rome Formation exposed near Moores Gap Church

*Compiled and updated from numerous earlier guidebooks

INTRODUCTION

This field trip has two principal goals: (1) to acquaint participants with representative rock types and the structural setting of the Oak Ridge area; and (2) to examine exposures that have been looked at by geologists and non-geologists alike from the context of their more regional significance. While each exposure we will visit contains representative rock types, each also has significance that goes far beyond the basic rock types present.

Oak Ridge and the Oak Ridge Reservation (ORR) are located in the western part of the Valley and Ridge geologic (and physiographic) province, and is very close to the transition into the Cumberland Plateau. At the latitude of Oak Ridge, almost all of the faults and other structures that we see in the Valley and Ridge do not exist beyond the topographic boundary between the Valley and Ridge and Plateau, which is at Oliver Springs. We call the area in the Plateau immediately NW of Oak Ridge the "Wartburg basin." It is a topographic high so it is a geologic and not a topographic basin. Immediately northeast of Clinton and just southwest of Harriman, however, the deformation that we commonly see in the Valley and Ridge propagated into the Plateau, so the geologic province continues into the Plateau to the area around Jellico to the northwest from Clinton, and to just beyond Crossville to the southwest. If we could reconstruct the topography that existed ~200 Ma, we would find that the rocks of the Cumberland Plateau today would have extended southeastward across the Valley and Ridge to the Blue Ridge. So, the uplift that accompanies the faulting and folding that we see today exposed at much greater erosional depths provided an opportunity for the Valley and Ridge to be unroofed subsequent to the uplift that occurred ~300 Ma. extended southeastward across the Valley and Ridge to the Blue Ridge. So, the uplift that accompanies the faulting and folding that we see today exposed at much greater erosional depths provided an opportunity for the Valley and Ridge to be unroofed subsequent to the uplift that occurred ~300 Ma. So, the uplift that accompanies the faulting and folding that we see today exposed at much greater erosional depths provided an opportunity for the Valley and Ridge to be unroofed subsequent to the uplift that occurred ~300 Ma. The primary evidence that the Plateau rocks extended across the Valley and Ridge is that there is a small remnant of these rocks immediately west of Whiteoak Mountain at Ooltewah, Tennessee. Other remnants occur farther northeast in Virginia and Pennsylvania, and farther southwest in Georgia and Alabama.

Oak Ridge and the DOE facilities (Y-12, ORNL, and ETTP) occur in a geologically complex region, and DOE has suggested that the Oak Ridge Reservation (ORR) is probably the most complex of all the DOE sites in the U.S. Despite the complexity, a number of important studies of geology and ground water have been undertaken beginning several decades ago and, while the surface geology is reasonably well understood, the nature and movement of ground water in the subsurface remains obscure (Hatcher et al., 1992; Solomon et al., 1992).

Each of the three facilities in Oak Ridge is located in a separate valley (Fig. 1), originally for safety reasons ETTP resides in a valley at the west end of the ORR that is underlain by limestone and minor

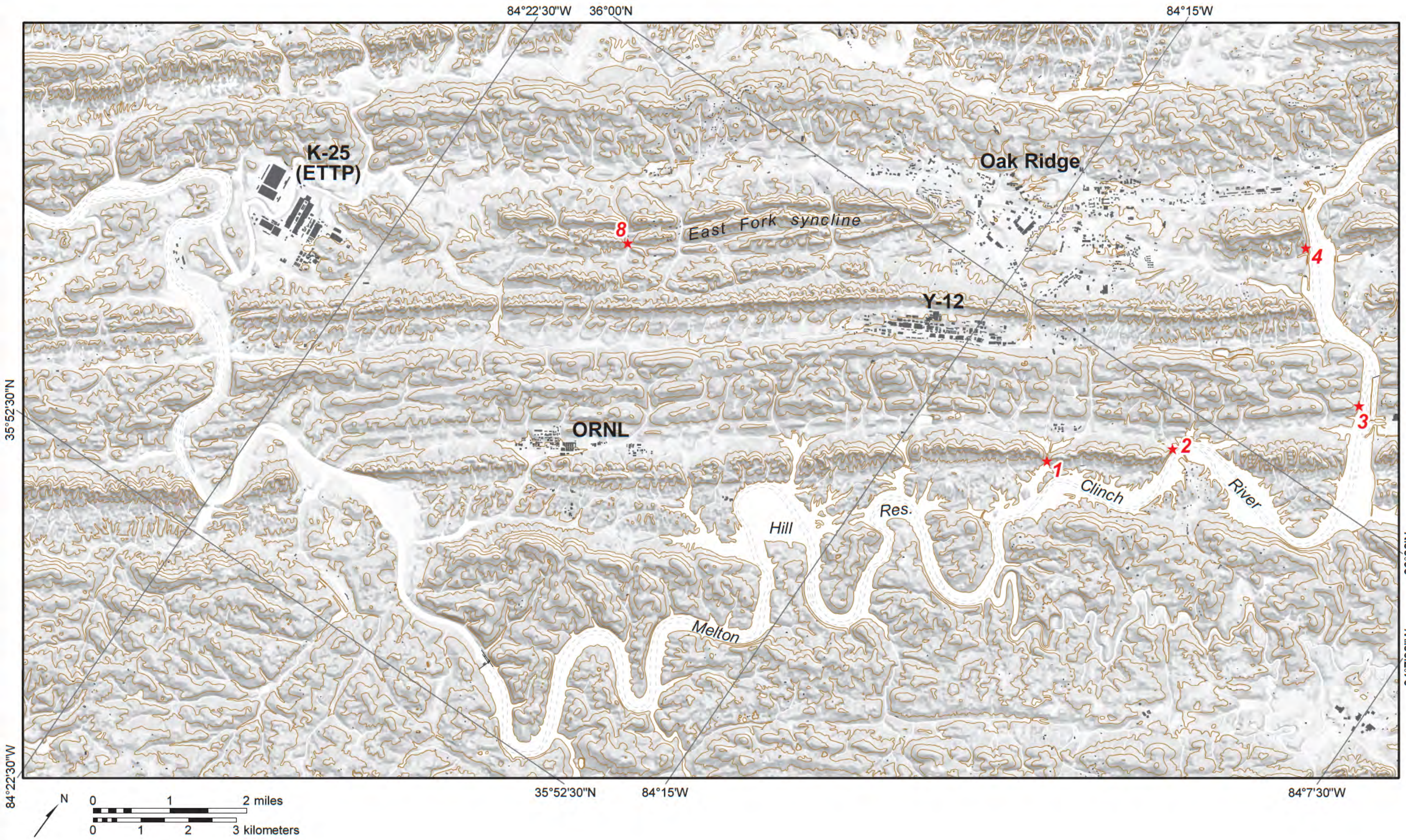


Figure 1. Topographic map of the Oak Ridge area (with shaded relief). The topography of the Oak Ridge area is typical of the Appalachian Valley and Ridge at this latitude. Narrow somewhat rugged ridges are underlain by Rome Formation sandstone, with broad rolling uplands underlain by Knox Group cherty dolomite. The ridges of the East Fork syncline are underlain by Rockwood Formation and Fort Payne chert. Limestone and shale underlie valleys. Note the straight reaches of many streams indicating local control of surface drainages by joints and faults.

amounts of shale. ORNL is similarly located in another valley underlain predominantly by limestone, but Y-12 is located in a valley underlain by mostly shale with minor amounts of limestone. Interestingly, transport of ground water contaminants occurs in all of these rock units, regardless of rock type, parallel to the trend (we call strike) of the rock units, i.e., northeast or southwest and not northwest to southeast, determined partly by the trend and inclination (dip) of the bedding in the rocks and how they intersect NE-trending natural fractures.

An important component of the geologic work that has been conducted in the ORR has been the construction of a detailed geologic map, which remains a work in progress, but is presently close to the point where it can be published (Fig. 2). In addition to constructing a detailed geologic map, a major goal of geologic studies on the ORR has been to understand the relationships between the surface and subsurface geology as we know it (Fig. 3) and the fracture systems that occur within each rock unit, which control the plumbing for ground water. This is also a major key to understanding contaminant transport not only on the Oak Ridge Reservation but also in fractured rock systems worldwide. Attempts to formulate a ground water model that can be used for the entire Oak Ridge Reservation have only been partially successful to date.

PHYSIOGRAPHY/GEOMORPHOLOGY

The ORR is located in the western portion of the Valley and Ridge geologic and physiographic province in East Tennessee (Fig. 1). In Tennessee, the Valley and Ridge Province is bordered to the west by the Cumberland Plateau and on the east by the Great Smoky Mountains. The ORR, located approximately 3 to 6 mi (5-10 km) east of the eastern Cumberland escarpment, has an elevation ranging from 740 to 1350 ft (225-410 m). The province extends from the St. Lawrence Lowlands to Alabama and varies in width from 14 to 80 miles (10-130 km). The general features that distinguish this from adjacent provinces are: (1) parallel ridges commonly oriented from northeast to southwest; (2) topography dominated by tilted alternating weak and strong rock units exposed to weathering and erosion long after folding and thrust faulting; (3) a few major streams that traverse the region with subsequent streams forming a trellis drainage pattern; (4) numerous ridges with accordant summit levels suggesting former erosion surfaces; and (5) many water and wind gaps through resistant ridges. Four rivers—the Powell, Clinch, Holston, and French Broad—join to form the Tennessee River after flowing many miles in northeast-southwest-trending valleys with headwaters in the eastern Blue Ridge of North Carolina and northeastern Georgia. These major streams have a long history of development and contain terrace deposits that are on the order of 200 ka (e.g., Hatcher et al., 2012). The fact that many tributaries of the Tennessee head on the east side of the Blue Ridge, and that the Tennessee cuts a deep gorge through the Cumberland Plateau west of Chattanooga, helps confirm the relative antiquity of these streams, but also the relative youth of the topography, contrasting with conventional wisdom that argues for the antiquity of the topography.

The Gray Fossil Site near Johnson City, Tennessee, provides a key spike in time for the age of the topography in the region. These late Miocene–early Pliocene sediments contain a diverse fauna of vertebrates and invertebrates trapped in a 6-7 million-year-old karst lake. Another critical point is the

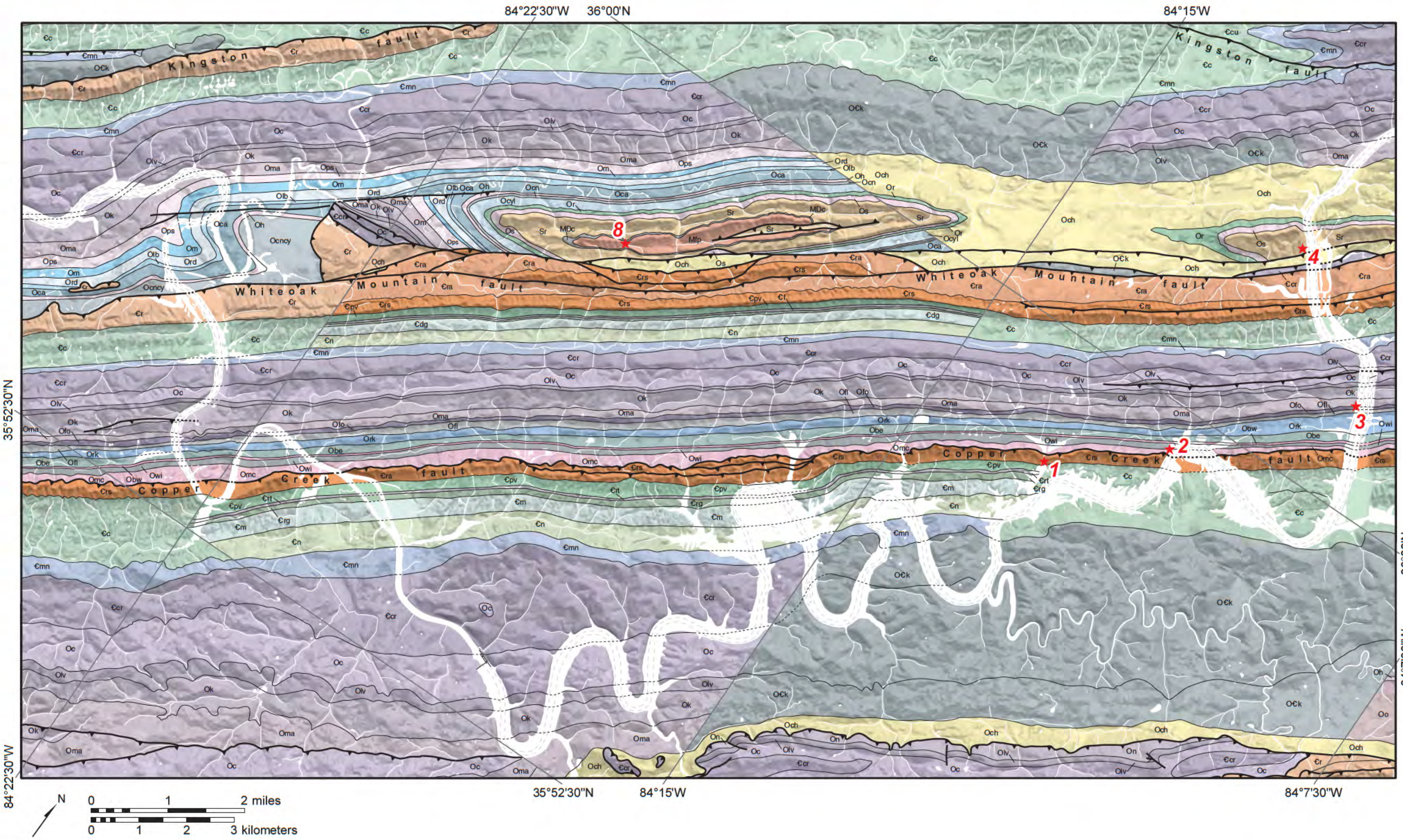


Figure 2a. Simplified geologic map of the Oak Ridge area. Explanation of map units is on the next page. Geology by Peter J. Lemiszki, Robert D. Hatcher, Jr., and Richard H. Ketelle with contributions from other maps by J. M. Cattermole (1960), W. M. McMaster (1962), G. D. Swingle (1964), J. W. Jewell (1996), and unpublished data from Richard R. Lee, C. N. Pruitt, G. G. Nalewaik, and R. C. Milici.

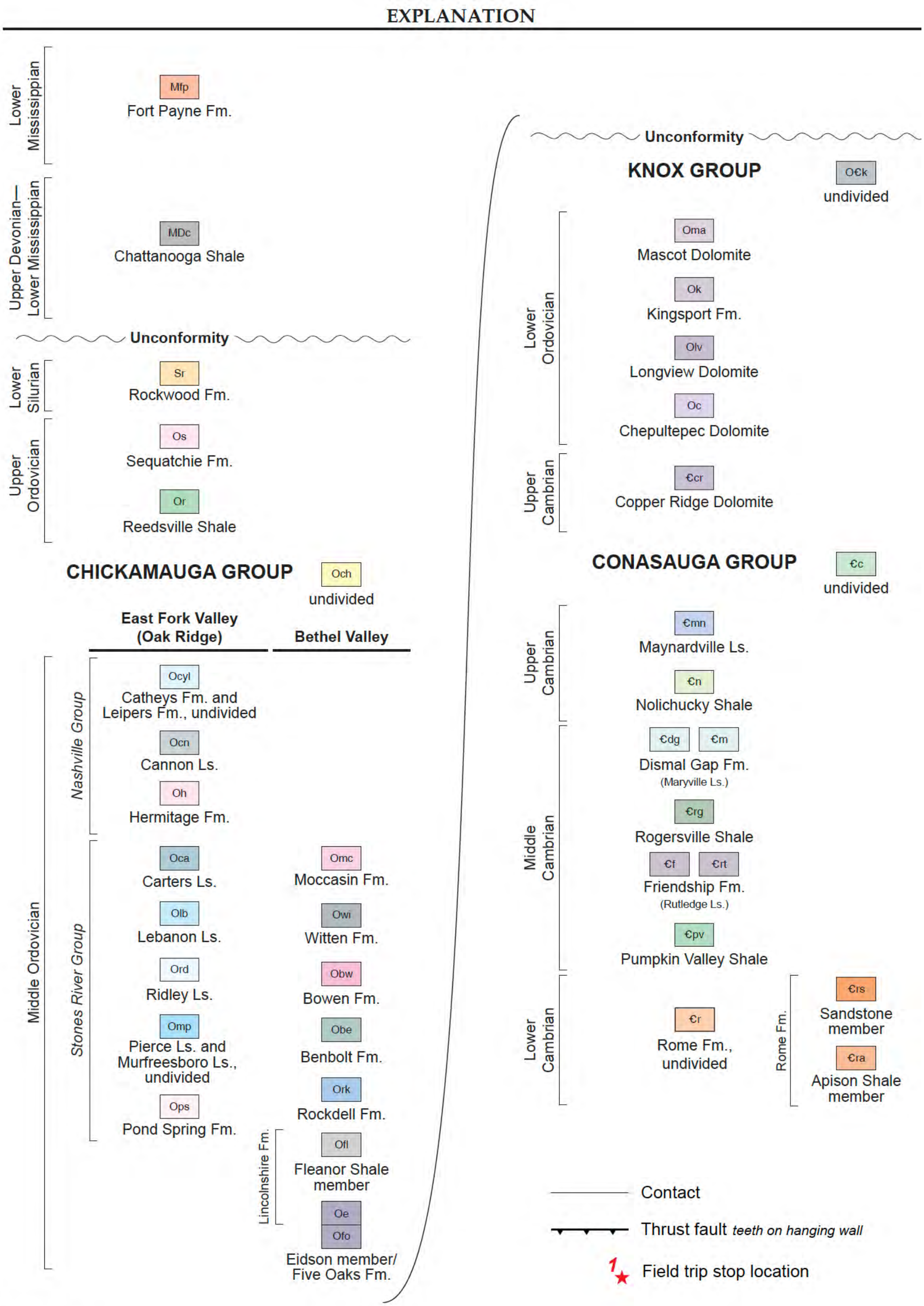

EXPLANATION
Lower Mississippian
Mfp
Fort Payne Fm.
Upper Devonian—Lower Mississippian
MDc
Chattanooga Shale
Unconformity
Lower Silurian
Sr
Rockwood Fm.
Upper Ordovician
Os
Sequatchie Fm.
Or
Reedsville Shale
CHICKAMAUGA GROUP
Och
undivided
East Fork Valley (Oak Ridge)
Bethel Valley
Middle Ordovician
Nashville Group
Ocyl
Catheys Fm. and Leipers Fm., undivided
Ocn
Cannon Ls.
Oh
Hermitage Fm.
Stones River Group
Oca
Carters Ls.
Olb
Lebanon Ls.
Ord
Ridley Ls.
Omp
Pierce Ls. and Murfreesboro Ls., undivided
Ops
Pond Spring Fm.
Omc
Moccasin Fm.
Owi
Witten Fm.
Obw
Bowen Fm.
Obe
Benbolt Fm.
Ork
Rockdell Fm.
Lincolnshire Fm.
Ofl
Fleanor Shale member
Oe
Ofo
Eidson member/ Five Oaks Fm.
Unconformity
KNOX GROUP
O€k
undivided
Lower Ordovician
Oma
Mascot Dolomite
Ok
Kingsport Fm.
Olv
Longview Dolomite
Oc
Chepultepec Dolomite
Upper Cambrian
€cr
Copper Ridge Dolomite
CONASAUGA GROUP
€c
undivided
Upper Cambrian
€mn
Maynardville Ls.
€n
Nolichucky Shale
Middle Cambrian
€dg
€m
Dismal Gap Fm.
(Maryville Ls.)
€rg
Rogersville Shale
€f
€rt
Friendship Fm.
(Rutledge Ls.)
€pv
Pumpkin Valley Shale
Lower Cambrian
€r
Rome Fm., undivided
Rome Fm.
€rs
Sandstone member
€ra
Apison Shale member
Contact
Thrust fault teeth on hanging wall
1
Field trip stop location

Figure 2b.

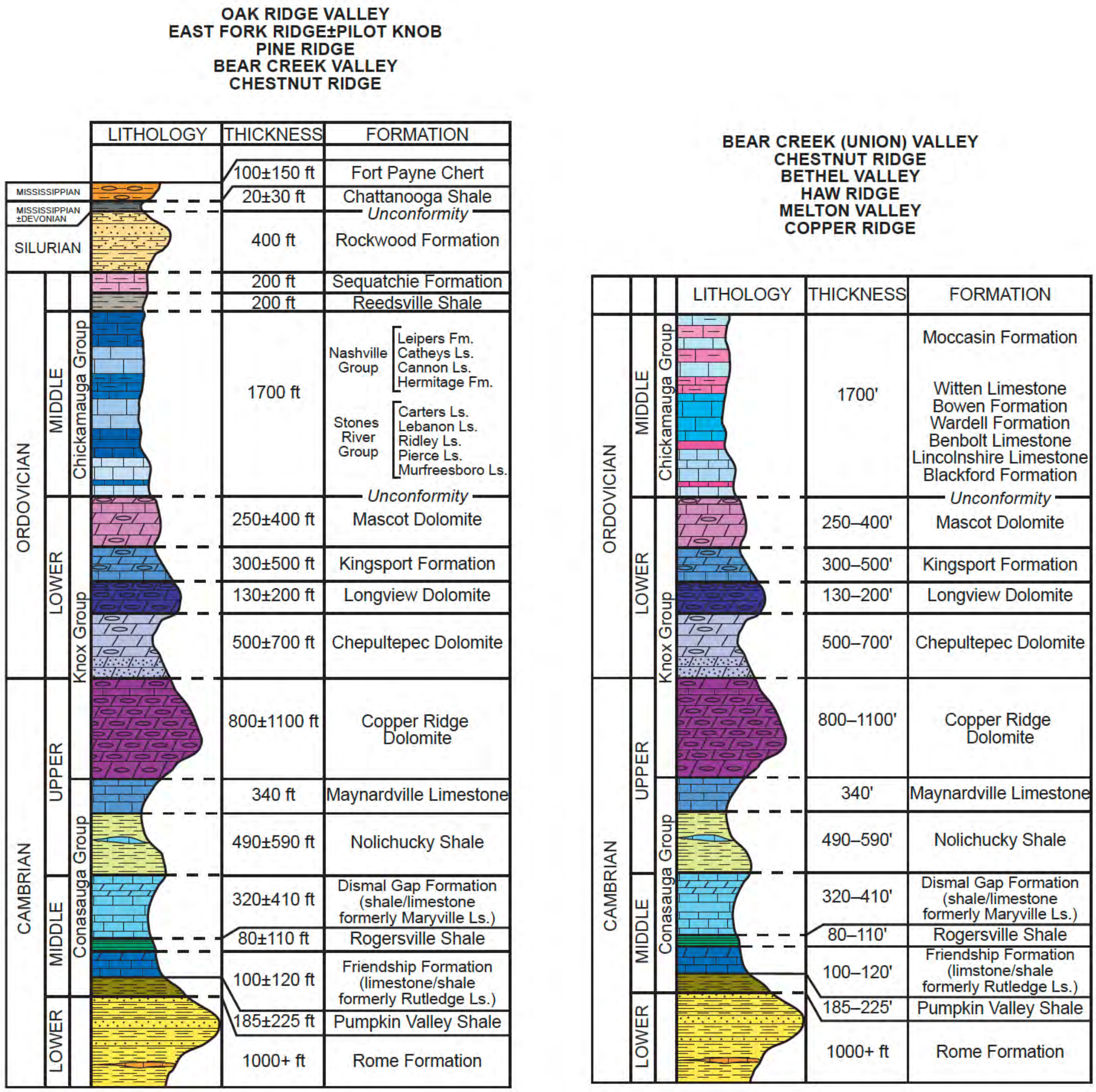


Figure 3. Stratigraphy of the Oak Ridge area. The column on the left is the stratigraphy in the NW of the Whiteoak Mountain fault. Note that it is the same until Middle Ordovician time, then it contrasts with that NW of the Copper Creek fault. The topographic expression of the rock units can be seen if you rotate the diagram 90° counterclockwise, e. g., the Rome Formation and lower Knox Group form ridges, the Middle Ordovician limestones form valleys. Also note that these vertical columns were constructed by removing any tilting and repetition by faulting or folding.

hilltop location of the Gray Site some 200 ft (70 m) above the nearest stream, confirming the topography is inverted. Deep incision of the Tennessee River west of Chattanooga, and its tributaries in the Blue Ridge, may indicate this topography is also < 7 m.y. old.

GEOLOGIC SETTING

The Oak Ridge area is located in one of the classic segments of mountain chains worldwide that contains a large assemblage of folds and thrusts faults (Fig. 4) that were formed by compression. Similar components of mountain chains called "foreland fold-thrust belts" occur in the Montana and Canadian Rockies, the Andes, Alps, Scandinavian Caledonides, and in other major mountain chains (Fig. 5). The intriguing fact about the geologic structures that occur in these segments is that the faults propagate horizontally within a weak sedimentary rock layer parallel to the layering in the rocks and then refract across strong rock sequences either to the surface or to higher zones of weakness in the sedimentary rocks that make up these belts. This left the ancient "basement" beneath these sedimentary rocks undeformed. Even more intriguing is the fact that all of the faults in the valley of East Tennessee formed in response to Blue Ridge and Piedmont crust forming an immense slab that was pushed westward some 400 or more miles (600 km) during the collision between Africa and North America ~300 Ma, like a snowplow pushing snow in front of it.

Prior to the deformation described above, the sedimentary rocks that we see exposed today were deposited on an ancient continental margin beginning ~520 Ma following the breakup of supercontinent Rodinia (~750 Ma) in the same way the modern continental margin of the East Coast formed as Africa moved away from North America and Atlantic Ocean crust filled the space between them following the breakup of supercontinent Pangea ~200 Ma. Deposition of sedimentary rocks occurred from 520 Ma until ~475 Ma when all of eastern and central North America were uplifted above sea level and an extensive sinkhole (karst) topography developed on the limestone surface that had been deposited shortly before. The assemblage of sedimentary rocks that make up the present-day Valley and Ridge consists of shale, sandstone, and some carbonate rocks that were deposited in very shallow water with a source of mud and sand from the interior of the continent. Limestone and dolostone (calcium-magnesium carbonate) are more abundant in the sediments toward the east, again confirming the continental interior as the source of the mud and sand deposited in the same rock units farther west. An immense deposit of limestone and dolostone formed on top of these older shales and limestone that extended across all of eastern and central North America. Uplift of the entire interior then occurred ~475 Ma following deposition of more than 1 km of limestone and dolomite. After formation of the sinkhole-dominated surface across eastern and central North America, the region subsided once more ~465 Ma and limestone deposition resumed (Fig. 6). At this time, carbonate deposition was interrupted along the eastern margin of North America by development and collision of a volcanic island arc system that formed offshore and was then pushed onto the North American margin, producing the first new mountains of the Appalachian cycle. This event is called the Taconic orogeny, and erosion of these new mountains shed sediments to the west onto the continental margin, causing it to subside and force shallow-water carbonate sedimentation to retreat farther and farther west (Fig. 7). The basin that formed to the east accumulated some 10,000 feet (~3 km) of mud and sand that was eventually deposited far enough westward (in the present-day Knoxville area) to kill the reefs composed of primitive bryozoans and other invertebrates. The reef deposits became the Tennessee "marble" that has been mined for

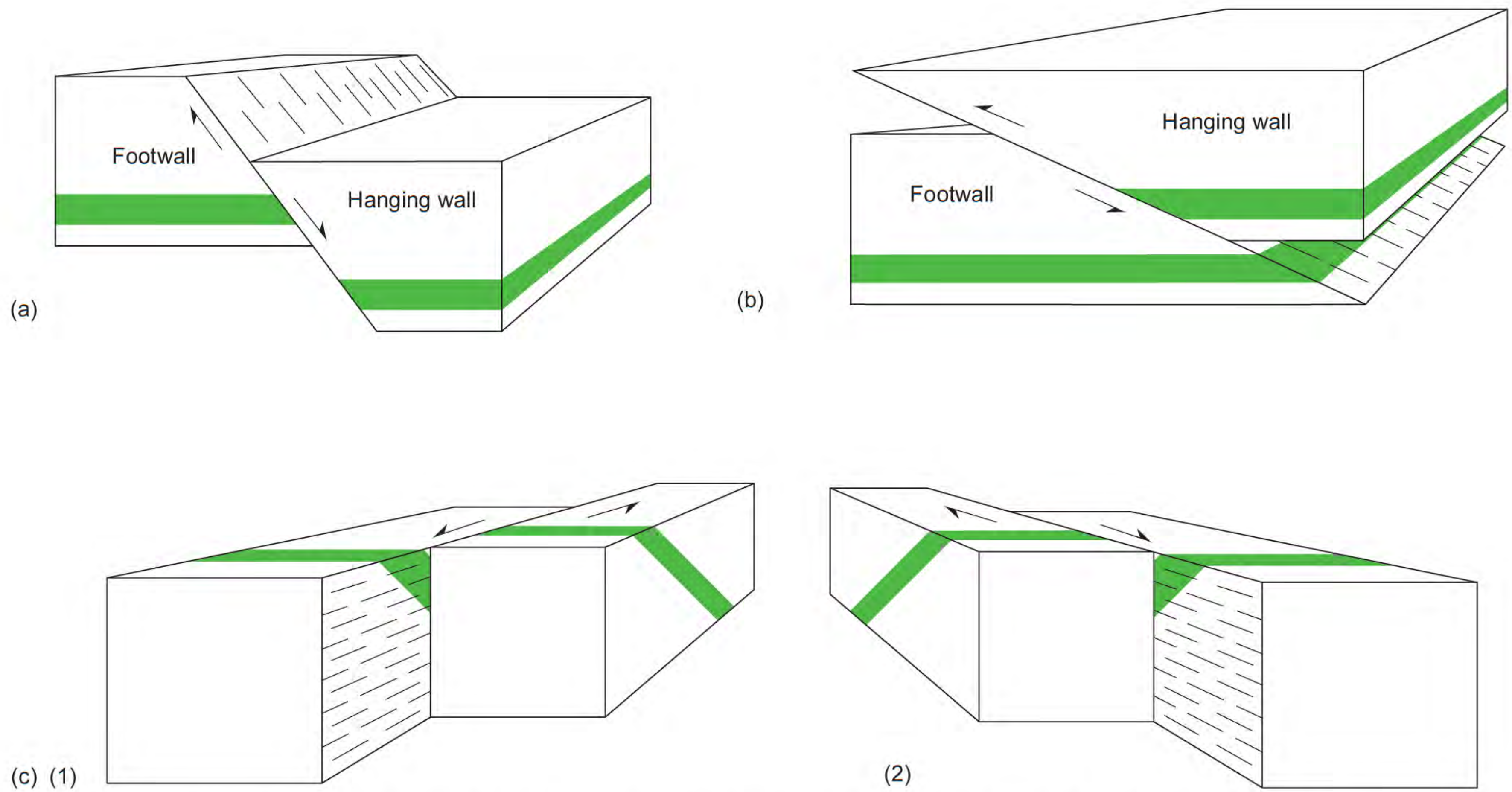


Figure 4a. Different classes of faults. (a) Normal fault. (b) Thrust fault. (c)(1) Left-lateral strike-slip fault. (c)(2) Right-lateral strike-slip fault.

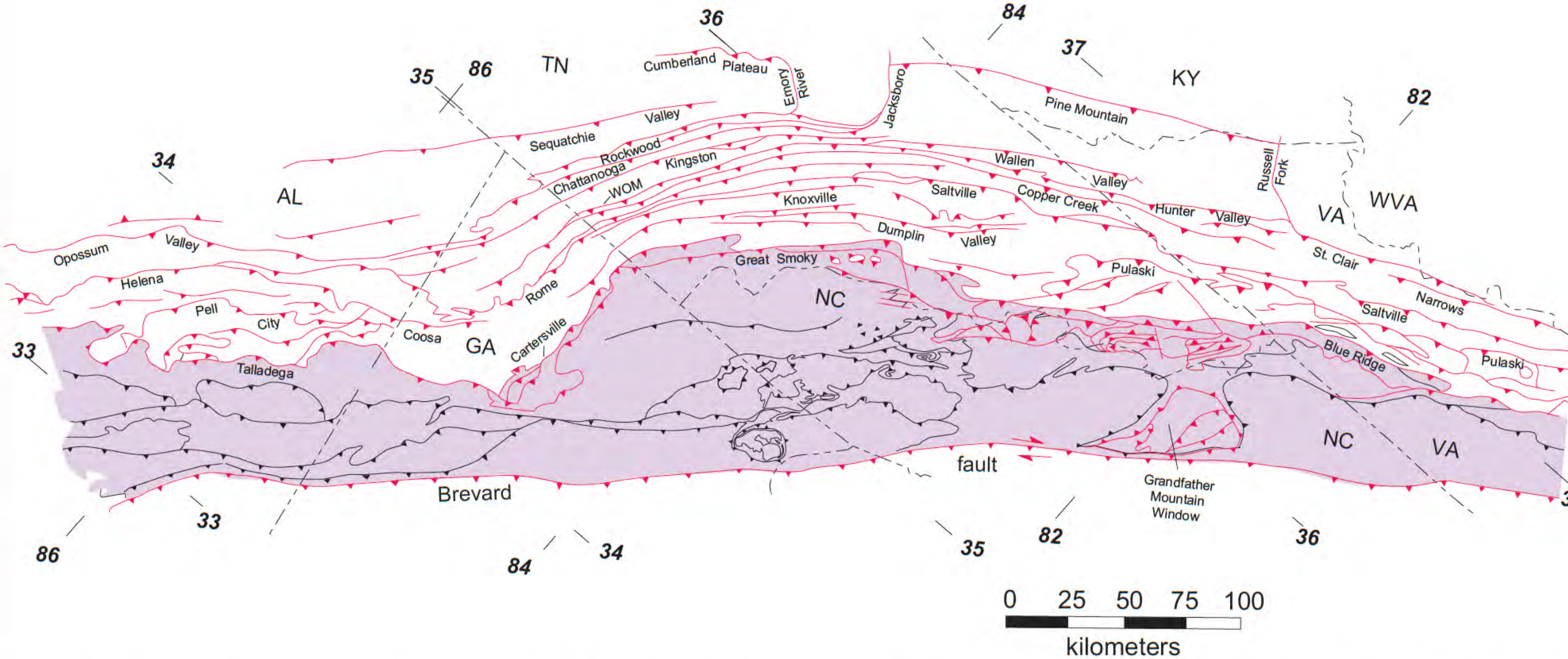


Figure 4b. Simplified tectonic map of the western half of the southern Appalachians. The lavender-colored area is the Blue Ridge. Thrust faults have teeth on the hanging wall. Red faults formed during the Alleghanian orogeny. Black faults formed in the Taconic or Neoacadian orogenies. WOM–Whiteoak Mountain fault.

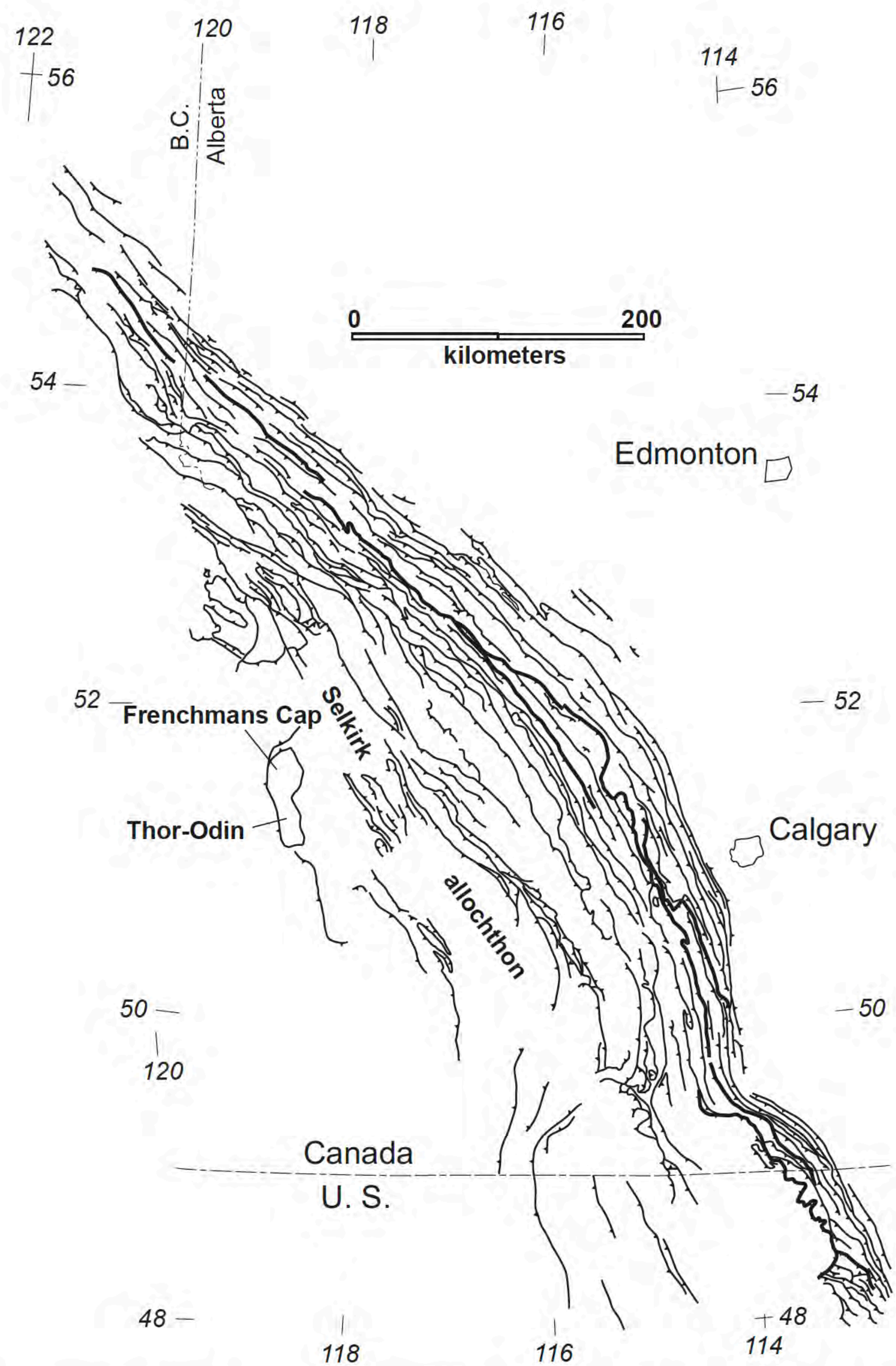


Figure 5. Map of the Alberta-British Columbia foreland fold-thrust belt. Bold line represents the approximate boundary between the Foothills and Rocky Mountains. From Hatcher (2005).

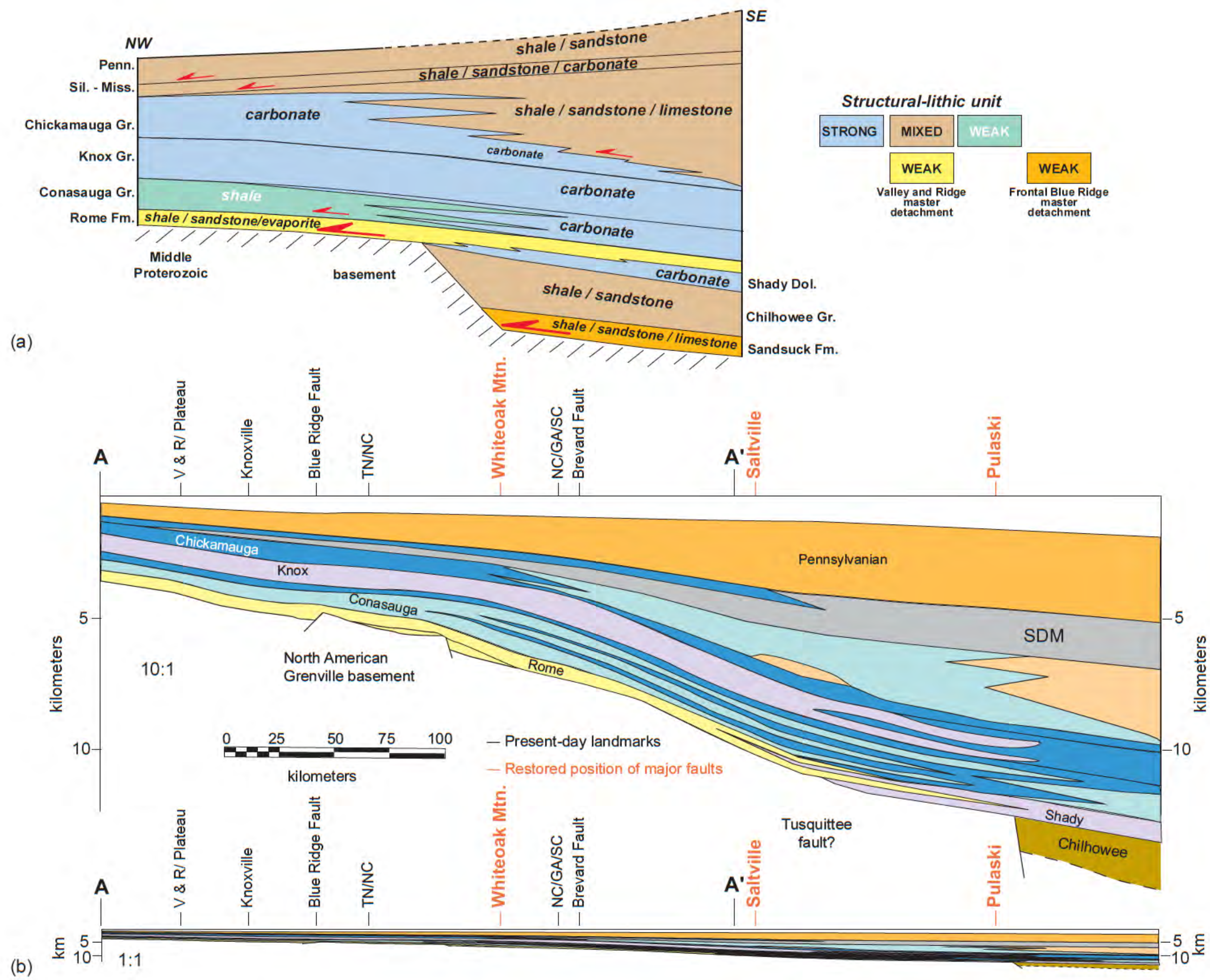


Figure 6. (a) Simplified restored stratigraphic section through the Tennessee Valley and Ridge and Plateau. Dip section showing location of future faults, and locations of strong and weak units based on changes in rock type in the depositional sequence. Red arrows indicate regional weak units along which future thrust faults propagated. (b) Retrodeformed diagram across the Tennessee Valley and Ridge and Plateau approximately at the latitude of Knoxville, Tennessee, reconstructed by pulling apart major faults and regional changes in rock type boundaries. The Pulaski fault is projected southward into the section. Blue–limestone facies. Lavender–dolomite facies. Green–shale facies. Light orange–coarse clastics and turbidites. Gray–siltstone facies. Light yellow–sandstone, shale and dolomite intertidal facies. SDM–Silurian, Devonian, and Mississippian rocks. From Hatcher et al. (2007a)

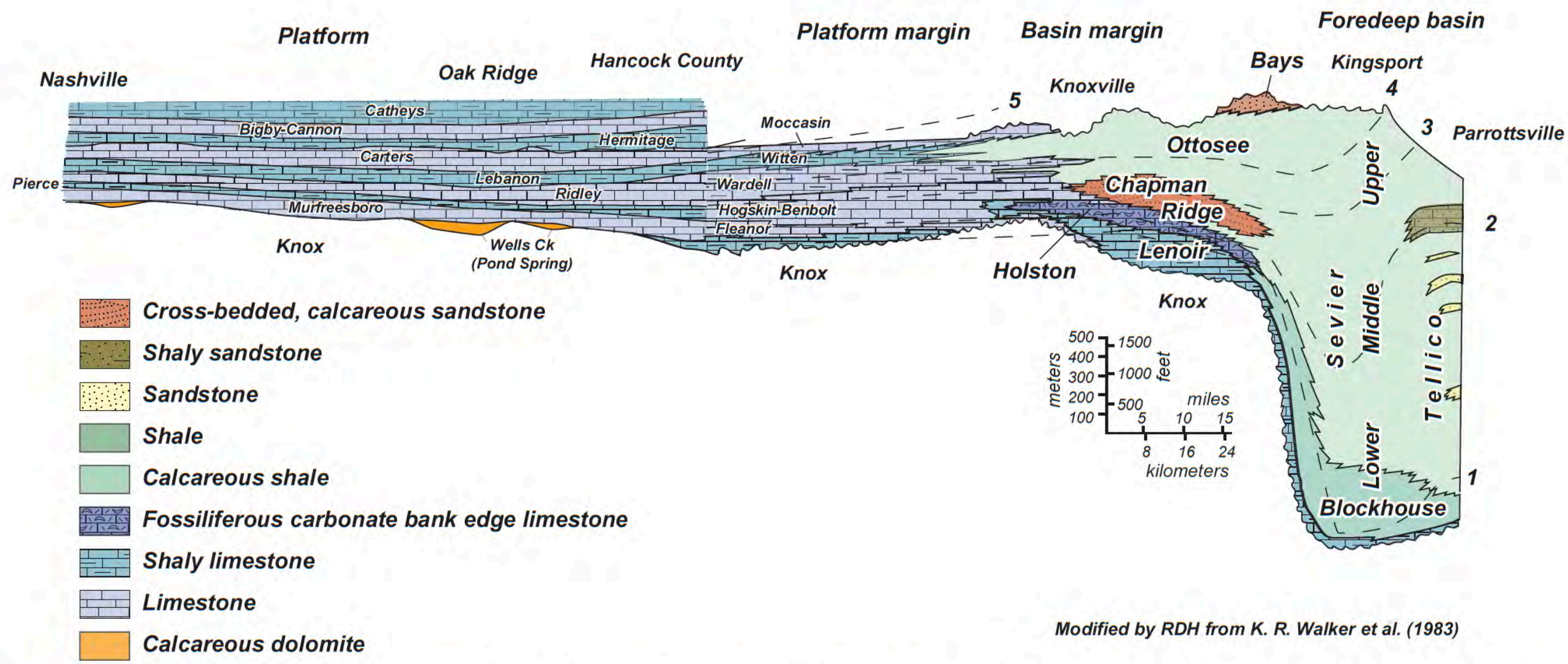


Figure 7. Stratigraphic reconstructions, removing all of the later faults and folds and returning the rocks to the original horizontal orientation in which they were deposited, of the Middle Ordovician rocks from Nashville to near Sevierville. Note the enormous change in thickness that takes place to the SE. Also, the nature of the rocks changes from a 700 m-thick limestone section to the NW to a 3,000 m-thick shale and sandstone section to the SE. Lines of the same age (numbered 1, 2, . . . —isochrons, lines of equal time) are dashed. The Moccasin Formation limestone at Stop 2 is equivalent to the Bays Sandstone farther east and NE (e.g., Bays Mountain State Park near Kingsport). The names are formation names. (Modified from numerous published papers by K.R. Walker and his graduate students by recent work by our group.)

decades and used as a building stone throughout the eastern U.S. and Canada.

Limestone deposition continued to the west until ~443 Ma while sand and mud derived from the east covered much of the area adjacent to the Taconic Appalachians. The sandy material in places was a very clean beach sand that became the Clinch sandstone (called Tuscarora in Pennsylvania) and today forms House Mountain in Knox County and Clinch Mountain farther northeast. We see a more shaly but still sandy and somewhat hematite-rich equivalent of this sandstone, the Rockwood Formation, in the Oak Ridge area where it is exposed on Melton Lake Drive (Stop 3). These deposits comprise the last erosional remnants of the Taconic mountains that existed from Georgia to Newfoundland. There were some deposits of limestone and shale above this unit, but the history is incomplete because the region was uplifted and remained above sea level until ~360 Ma when the sea covered the region again from Tennessee to Pennsylvania. For reasons we don't completely understand, the sea bottom involved very poor circulation with almost no oxygen available for organisms or movement of sediments. This permitted abundant organic matter to accumulate on the seafloor and not be destroyed by oxidation. This became the Chattanooga black shale in Tennessee and its equivalent in Kentucky, where farther north it is the slightly older Marcellus Shale—a prolific source of natural gas.

On the eastern margin the black shales give way to more sand and cleaner mud that became sandstone and shale, forming a great delta that was sourced from the east, indicating the formation of a second great mountain range along the eastern North American margin. This mountain range is the product of collision of a land mass consisting of even more ancient volcanic arc crust (formed from 625–550 Ma) that formed close to Africa and Europe. We call this small continent "Avalonia," but we see similar remnants of this volcanic arc system in western Europe, South America, and Africa, where they collectively are referred to as peri-Gondwanan or Pan African volcanic arcs that formed at the same time. From depositional patterns that produced older sediments in the northern Appalachians, we have concluded that the collision of Avalon with North America began in the north and rotated, producing a zippered closing of the intervening ocean so that younger sediments were deposited farther south (Merschat and Hatcher, 2007) (Fig. 8). We call this collisional event the Acadian/Neoacadian orogeny (407–350 Ma).

The final Appalachian mountain-building event was the collision of Africa with North America that produced a mountain chain that would rival today's Himalayas in height and extent and it similarly involved a doubled crust. This collision initially involved pieces of crust that moved southward out of the collision zone but then collided head-on to produce the huge mass of crust that moved horizontally up onto southeastern North America (Fig. 9), producing the folds and faults that we see today in the Valley and Ridge from Alabama to southern New York. We call this event the Alleghanian orogeny (it was called the "Appalachian Revolution" in the older literature). Uplift of the chain resulted in erosion that shed sediments into an enormous delta along the western flank of the Appalachians that extended from Alabama to eastern Canada and as far westward as Illinois, Missouri, and Kansas. Deformation in the collision zone produced faults that are older in the north and in the interior parts of the mountain chain that pushed blocks of crust southwestward as Africa apparently collided first in the north and then began to rotate as it was moving southward, and then collided head-on from southern New York southward to Alabama, producing the Valley and Ridge and extensive thrust faults and folds that we see here (Fig. 9). This was another zippered closing of an ocean (Hatcher, 2002). This event completed the lengthy history of the Appalachians, which involved amalgamation of a variety tectonic components in the Taconic, Acadian-Neoacadian, and Alleghanian orogenies to form supercontinent Pangea (Fig. 10).

The Appalachian chain was deeply eroded with debris filling basins that had begun to form some 220 Ma immediately prior to the breakup of Pangea, which occurred ~200 Ma. Opening of the Atlantic Ocean occurred from south to north, in contrast to the zippered collision process that formed Pangea (Fig. 9). The Appalachians continued to erode until some 140 Ma (Late Jurassic) when carbonates were deposited on the continental margin and in the Gulf of Mexico region. Carbonate deposition continued to ~80 Ma when uplift occurred once more, and sand and mud accumulated along the eastern margin and Gulf. The highlands were again eroded to a topography that probably looked like today's Piedmont and some carbonate deposition resumed until ~7 Ma when the chain was uplifted again (by an unidentified mechanism), producing the present high topography in the southern Appalachians and New England.

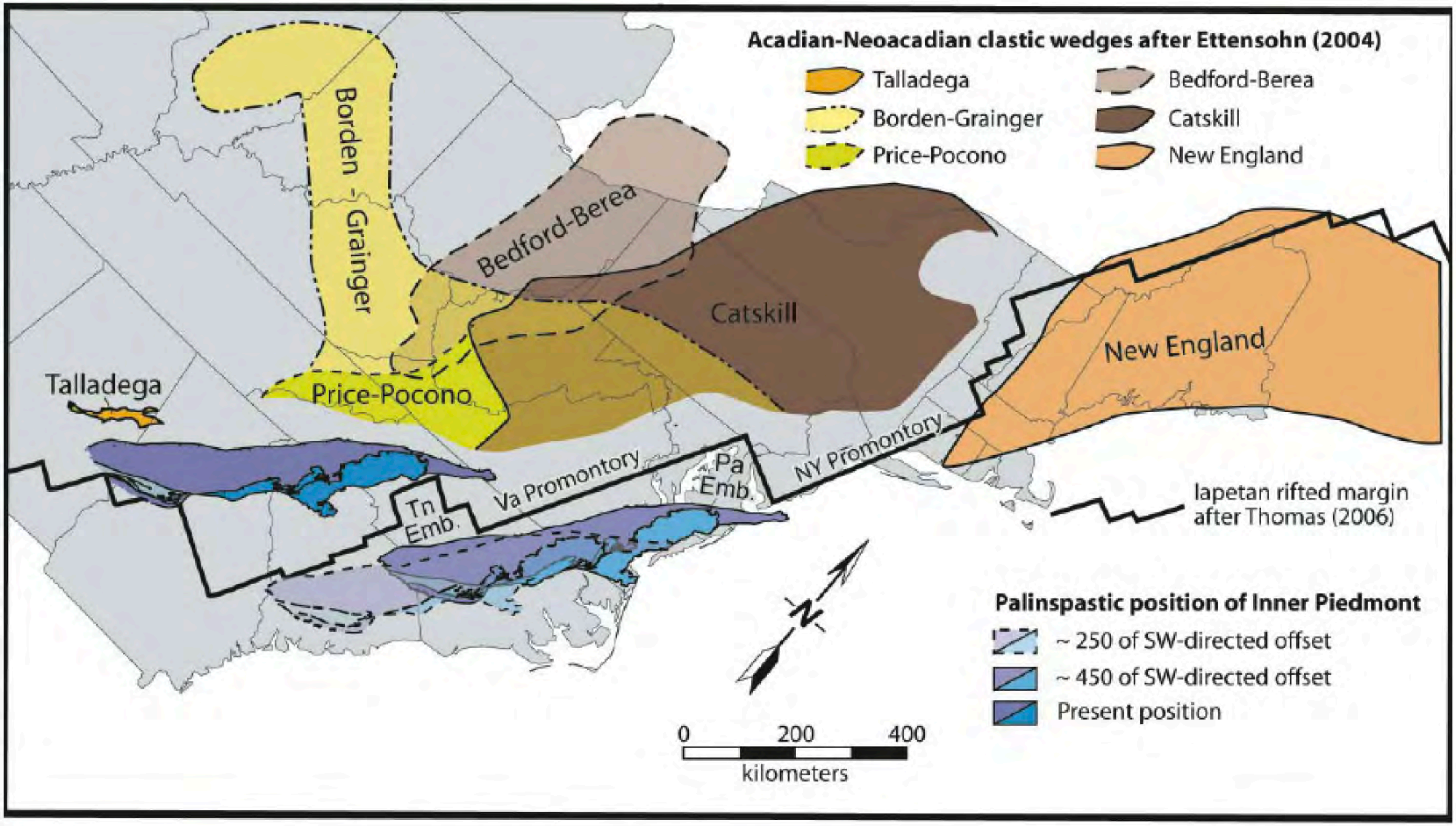


Figure 8. Palinspastic location of the Inner Piedmont and distribution of major delta complexes of the Acadian-Neoacadian clastic wedge. Locations and shape of clastic wedges are from Ettensohn (2004), and Iapetan rifted margin (solid jagged black line) is from Thomas (2006). Emb.—embayment.

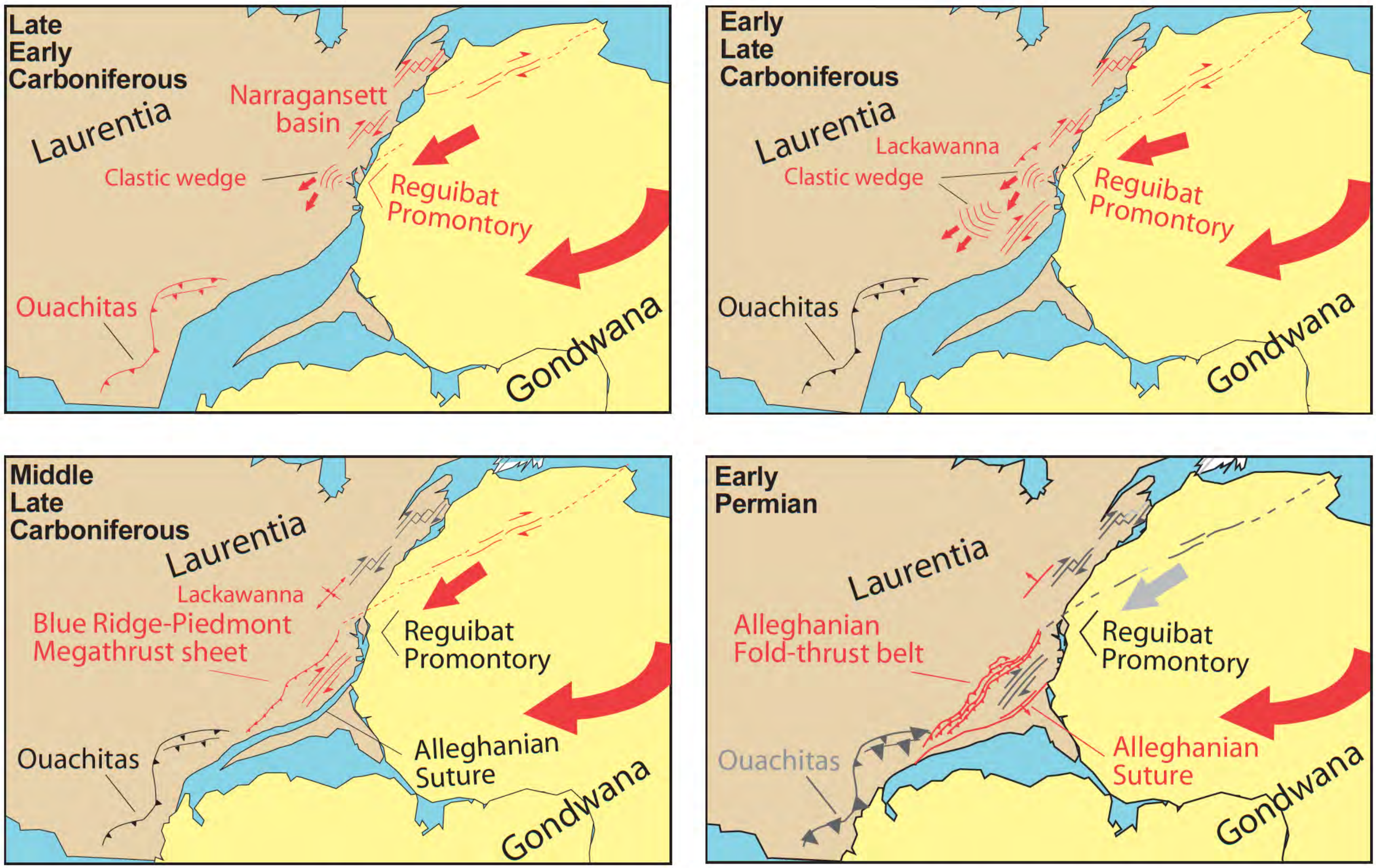


Figure 9. Rotational oblique, then head-on collision of Gondwana (Africa and other continents) with Laurentia during the Carboniferous and Permian forming the supercontinent of Pangea. Note the formation of the thrust system in the southern Appalachians is one of the last events, so the deltaic deposits that formed during the Pennsylvanian today preserved in the Cumberland Plateau actually became deformed as faults and folds propagated into the delta. From Hatcher (2002)

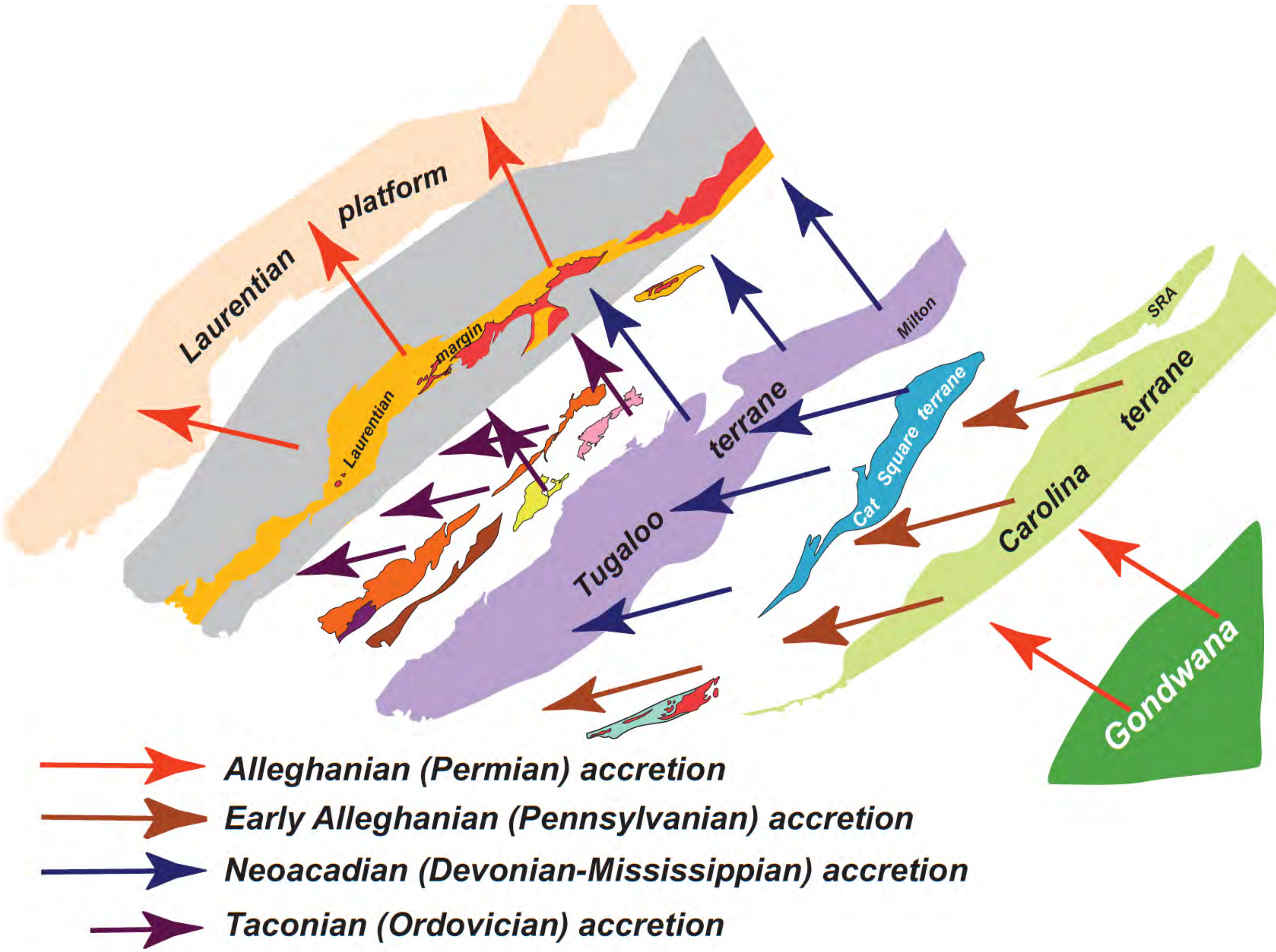


Figure 10. Southern Appalachian tectonic blocks terranes moved back to show the directions from which they moved to where they are today. Arrows indicate broad transport directions. From Hatcher et al., (2007b)

FIELD TRIP GUIDE

This field trip is intended to illustrate several of the rock units and features of regional importance that exist in the Oak Ridge area (Figs. 2 and 11). The locations of field trip Stops 1 through 8 are indicated in Figure 11.

STOP 1— Rome Formation and Conasauga Group Rocks at Clark Center Park [OPTIONAL STOP]
GPS Location: 35.976867° N 84.219233° W

The Conasauga Group is the primary unit used for waste disposal in Bear Creek Valley (Y-12) and in Melton Valley (ORNL). The section in Clark Center Park contains the best continuously exposed section of Middle to Upper Cambrian Conasauga Group and Lower Cambrian Rome Formation rocks in the area. The Conasauga Group here consists dominantly of shale (westward source, more limestone to the east) with some interbedded limestone in particular parts of the section. The uppermost units in the Conasauga, the Maynardville Limestone and Nolichucky Shale, are not exposed in this section and will not be seen on the field trip. The Rome Formation exposed in Clark Center Park is typical of the region, consisting of multicolored, greenish-gray, maroon, reddish-brown, and gray shale and siltstone interbedded with sandstone, with intermittent dolomite beds. We will see very representative rocks of the Rome Formation at Moores Gap Church (Stop 5), and hence the intention to make this an optional stop. This is a very good stop to explore in the spring and summer during a picnic and short hike in Clark Center Park.

Overlying the Rome is the Pumpkin Valley Shale, which lithologically is the same as the Rome Formation (mostly variegated shale) without the dolomite and ridge-forming sandstone. The Friendship Formation (Rutledge Limestone equivalent) consists of greenish-gray shale interbedded with thin to medium-bedded limestone. To the southeast the Rutledge consists of a major limestone unit in the Conasauga that contains little shale. The Friendship Formation is exposed in the southeasternmost parts of the Park, along with the overlying Rogersville Shale. The Rogersville consists of greenish-gray shale with possibly a thin sequence of limestone that may represent the western extent of the Craig Limestone Member of the Rogersville. It is not exposed in this section, although some Rogersville is probably exposed that we will not visit.

Overlying the Rogersville Shale is the Dismal Gap Formation (Maryville Limestone to the southeast). This unit here consists of interbedded shale and limestone, and is probably located beneath Melton Hill Lake. The Nolichucky Shale overlies the Dismal Gap Formation; it consists of olive green, reddish brown, and brown shale with minor interbedded limestone. The Nolichucky is well exposed in the Clark Center Park section. The Nolichucky is one of the most persistent units in the Conasauga, and can be mapped throughout East Tennessee below the Maynardville Limestone and above the Dismal Gap Formation.

The regional significance of these two units is: the ~520 Ma Rome can be recognized with different names from Alabama (Rome Fm.) to northern Virginia and Maryland-Pennsylvania (Waynesboro Fm.) to Vermont (Winooski Fm.) to Newfoundland, where it was deposited under identical intertidal conditions, reflecting the evolution of the Cambrian continental margin of eastern North America. The Rome and equivalents become more carbonate rich to the east. The overlying Conasauga contains a more complex intertonguing relationship of shale and limestone, but similar units occur throughout the eastern margin of Laurentia. Remarkably, shale and limestone similar to the Conasauga that were deposited at the same time occur in the western U.S. and western Canada, and they contain the same fossils.

STOP 2—Chickamauga Group (and Rome Formation) at Solway Bridge
GPS Location: 35.992214° N 84.195985° W

The rocks at Stop 2 dip uniformly toward the southeast. Chickamauga Group rocks exposed at Stop 2 consist of thin- to thick-bedded medium-gray limestone typical of the upper part of the Chickamauga Group in

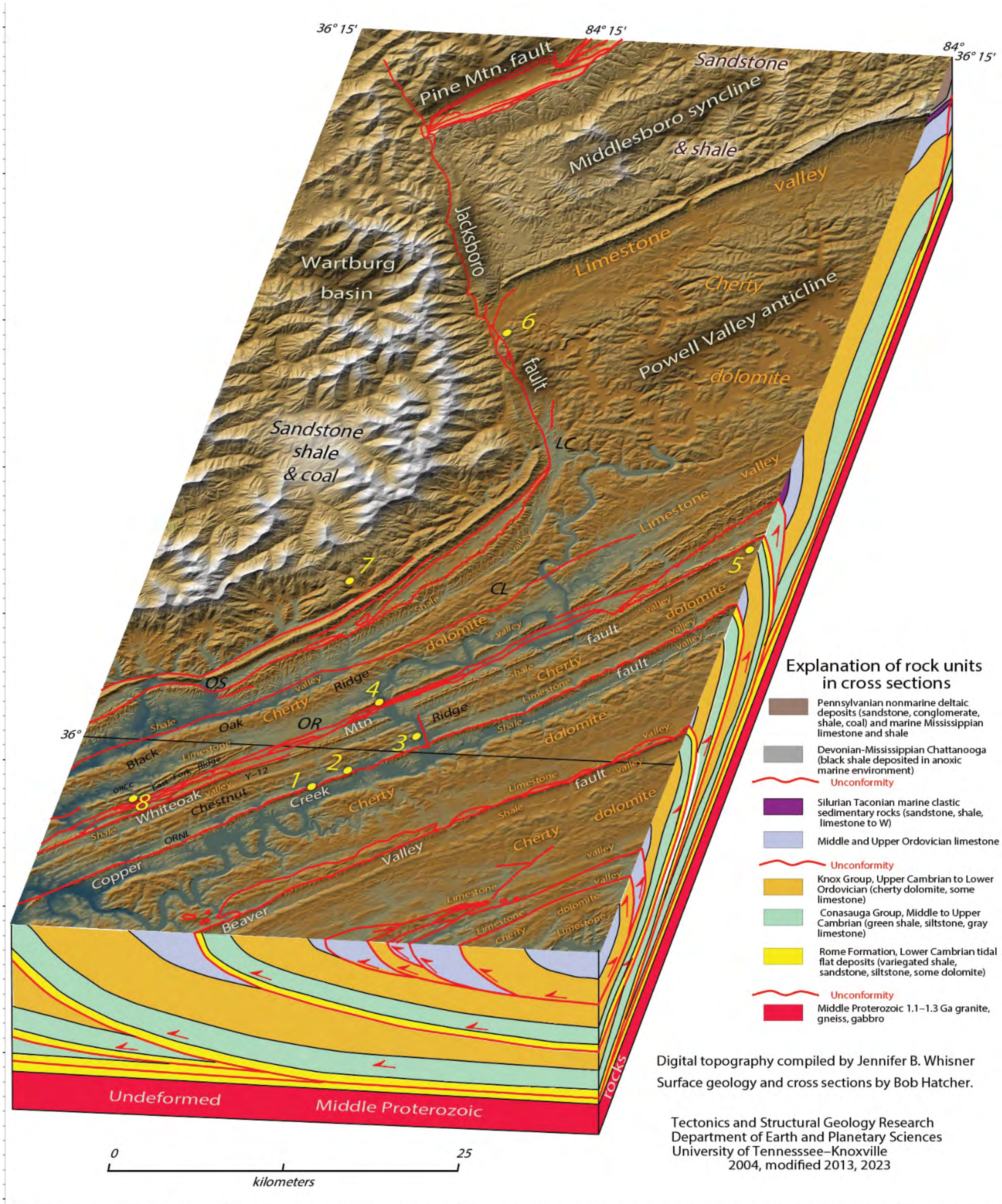


Figure 11. Block diagram showing the relationships between surface topography and subsurface bedrock geology in the vicinity of Oak Ridge, Tennessee. Note that the subsurface consists of a series of gently SE-dipping thrust faults that repeat the same rock units several times, indicated by repetition of the same colors, above undeformed crystalline (igneous and metamorphic) "basement" rocks (red).

Bethel Valley, and belong to the Witten and Moccasin Formations. One of the redbed units below the Witten (the Bowen Formation) is present but not well exposed in the cut across the road from the main exposure. The limestone on the NW side of the Edgemoor Road ramp is very fossiliferous, containing a variety of shallow-water invertebrates (Fig. 12). Most of the limestone in the Witten and Moccasin is micritic (very fine uniform grain size), but frequent zones of fossil hash are also present producing coarsely crystalline biosparite. Burrows are also present here.

Dip slopes in the lower Witten Formation exposed on the northwest side of the road expose an abundant fauna of brachiopods, trilobite fragments, bryozoans, and ostracodes. The unit locally contains abundant fossils on the southeast side of the road, but the fossils are more difficult to observe or collect because the exposure is not a dip slope.

Most of the Moccasin Formation is present at Stop 2. The Moccasin contains a very thin (4–6 m) but distinctive maroon-gray calcareous siltstone and shale overlain by more than 75 m of limestone, nodular limestone, and calcareous siltstone. The uppermost Moccasin consists of gray, olive, and maroon-gray limestone and calcareous siltstone with occasional fossiliferous and burrowed horizons.

This unit is truncated on the southeast by the Copper Creek fault, exposed toward the top of Haw Ridge (not at road level) near Solway Bridge where it crosses Melton Hill Lake. The fault truncates the Moccasin at a low angle and thrusted the Lower Cambrian Rome Formation over the Upper Ordovician Moccasin.

The regional significance of these exposures is: they represent shallow-water deposition of lime mud with only minor and intermittent influx of clay-rich sediment. At the same time farther southeast (today's Dandridge to Sevierville area) large amounts of sand and mud were being deposited in deep water as the sediment built up on the edge of the source area, became unstable, and flowed into the basin as submarine landslides (turbidity flows). This sand and mud became the 3 km of thick sediment in the basin (there), while only 700 m of shallow-water limestone was being deposited on the shelf (here).

STOP 3—Top-of-Knox unconformity at Edgemoor Road–Melton Lake Drive intersection
GPS Location: 36.018343° N 84.166181° W

The rocks exposed here consist of thin to medium-bedded limestone, some of which is conglomeratic, of the Chickamauga Group overlying massive fine-grained dolostone of the upper Knox Group (Fig. 12). The Chickamauga Group rocks belong to the Blackford Formation and consist mostly of carbonate-cemented erosional debris from the ancient uplifted Knox karst surface. Interesting red (jasper) and other colors of chert fragments occur here that were derived from erosion of the Knox Group rocks below. John Repetski (USGS) collected samples of carbonates from both sides of the boundary, separated the fossils by dissolving the limestone, and determined that the Knox here has an age of 475 Ma, while the overlying rocks have an age of 467 Ma, so there are 8 m.y. missing on the erosional boundary between the two units (Fig. 13).

The regional significance of this exposure is: this boundary has been recognized throughout eastern and central North America, as far west as the Franklin Mountains near El Paso, Texas and in Utah, then northward into eastern Canada where it is present at the northeastern limit of the Appalachians in Newfoundland. The origin of this erosion surface is attributed in many published papers (likely some of RDH's as well) to loading of the eastern margin of North America at this time by volcanic arcs that formed at this time, along with some ocean crust and mantle. The load pushed the crust down in the area of the stack of volcanic materials and ocean crust, which caused the crust to rise up farther into the continent. This relationship can be proved mathematically and has been successfully modeled in computers. However, the fact that the unconformity is so widespread (it even occurs in Morocco) makes it unlikely that the loading hypothesis is correct, and the cause likely is related to some more deep-seated mantle process that we cannot easily conceptualize or reconstruct.

Figure 12. Limestone sample from Stop 2 containing abundant invertebrate fossils.

STOP 4—Silurian (~440 Ma) Rockwood Formation on Melton Lake Drive
GPS Location: 36.041550° N, 84.200833° W

This exposure is made up of a variety of sedimentary rock types, which are the equivalents of the rocks that are responsible for holding up House Mountain in Knox County and Clinch Mountain farther northeast (as well as the prominent ridges from Virginia to Pennsylvania where it is called the Tuscarora Sandstone). Here, however, instead of one dominant rock type, there is a mixture of shale sandstone, and red oölitic iron ore (hematite). In central Tennessee the same unit is a clean limestone containing specks of a green mineral (glauconite).

The regional significance of this exposure is: it is near the western edge of the last sediment eroded from the Taconic mountains. The source in the internal parts of the mountain chain is confirmed by the distribution of different kinds of sediments, from sandstone (and actually conglomerate in parts of Pennsylvania) to the east and northeast to shale and sandstone, and then limestone to the west in the Nashville and Lexington-Cincinnati areas.

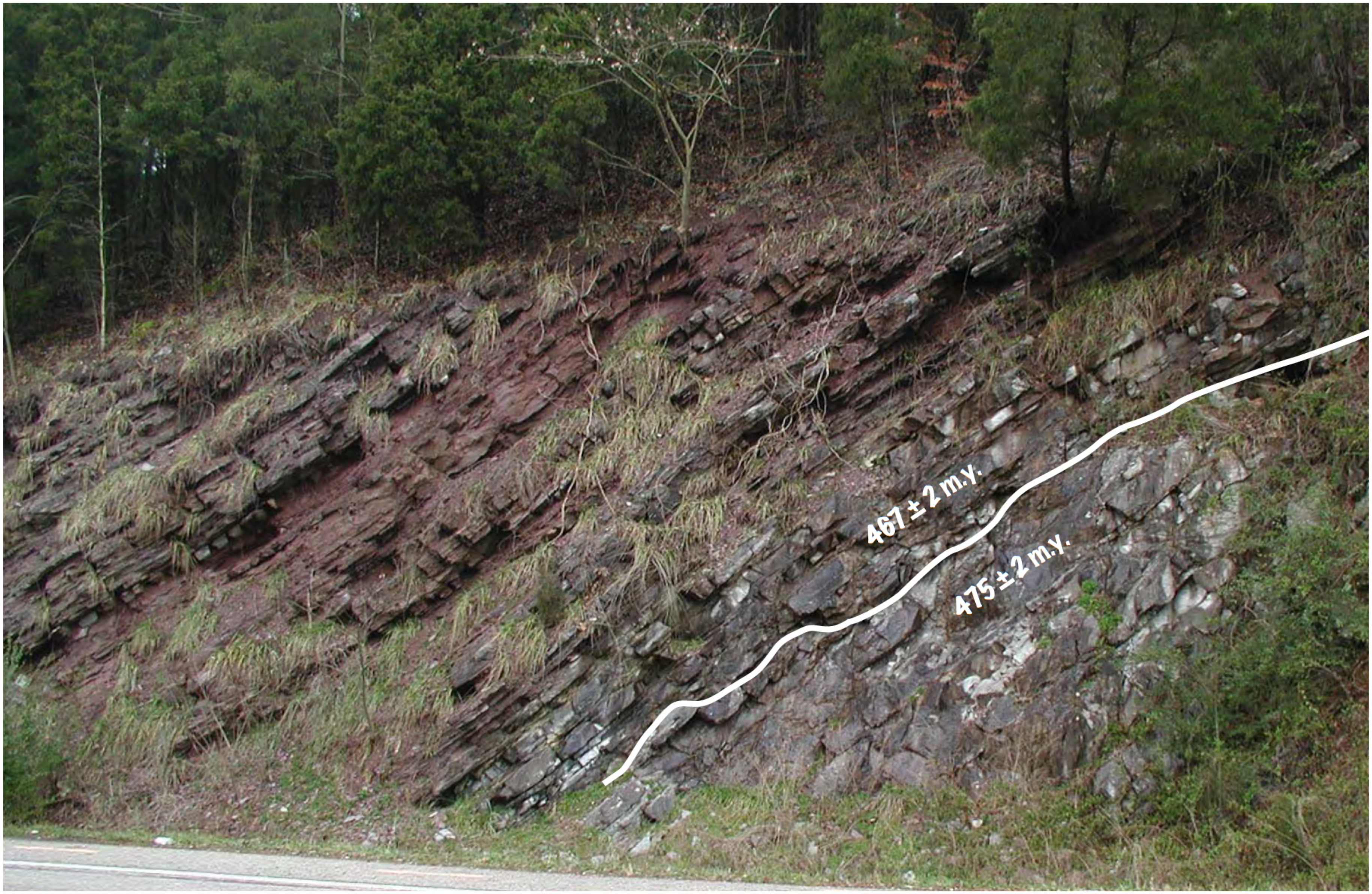


Figure 13. Knox unconfomity exposed at the intersection of Melton Lake Drive and Edgemore Road in Oak Ridge. The ages of the rocks shown in the diagram were determined by John Repetski (USGS) from conodonts separated from the rocks at this locality. Actually, a new species of conodont was discovered here.

We will make a pit stop at McDonald's in Clinton on the way to Stop 5.

STOP 5—Rome Formation at Moores Gap Church on Moores Gap Road (I-75 Frontage Road)
GPS Location: 36.137760° N, 84.045085° W

The Rome Formation exposed here is very typical of the Rome in this region, with a wide variety of rock types including shale in several colors, mostly tan to red sandstone, and gray to tan dolostone (Fig. 14). In addition to the rock types, there is a small fault here, which likely is a branch (splay) from the larger fault present but not exposed ~25 m to the northwest along Moores Gap Road (Fig. 15). How much displacement is there on the small fault?

The regional significance of the Rome (from Stop 1) is: the ~520 Ma Rome can be recognized with different names from Alabama (Rome Fm.) to northern Virginia and Maryland-Pennsylvania (Waynesboro Fm.) to Vermont (Winooski Fm.) to Newfoundland, where it was deposited under identical intertidal conditions, reflecting the evolution of the Cambrian continental margin of eastern North America. The Rome and equivalents become more carbonate rich to the east.

Note the contrasting rock types and topography to the left and right of the highway as we drive from Lake City to the Caryville exit.

STOP 6—Relationships along I-75 from Clinton to Caryville Exit (I-75 Frontage Road)
GPS Location: 36.268009° N, 84.195156° W

The topography from Clinton northwestward along I-75 is spectacular with a right-angle turn in the Plateau boundary with the Valley and Ridge. Exposures along the highway contain the Knox in the Clinch River, then the Rome Formation in roadcuts where the highway narrows, gray to brown Pennsylvanian (Plateau) rocks down the slope along the railroad tracks, and then carbonate (Knox) on the right before going downhill to the Caryville exit. As we pass Clinton and Lake City, look forward out the front of the vehicles to see a sharp V-shaped valley to the northwest (Fig. 16). This valley contains the Jacksboro tear fault, which bounds the southwest end of the Pine Mountain block. The significance of this structure was first recognized from an airplane by John L. Rich, who then studied the geology on the ground and published a classic paper describing the faults present here and correctly estimated the displacement on each (Fig. 17). Geologists throughout the world have read this paper (Rich, 1934) and a more recent paper (Mitra, 1988) that added significant modern data, but did not change Rich's original conclusions.

The regional significance of this stop is: Rich correctly interpreted the subsurface geology beneath the Pine Mountain block using only surface observations. He suggested that the thrust fault that underlies the block refracted (ramped) from the weak Rome Formation in the sedimentary sequence across the strong Knox and Chickamauga Group limestone units to the higher weak unit, the Chattanooga Shale. The Pine Mountain fault is exposed (not very spectacularly) on the northwest side of the block along I-75 where the highway descends into Jellico, Tennessee. The sharp corner in the topography near Clinton and Lake City was formed by the Chattanooga fault turning the corner (from the southwest) and becoming the Jacksboro fault discussed above. The Jacksboro fault trends northwest along the valley subsequently eroded along its trace and turns back to the northeast near Jacksboro and becomes the Pine Mountain fault along the northwest side of the block. This fault is present beneath the entire Pine Mountain block (Fig. 18).

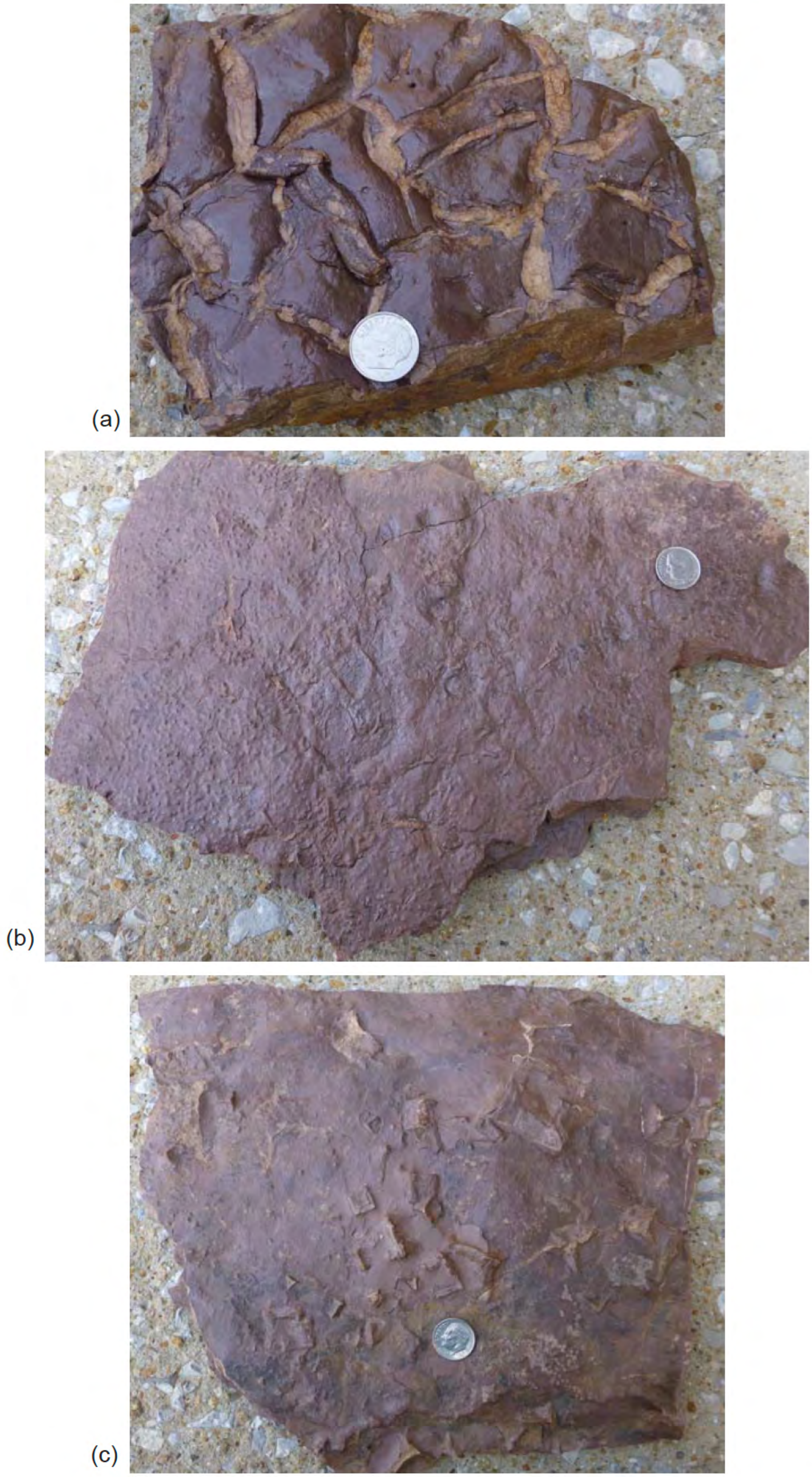


Figure 14. Examples of primary structures found at Stop 5. (a) Mud cracks. (b) Rain impacts and trace fossils. (c) Salt casts.

Figure 15. Multicolored Rome Formation rocks at Moores Gap. Note the small fault in the center of the photo. How much displacement would you estimate occurs on the fault? How can you figure this out?

Figure 16. View from a helicopter along I-75 near Caryville, Tennessee. V-shaped valley on the upper left side of the photo is underlain by the Jacksboro fault. Agricultural land in the right-center of the photo is underlain by limestone and dolostone.

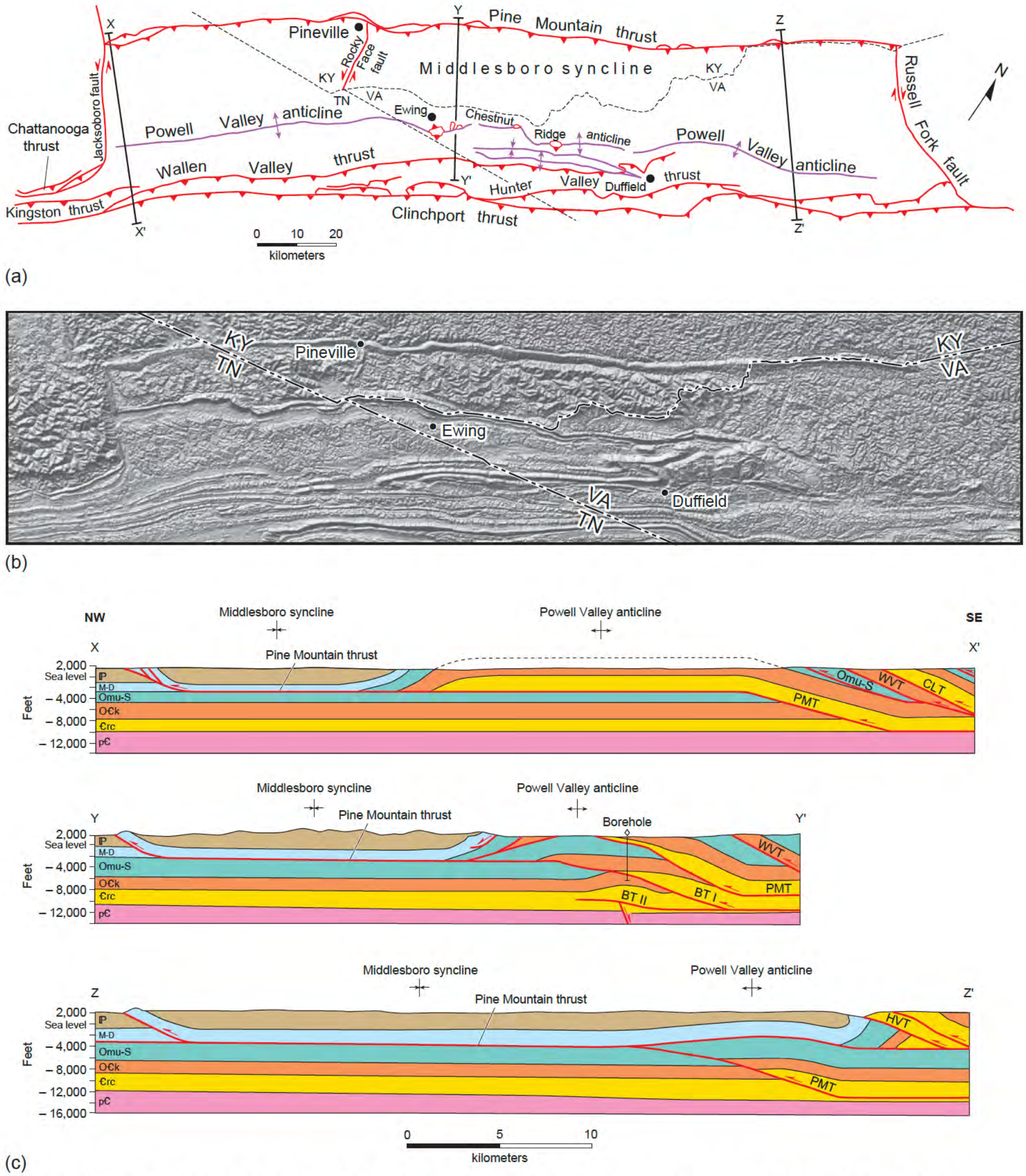


Figure 17. (a) Attributes of the Pine Mountain thrust sheet, Tennessee, Virginia, and Kentucky. The three lines X–X', Y– Y', and Z–Z' locate the sections in (c). (b) Digital elevation model for the map area shown in (a). Note the clear correlation of structures with topography. (c) Sections through the Pine Mountain block showing the fault-bend fold character of the Pine Mountain thrust (PMT). WVT—Wallen Valley thrust. CLT—Clinchport thrust. IP—Pennsylvanian rocks. M-D—Mississippian and Devonian rocks. Omu-S—Middle to Upper Ordovician and Silurian rocks. O€k—Cambro-Ordovician (Knox Group) carbonate rocks. €rc—Cambrian clastic rocks. p€—Precambrian basement rocks. O€k, Omu-S, and IP are strong rock units; €rc and M-D are weak units. HVT—Hunter Valley thrust. BT I and BT II in the middle cross section are Bales thrusts I and II. (a and c from S. Mitra, 1988.)

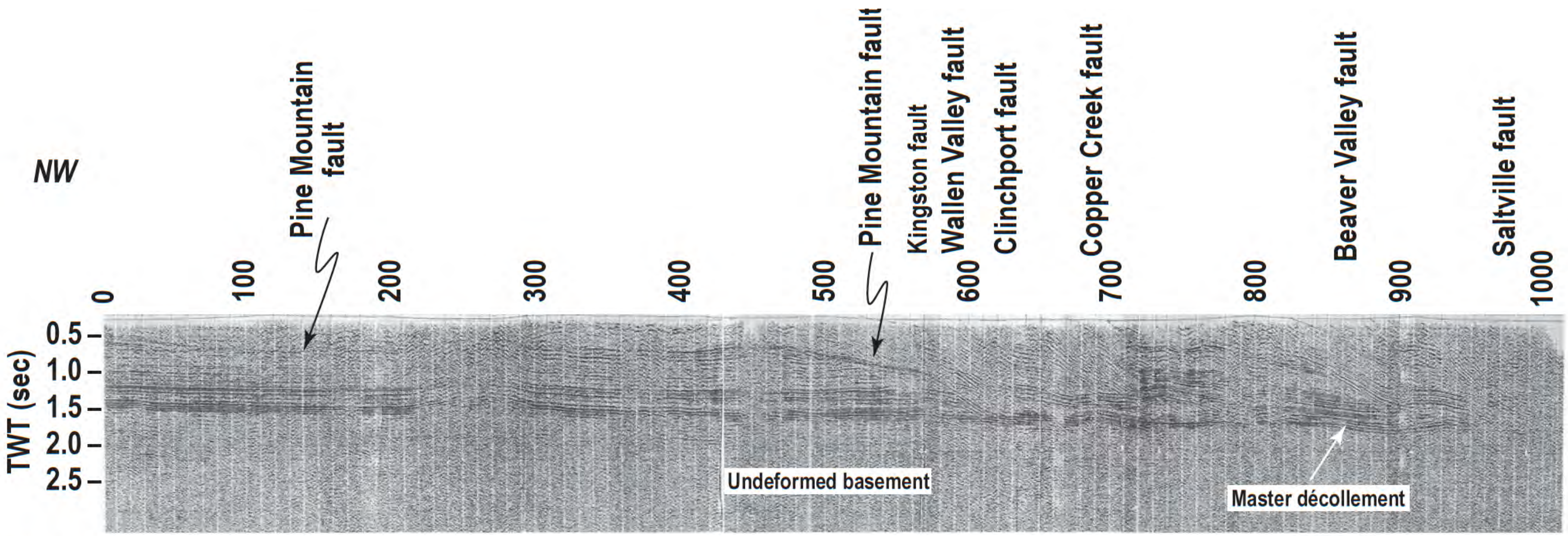


Figure 18. Industry seismic-reflection profile from the Pine Mountain block southeastward to just northwest of Knoxville. Note the steeper dip of faults southeast of the Pine Mountain fault. We assume that steepening occurred as the master fault (decollement) on top of basement propagated westward rotating thrusts that had already formed to the southeast to steeper dips. Also note the gentle southeast dip of the basement surface (immediately beneath the series of strong reflectors—Rome Formation shale and sandstone—that rests on basement) from northwest to southeast. From Hatcher et al. (2007a).

STOP 7—Pennsylvanian Rocks across from Recycle Center on Frost Bottom Road at Waste Connections convenience center East of Oliver Springs GPS Location: 36.050831° N, 84.314182° W

The rocks here consist of sandstone, shale, and coal deposited in a near sea level swamp environment as part of a great delta that formed from erosion of the Appalachians following the collision of Africa with North America that produced the Alleghanian orogeny. Collision began in the north ~325 Ma and was complete ~260 Ma. These sedimentary rocks were deposited just above sea level, and contain abundant plant fossils, along with the coal, that provide insight into the environment of deposition. The bituminous coal formed from burial and compression of plants through several ranks (peat, lignite) to the bituminous coal rank where it is today. It takes 10 ft (3 m) of plant material to compress to 1 ft (0.3 m) of bituminous coal (www.nationalgeographic.org).

The regional significance of this exposure is: the rocks here are very representative of the sequence that occurs throughout the Appalachian region. We know that rocks of the same age in western Kentucky, Illinois, and Kansas contain increasing amounts of limestone and other marine sedimentary rocks and fossils that tell us about the environment of deposition. These marine sediments to the north and west occur in an alternating sequence with non-marine deltaic sediments, whereas there are few if any marine sedimentary rocks in this sequence in Tennessee.

STOP 8—Rocks Exposed at the Southwest end of Country Club Estates in Oak Ridge GPS Location: 35.967116° N, 84.327849° W

Exposed here are rocks of the Chattanooga Shale and the overlying Ft. Payne Formation. The shale is black, very fine grained, and is deformed because it is close to the large Whiteoak Mountain thrust fault that lies immediately to the southeast. The Ft. Payne is poorly exposed, but consists of some greenish-brown shale and tan calcareous siltstone. Fragments of fossiliferous (mostly crinoids) chert may be present, but the contact is located uphill from the Chattanooga Shale exposed at the base of the hill.

The regional significance of this exposure is: the Chattanooga Shale (Devonian-Mississippian, ~360 Ma) is the southern equivalent of the Marcellus Shale (Devonian ~380-400 Ma) in West Virginia and Pennsylvania, although it is slightly younger. The reason for this equivalence and slight difference in age is that the delta these rocks are part of began to form first in the northeast because that area was uplifted first and received coarse sediments close to the source (Catskills) and produced a deep basin that was largely anoxic in which black mud was deposited (Fig 8). The anoxic part of this basin migrated southwestward through time as the basin to the northeast was sequentially filled with sediment. The migration of the black shale basin southwestward parallels the zippered north-to-south collision of the peri-Gondwanan terranes (Avalon and Carolina) with North America.

End of trip. Return to Roane State visitor parking lot.

GEOLOGIC TERMS

Acadian Orogeny. A crust-forming event that occurred from 406 to 380 Ma in New England; it produced deformation, metamorphism, and numerous plutons there. A similar event (we call Neoacadian) occurred in the southern Appalachians from 360-345 Ma, and is responsible for much of the metamorphism and deformation in the easternmost Blue Ridge and Inner Piedmont (including the early motion on the Brevard fault), and plutons in the eastern Inner Piedmont and eastern Blue Ridge, including the Spruce Pine pegmatites. The southern Appalachian Neoacadian event is related to closing of the Iapetus ocean by collision of the exotic Carolina terrane with the Inner Piedmont (formation of the Central Piedmont suture) and subduction of the Inner Piedmont beneath Carolina.

Alleghanian Orogeny. A crust-forming event that occurred from 320-265 Ma resulting from the collision of Africa (Gondwana) with North America producing metamorphism and plastic deformation in the eastern Piedmont, and eastern Inner Piedmont, plutons (like the Stone Mountain Granite near Atlanta), renewed movement on the Brevard fault, and the thrust sheets of the Blue Ridge and Valley and Ridge.

Alluvium. Unconsolidated clay, silt, sand, gravel, or other detrital material deposited during comparatively recent geologic time by a stream or other body of running water, as a sorted or semi-sorted sediment in the bed of the stream or on its flood plain or delta, as a cone or fan at the base of a mountain slope; esp. such a deposit of fine-grained texture (silt or silty clay) deposited during time of flood.

Anticline. Fold in which the layering is concave toward older rocks in the structure and the rocks appear to have been moved upward. An anticline contains older rocks in the center.

Basement. Rocks formed during one cycle of crust formation (usually mountain building—orogeny) that are incorporated into crust formed during a newer crust-forming event. Middle Proterozoic rocks formed during the Grenville orogeny have been incorporated into crust formed during the Appalachian events (Taconic, Acadian, Alleghanian orogenies).

Calcite. Mineral composed of $CaCO_3$. Principal constituent of limestone.

Carbonate bank. Deposits of carbonate sediments that form an escarpment adjacent to open ocean. Carbonate sedimentation may extend far inland on a continent or may be restricted to the continental shelf. The Bahamas extend out to a modern carbonate bank; the Early Ordovician carbonate bank extended inland from the Iapetan margin to present-day Kansas and Texas.

Colluvium. Loose, heterogeneous, and incoherent mass of soil material and/or rock fragments deposited by rainwash, sheetwash, or slow continuous downslope creep, usually collecting on hillsides.

Continental crust. The type of the Earth's crust that underlies the continents and continental shelves; it ranges from about 35 km to as much as 70 km thick under mountain ranges. The density of the upper layer of the continental crust is ~2.7 g/cm^3, and velocities of compressional seismic waves through it are less than ~7.0 km/sec.

Detrital. Mechanically deposited particles derived from outside the area where they were deposited.

Dolomite. Carbonate mineral composed of $CaMg(CO_3)_2$. Also used as a sedimentary rock name for rocks composed mostly of dolomite mineral. The rock is sometimes called dolostone.

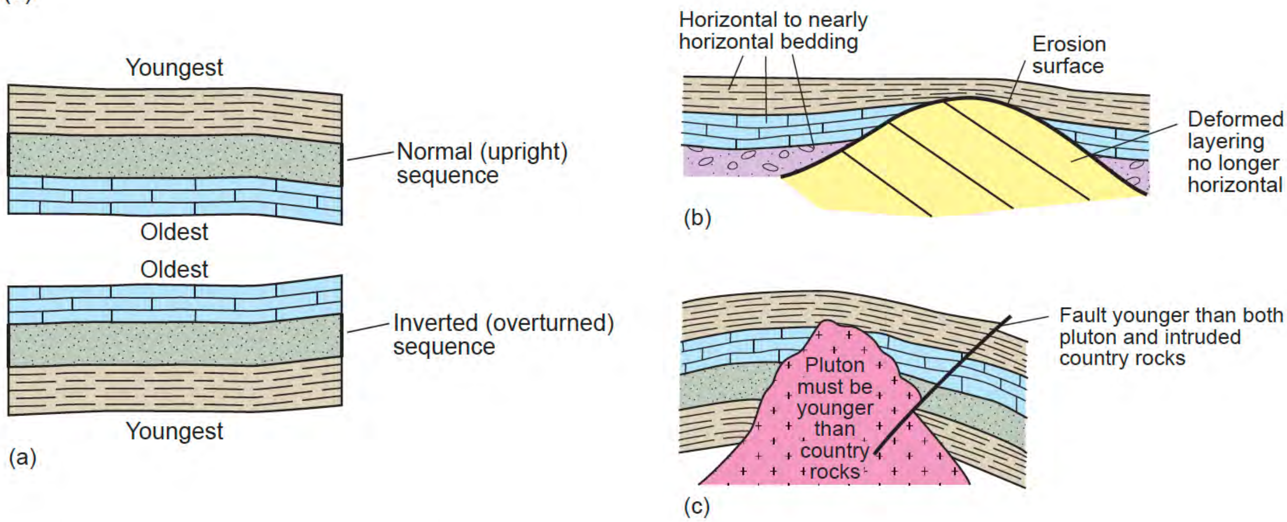
Fault. Fracture having appreciable movement that produces measurable displacement parallel to the plane of the fracture on the scale of observation. Mode II and III fractures.

Fold. A curve or bend of a planar structure, such as bedding, foliation, or cleavage. A fold is usually a product of deformation, although its definition is descriptive and not generic, and may include primary structures formed in soft sediment.

Formation. Rock type or group of rocks that possesses common characteristics so it can be mapped as a unit on a geologic map. (One color in Figure 2a.)

Ga. Billions of years before the present.

Geologic Laws. *Superposition*: Oldest rocks should be at the bottom of a sequence of sedimentary rocks unless they have been tectonically overturned (a) and (b). *Original Horizontality*: Sedimentary rocks are commonly deposited in horizontal beds (b). Tilted layering is usually the result of deformation. *Crosscutting Relationships*: Igneous rocks are younger than the rocks they intrude; faults are younger than the rocks they cut (c).



Iapetus ocean. A sea that existed during the Ordovician and Silurian Periods in the general position of the present Atlantic Ocean before several exotic terranes and Europe and Africa collided with North America. Iapetus was the father of Atlas, for whom the Atlantic Ocean is named.

Immature sediment. Clastic sediment that has been differentiated or evolved from its parent rock by processes acting over a short time and/or with a low intensity so that relatively unstable minerals (such as feldspar), mobile oxides (such as alumina), and other weatherable material (such as clay) survives, and having poorly sorted, angular grains.

Inverted topography. Topographic features that once occupied high areas now occupy low areas, and vice-versa. The Gray Site in NE Tennessee occurs in an inverted topography.

Laurentia. Proterozoic to Paleozoic North America.

Limestone. Sedimentary rock composed mostly of calcite.

Ma. Millions of years before the present.

Mantle. The part of the Earth between the core and the crust. It is composed of Mg-Fe rich minerals (pyroxenes, olivine, garnet, and high T-P equivalents, such as spinel). Compressional seismic-wave velocities traveling through it are 8.0 km/sec or greater.

Mature sediment. Clastic sediment that has been differentiated or evolved from its parent rock by processes acting over a long time and with a high intensity and that is characterized by stable minerals (such as quartz), deficiency of the more mobile oxides (such as hematite), absence of weatherable material (such as clay), and consists of well-sorted rounded to subangular grains.

Oceanic crust. Kind of the Earth's crust that underlies the ocean basins, and is composed mostly of basalt. The oceanic crust is about 5-10 km thick; it has a density of 3.0 g/cm^3, and compressional seismic-wave velocities traveling through it exceed 6.2 km/sec.

Quartz. Crystalline silica, an important rock-forming mineral: SiO_2, having a widespread distribution in igneous (esp. granitic), metamorphic, and sedimentary rocks. It has a vitreous to greasy luster, a conchoidal fracture, and absence of cleavage, and a hardness of 7 on Mohs scale (scratches glass easily, but cannot be scratched by a knife). It occurs in either clear crystals or grains, or in a wide variety of colors Cristobalite, tridymite, stishovite, coesite, and keatite are polymorphs; lechatlierite is quartz glass commonly formed where lightning strikes beach sand. Agate, chalcedony, and flint are forms composed of submicroscopic crystals. Opal is amorphous, hydrated SiO_2.

Rift. A long, narrow continental trough that is bounded by normal faults; a graben of regional extent. It marks a zone along which the entire thickness of the lithosphere has ruptured under extension.

Rift-to-drift transition. Process initiated by formation of a continental rift followed by pulling the rifted components apart so that oceanic crust and eventually open ocean forms in the space between. When supercontinent Rodinia broke apart ~750 Ma, first there was rifting followed by drifting of continents. The segment of time between is the rift-to-drift transition. The Rome Formation was deposited at the beginning of the drifting stage.

Sandstone. Medium-grained clastic sedimentary rock composed of abundant rounded or angular sand-size fragments cemented by silica, iron oxide, or calcium carbonate. The consolidated equivalent of sand, intermediate in texture between conglomerate and shale.

Saprolite. Weathered rock that retains the original structures and textures of the rock despite wholesale chemical decomposition. Literally: rotten rock.

Shale. Fine-grained detrital sedimentary rock, formed by the consolidation of clay, silt, or mud. It is characterized by finely laminated structure, fissility, developed parallel to bedding, along which the rock breaks readily into thin layers; similar rocks are claystone, siltstone, and mudstone.

Structural geology. Branch of geology that deals with the form, arrangement, and internal structure of rocks, and especially with the description, representation, and analysis of structures, chiefly on a moderate to small scale. The subject is similar to tectonics, but the latter is generally used for the broader regional or continent-scale structures.

Supercontinent. Large continent formed by amalgamation of smaller continents. Supercontinents have existed at several times during the geologic past, forming Rodinia at ~1 Ga and Pangea at ~300 Ma.

Suture. Boundary separating two continents or tectonic terranes.

Syncline. Fold in which layering is concave toward the younger rocks; as a result, younger rocks are found in the central part of the structure and appear to have been folded downward.

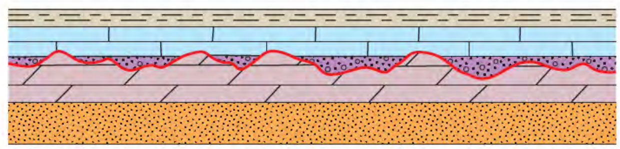
Taconic orogeny. A crust-forming event that occurred 460 to 420 Ma that, in the southern Appalachians, related to subduction of oceanic crust and the western Blue Ridge beneath a the 480-460 Ma Ordovician island arc that had formed off Laurentia. This event produced deformation, high grade metamorphism, and plutons like the Whiteside Granite near Highlands, NC, and the basin of thick Middle Ordovician sedimentary rocks next to the Blue Ridge.

Tectonics. Study of large crustal or mantle features — mountain ranges, parts of continents, trenches and island arcs, oceanic ridges, mantle plumes, and entire continents and ocean basins — and their relationships to stresses and tectonic plates.

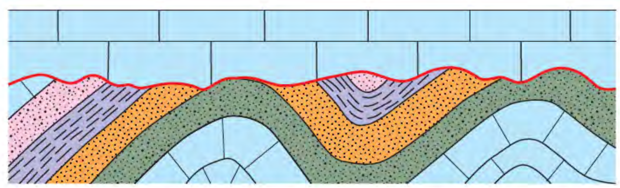
Thrust fault. Fault in which the hanging wall has moved up relative to the footwall. The fault plane commonly has a low dip angle (25° or less).

Thrust sheet. The body of rock above a large thrust fault whose surface is horizontal or very gently dipping.

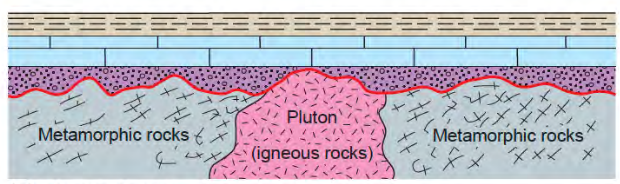
Unconformity. Boundary along which part of the geologic record has been removed either by erosion or less commonly by nondeposition. A disconformity (a) involves only an erosion surface with sedimentary rocks above and below with no angular discordance. An angular unconformity (b) involves and erosion surface where there is an angular discordance above and below the unconformity. A nonconformity (c) is an erosion surface where igneous or metamorphic rocks occur below the erosion surface and sedimentary rocks occur above.



(a) Disconformity



(b) Angular unconformity



(c) Nonconformity

Window. Erosional hole in a thrust sheet. Fenster (original German name for this structure; window Ger.).

Geologic Time Scale