**12th International Symposium on the Ordovician System**

# Ordovician of the Southern Appalachians, USA
# Pre-Symposium Field Trip

June 3rd – 7th, 2015

Achim Herrmann[1]
John T. Haynes[2]

*[1]Assistant Professor, Department of Geology & Geophysics, Louisiana State University Baton Rouge, LA 70803, aherrmann@lsu.edu*

*[2]Associate Professor, Department of Geology and Environmental Science, James Madison University, Harrisonburg, VA 22807, haynesjx@jmu.edu*

**TABLE OF CONTENTS ..........................................................................................................pg. #**

**DAY 1. ORDOVICIAN CARBONATE AND CLASTIC DEPOSITS ALONG STRIKE AND ACROSS THE HELENA THRUST FAULT, NORTH CENTRAL ALABAMA**. ....206
**Introduction**.......................................................................................................................206

**Stop 1-1.** Red Mountain Expressway section, Birmingham AL; 8:30 – 10:30 am.....................217

**Stop 1-2**: Tidwell Hollow section along Blount County Highway 15, ~5 miles SW of Oneonta, AL; 12:30 – 2:30 pm..............................................................................................................217

**Stop 1-3**: Alexander Gap, and roadcut through Colvin Mountain along the E side of northbound US Highway 431, Glencoe, AL; 3:45– 4:45 pm ..........................................................................219

**DAY 2. ORDOVICIAN CARBONATE AND CLASTIC DEPOSITS ACROSS STRIKE FROM ALABAMA TO GEORGIA**..........................................................................................222
**Introduction**.......................................................................................................................222

**Stop 2-1**: Ft. Payne, AL, at Exit 222 on I-59; exposures along entrance ramp to northbound I-59 and just to north on E side of I-59 N; 8:30 – 10:00 am....................................................... 228

**Stop 2-2**: Horseleg Mountain, along Radio Springs and Mont Alto Roads, crest of Horseleg Mountain, just south of Rome, GA; 11:15 am – 1:00 pm..........................................................229

**Stop 2-3**: Dug Gap, cuts along State Highway 52 across Rocky Face Mountain, just west of Dalton, GA; 2:20 pm – 3:45 pm .........................................................................................230

**Stop 2-4**: Reed Road, low cut along the east side of the road where it parallels Hamilton Mountain between West Haig Mill/Caprice/Raindance Roads (south of cut) and Battle Way (north of cut), north of Dalton, GA; 4:00 – 4:30 pm .................................................................. 230

**DAY 3. ORDOVICIAN CARBONATE AND CLASTIC DEPOSITS ACROSS STRIKE FROM VIRGINIA TO TENNESSEE**..........................................................................................231
**Introduction**.......................................................................................................................231

**Stop 3-1**: Hagan, outcrops along railroad at Hagan, VA; 9:30 – 11:30 am ...............................233

**Stop 3-2**: Dandridge Municipal Park, sections along shoreline of Douglas Lake just off of Chestnut Hill Road (State Highway 92), at Dandridge, TN; 1:00 – 2:30 pm.............................235

**Stop 3-3**: Exposure along north side of State Highway 70 in gap between Dodson and Kite Mountains in the western Bays Mountains synclinorium, southeast of Rogersville, TN; 3:30 – 5:00 pm ..................................................................................................................................238

**DAY 4. ORDOVICIAN PROXIMAL CARBONATE AND CLASTIC DEPOSITS OF THE BLOUNT FOREDEEP IN TENNESSEE AND VIRGINIA** .......................................... 242
**Introduction**.................................................................................................................... 243

**Stop 4-1**: Exposures along Holston Dam/Ruthton Roads below South Holston Dam, TN; 8:50 – 9:50 pm ............................................................................................................ 244

**Stop 4-2**: Cuts along State Highway 107 in Rich Valley northwest of Chilhowie, VA; 10:45 am – 12 Noon............................................................................................................ 244

Welcome to the Southern Appalachians pre-meeting field trip that is a part of the 2015 International Symposium on the Ordovician System meeting! This trip is scheduled to consist of three full days of stops at selected locations. Each day will provide you with a west-to-east traverse across the Valley and Ridge province from the predominantly carbonate depositional environments in the western and northwestern strike belts to the predominantly clastic depositional environments in the eastern and southeastern strike belts.

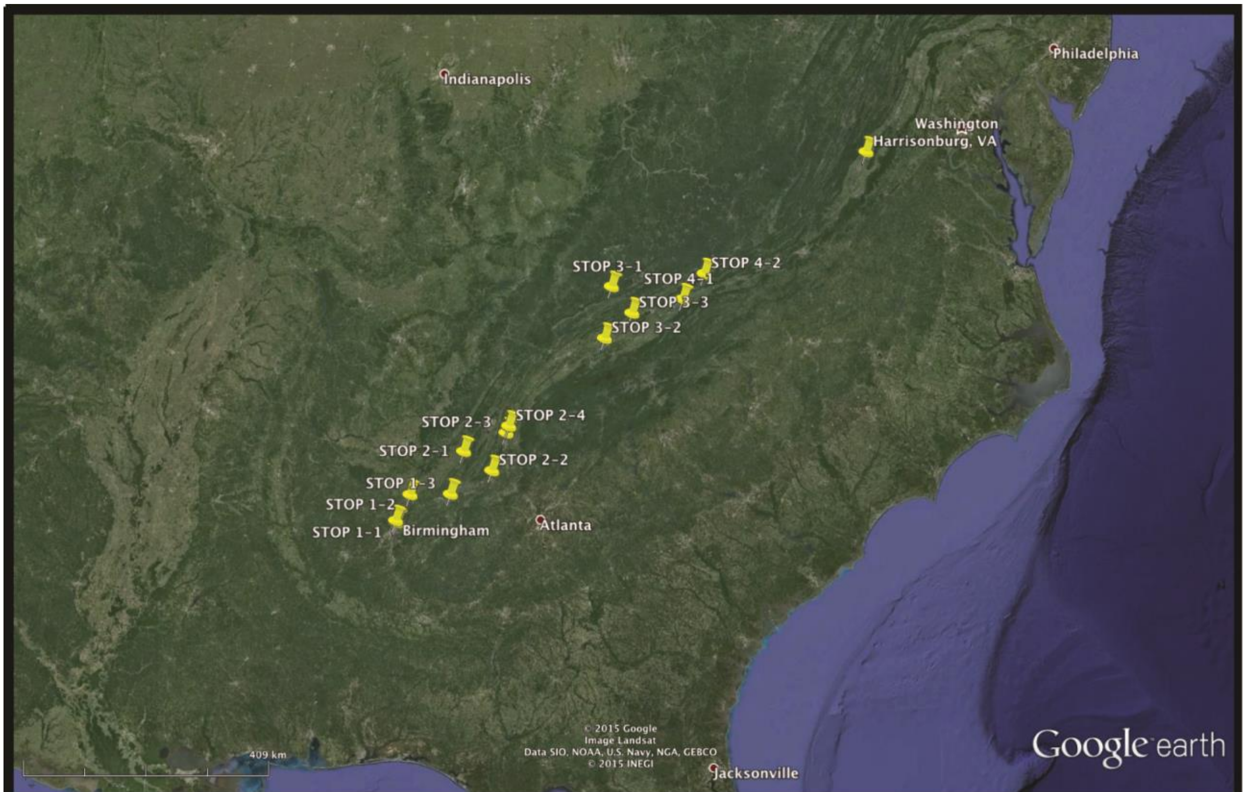
## DAY 1. ORDOVICIAN CARBONATE AND CLASTIC DEPOSITS ALONG STRIKE AND ACROSS THE HELENA THRUST FAULT, NORTH CENTRAL ALABAMA

### Introduction

At today's stops we will examine three exposures of Ordovician strata in Alabama (Fig. 1). Two of these exposures (Red Mountain Expressway, Stop 1-1, and Tidwell Hollow, Stop 1-2) consist of predominantly carbonate strata originally deposited in platform and shelf margin settings, and the third exposure (Alexander Gap, Stop 1-3) is of siliciclastic strata originally deposited in nearshore marine settings (Fig. 2). At all three locations, the Deicke and Millbrig K-bentonites of Katian and Sandbian age (~452-453 Ma) are present, and they provide chronostratigraphic control for these strata of Katian, Sandbian, and upper Darriwilian age across the region (Fig. 2). They are also important for tying together newly generated carbon and oxygen isotope curves for the Red Mountain Expressway, Tidwell Hollow, and other stratigraphic sections in this area.

#### *The Paleoceanographic conditions across the Turinian/Chatfieldian Boundary, and paleoenvironmental changes*

The stops today will mostly span the M4 and M5 sequences of Holland and Patzkowsky (1996), including the GICE interval (Young et al., 2005) (Fig. 4). In Middle and Upper Ordovician strata of the eastern North American mid-continent, 14 sequences are identified (Holland and Patzkowsky, 1996). Of these 14 sequences, 6 are Mohawkian in age (458-453 m.y., Webby et al., 2004) and are designated as M1 through M6. The M4-M5 sequence boundary is a possible climatic turning point (Fig. 4). This boundary coincides with several distinct lithological changes suggesting a transition from warm-water to cool-water conditions within the shallow epicontinental sea of Laurentia during the early Late Ordovician (Brookfield and Brett, 1988; Brookfield and Elgadi, 1998; Holland and Patzkowsky, 1996; Lavoie and Asselin, 1998; Patzkowsky and Holland, 1996; Pope and Read, 1997). In particular, the change to a skeletal association reminiscent of brynoderm and bryomol associations of modern and ancient temperate water settings supports cooling at this time, analogous to other Paleozoic ice-house intervals (Beauchamp and Desrochers, 1997; Samankassou, 2002). The M4-M5 lithologic transition coincides with an extinction event recognized in the eastern United States (Patzkowsky and Holland, 1993; 1996; 1999) that affected articulate brachiopods (Patzkowsky and Holland, 1993;




**STOP 1-1: Red Mountain Expressway, Birmingham AL; Birmingham South 7½ min quad (33.49598 N 86.78822 W)**
**STOP 1-2: Tidwell Hollow, ~5 miles SW of Oneonta, AL; Cleveland 7½ min quad (33.87806 N 86.57555 W)**
**STOP 1-3: Alexander Gap, Glencoe, AL; Glencoe 7½ min quad (33.90011 N 85.91659 W)**
**STOP 2-1: Ft. Payne, AL; Fort Payne 7½ min quad (34.47875 N 85.71029 W)**
**STOP 2-2: Horseleg Mountain, Rome, GA; Rome South 7½ min quad (34.22755 N 85.24566 W)**
**STOP 2-3: Dug Gap, just west of Dalton, GA; Villanow 7½ min quad (34.73725 N 85.01925 W)**
**STOP 2-4: Reed Road along Hamilton Mountain, N of Dalton, GA; Dalton North 7½ min quad (34.82733 N 84.97808 W)**
**STOP 3-1: Hagan, VA; Rose Hill 7½ min quad (36.69942 N 83.28762 W)**
**STOP 3-2: Dandridge, TN; Jefferson City 7½ min quad (36.00676 N 83.40711 W)**
**STOP 3-3: Dodson Mountain, southeast of Rogersville, TN; McCloud 7½ min quad (36.34248 N 82.95024 W)**
**STOP 4-1: South Holston Dam, TN; Holston Valley 7½ min quad (36.52251 N 82.10027 W)**
**STOP 4-2: Rich Valley, northwest of Chilhowie, VA; Chilhowie 7½ min quad (36.85539 N 81.73396 W)**

**Figure 1.—Location of field trip stops between Birmingham, Alabama, and Harrisonburg, Virginia.**

1996; Patzkowsky and Holland, 1997), cephalopods (Frey, 1995), corals (Patzkowsky and Holland, 1996), and crinoids (Eckert, 1988). Onset of late Ordovician glaciation has been advanced as a cause of these changes (Lavoie and Asselin, 1998; Pope and Read, 1997), and, based on sequence stratigraphic evidence and carbon isotope data, Saltzman and Young (2005) suggested that the transition to Late Ordovician ice-house conditions occurred during this time. Nonetheless, significant cooling in the mid-continent epicontinental sea is problematic because eastern North America was then at tropical to subtropical latitudes (Scotese and McKerrow, 1990; 1991). Furthermore, whereas evidence for benthic cooling exists below the Deicke K-bentonite (Herrmann et al., 2010), the best paleotemperature estimates available suggest, if

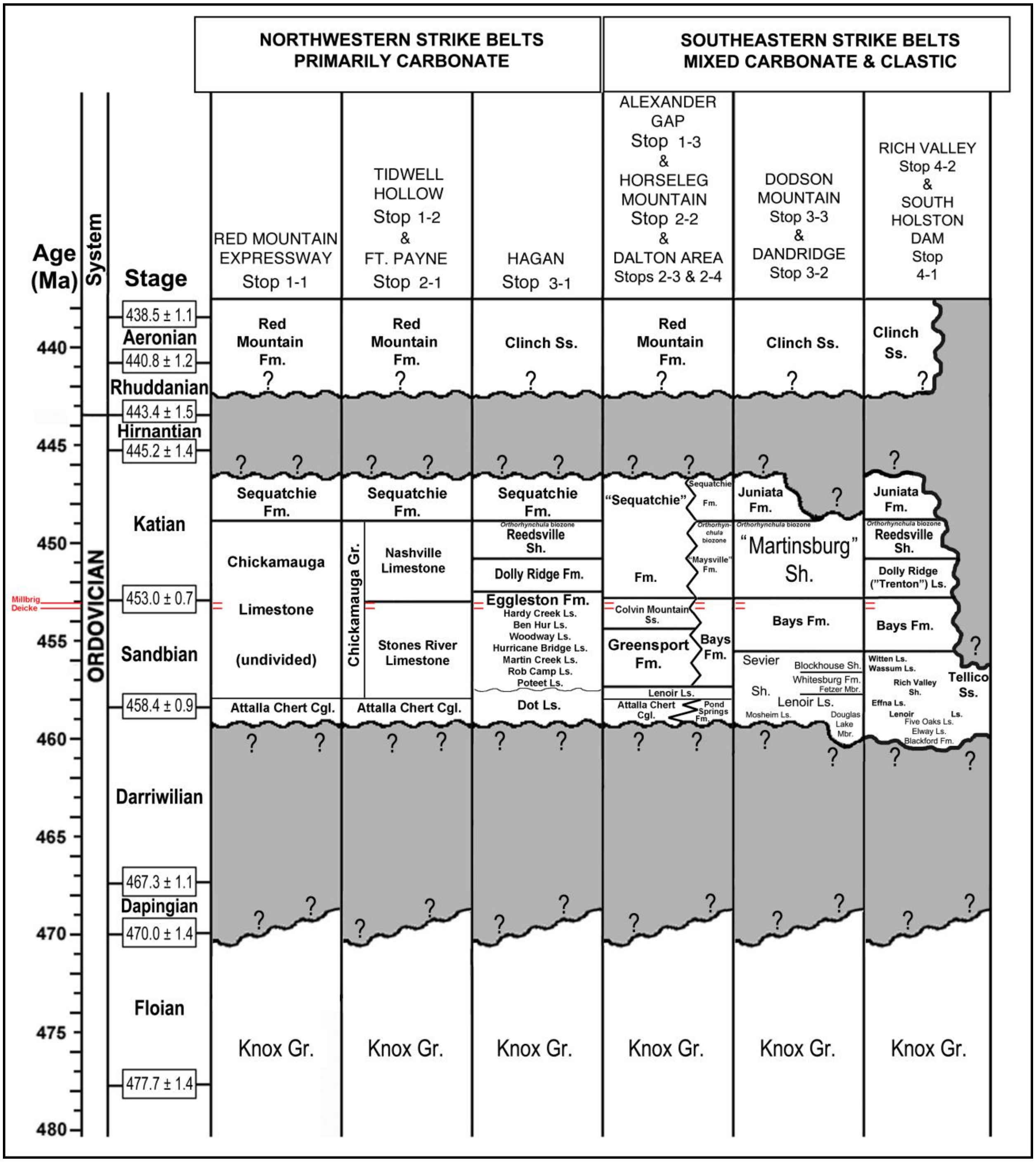



**Fig. 2.—Stratigraphic correlation chart of the locations visited.**

anything, warming across this interval in Minnesota and Kentucky (Buggisch et al, 2010) and Oklahoma (Rosenau et al., 2012). The leading alternative hypothesis to a shift in climate modes invokes oceanographic and sedimentological responses to the Taconic orogeny (Holland and Patzkowsky, 1996).

One interpretation of the lithologic and faunal changes is that they are a response to initiation of cooling during the later Ordovician, which eventually led to a glaciation in the Hirnantian (Lavoie and Asselin, 1998; Pope and Read, 1997). In response to the global cooling, the tropical belt shrank and cold water was able to penetrate into tropical areas (Lavoie, 1995); the mechanism(s) proposed for cooling vary. Kolata et al. (2001) hypothesized that the Sebree Trough acted as a passage through which cold oceanic waters could reach the Laurentian epeiric sea. Herrmann et al. (2004), using a 3-dimensional global ocean circulation model, demonstrated that changes in paleogeography and atmospheric $pCO_2$, could have led cold water currents from higher southern latitudes to inundate the shallow epeiric ocean of Laurentia. Upwelling of cold, open ocean water was also suggested as an explanation for changes in epicontinental seas by Pope and Steffen (2003), who cited the widespread deposition of phosphatic and cherty carbonates along the southern and western margin of Laurentia as evidence for vigorous thermohaline circulation, and, therefore, the influence of cold deep ocean water as early as the late Middle Ordovician. Finally, Young et al. (2005) concluded that the Chatfieldian Guttenburg $\delta^{13}C$ excursion (GICE) (e.g., Hatch et al., 1987; Ludvigson et al., 1996; Ludvigson et al., 2004; Patzkowsky and Holland, 1997) reflected enhanced upwelling along the southern margin of Laurentia during the Chatfieldian. From a conodont perspective, the GICE begins in the upper part of the *P. undatus* Zone, continues through the *P. tenuis* Zone, and ends in the *B. confluens* Zone. That places the GICE within the M5 sequence. Estimates of cooling, where given, are typically a few degrees, but as already noted conodont $\delta^{18}O$ analyses do not support cooling across this interval (Buggisch et al., 2010; Rosenau et al., 2012).

Our stops today will provide a transect from shelf and platform margin carbonate environments to siliciclastics that accumulated atop the nearly filled Blount foredeep that had developed along the southern margin of Laurentia during the early stages of the Taconic orogeny (Fig. 3). The exposures we have selected for examining today will provide us with ample opportunity to discuss different driving mechanisms for environmental change during the middle and later Ordovician.

### *The Ordovician carbonate succession northwest of the Helena thrust*

From the Cambrian – Ordovician boundary, which in this region occurs in the lower Knox Group, to the Knox unconformity (which is variously Floian, Dapingian, to Darriwilian in its stratigraphic extent; Fig. 2), Ordovician strata are primarily shallow water peritidal and lesser open shelf carbonates, both limestones and dolomites (Read and Repetski, 2012). Immediately above the Knox unconformity in north central Alabama is the Attalla Chert Conglomerate, a deposit of chert-rich karst regolith and rubble that accumulated on and around lows on the Knox unconformity paleokarst during the long periods of subaerial exposure that occurred during Floian to Darriwillian time as the Knox unconformity developed throughout much of eastern North America.

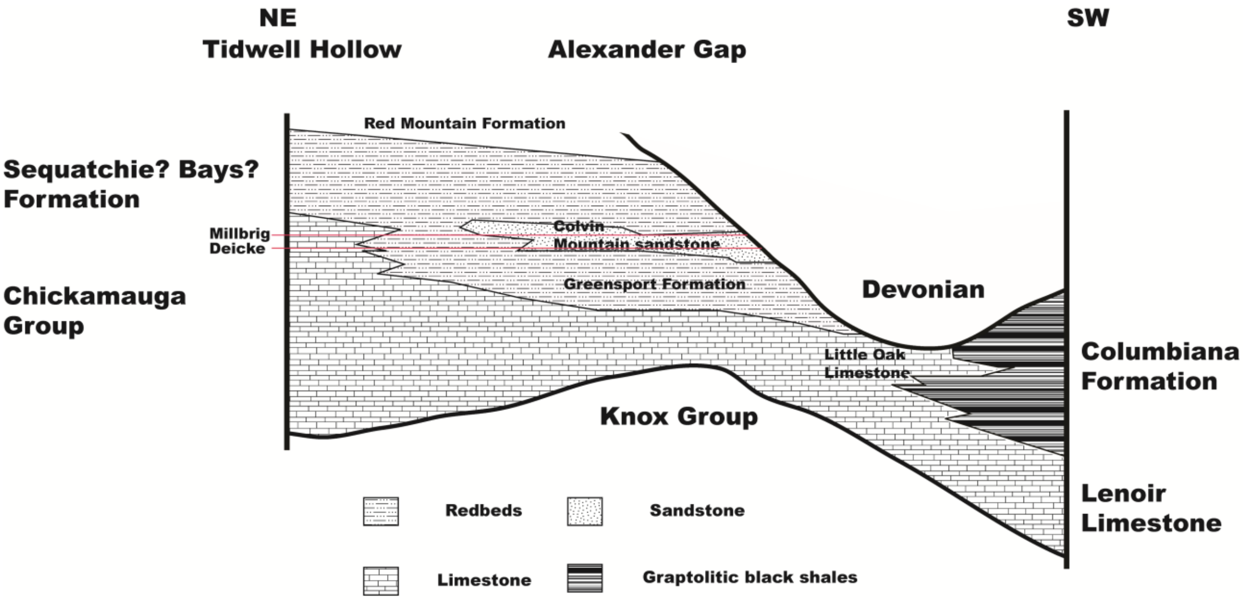



**Figure 3.—Stratigraphic cross section across northeastern Alabama showing the stratigraphic and depositional relationship between the second (Tidwell Hollow) and third (Alexander Gap) stops of day 1. Modified from Chowns and McKinney (1980).**

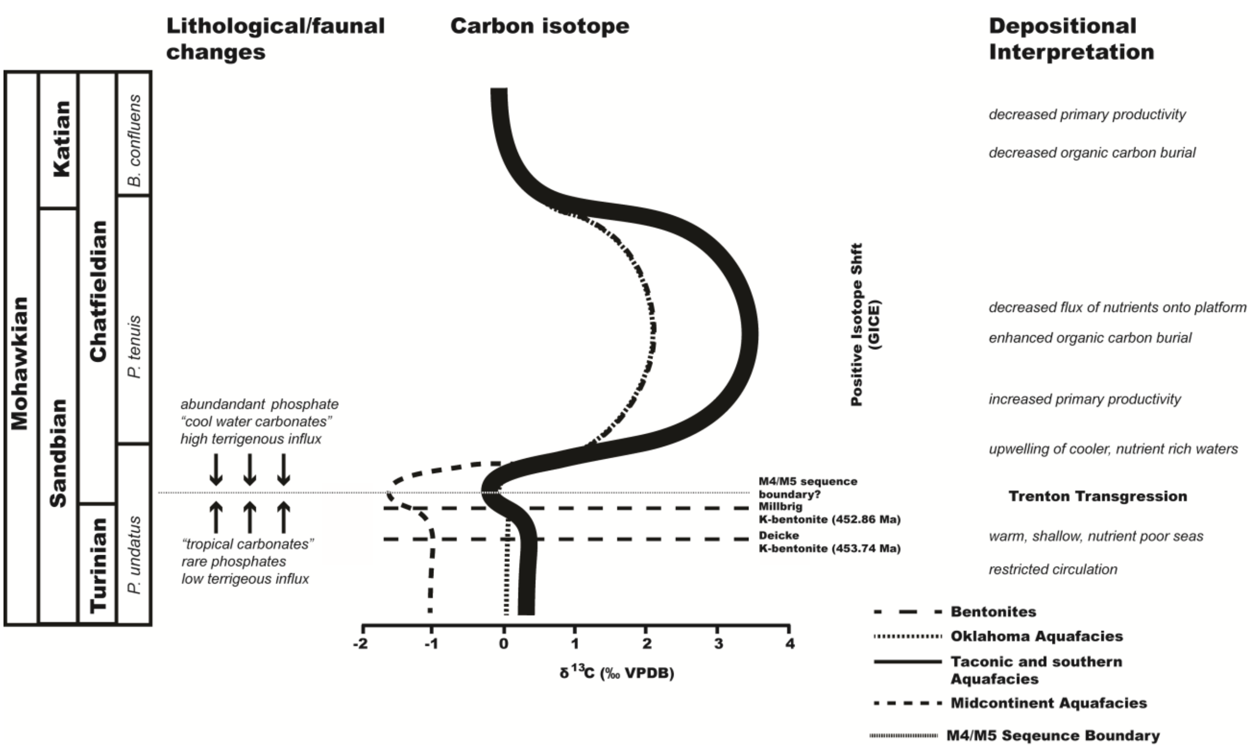



**Figure 4.—Paleoceanographic model for the Guttenberg Isotope Carbon Excursion (based on Young et al., 2005). Age of Deicke and Millbrig K-bentonites from Sell et al. (2013, 2015). M4/M5 sequence boundary and lithological changes based on Holland and Patzkowsky (1996).**

Above the Attalla, the character of the strata changes gradually upsection, with the occurrence of more open shelf and slope carbonates, and even some buildups. In the area of today's stops, most of these strata are placed into the Chickamauga Limestone undivided because facies changes and erosional truncation has removed the upper part of the sequence (Red Mountain Expressway) or the Chickamauga Group and its component Stones River and overlying Nashville Limestones (Tidwell Hollow), with the later Katian strata being split out as the Sequatchie Formation (Fig. 2).

At over 60 m in elevation change from the crest of Red Mountain to the roadbed, the Red Mountain Expressway cut is the deepest highway cut in this region (Fig. 5), and it exposes over 200 meters of section from Upper Cambrian carbonates of the Copper Ridge Formation to Lower Mississippian cherts of the Fort Payne Formation, a stratigraphic thickness that includes the approximately 75 meters of Chickamauga Limestone. The Chickamauga Limestone at the Red Mountain Expressway records deposition in a more open marine and deeper shelf setting, whereas the equivalent but much thicker stratigraphic interval at Tidwell Hollow includes many beds deposited in shallower, peritidal settings. The oldest Chickamauga limestones that overlie the Attalla are now mostly covered by ~45 years of vegetation growth and slope retreat at the northwest end of the deep cut, but they include about 7 m of fenestral lime mudstones and mudcracked algal laminates that were deposited in supratidal and intertidal environments. These are overlain by about 70 m of bioclastic and peloidal wackestones and packstones, with several thin grainstones. Some intervals are noticeably argillaceous, and these tend to be characterized by nodular bedding. Fossil abundance and diversity varies, with some beds containing a restricted fauna of ostracodes and gastropods, whereas many other beds have a diverse open marine fauna that includes crinoids, brachiopods, trilobites, bryozoans, calcareous algae, stromatoporoids, corals, and mollusks.

The long roadcut at Tidwell Hollow is the most complete and extensive exposure of the limestones of the Chickamauga Group in Alabama. The carbonate lithologies that occur in the almost 200 m thick section of Chickamauga Group limestones include lime mudstones and dolomites, some of which are mudcracked, burrowed, and/or fenestral, with some ostracodes and gastropods, and which alternate with peloidal and bioclastic wackestones, packstones, and some grainstones that have a more diverse assemblage of crinoids, bryozoans, trilobites, tabulate corals, calcareous red algae, and brachiopods. Oolitic, oncoidal, and intraclastic packstones and grainstones are present as well. Low-angle cross-bedding occurs in some of the skeletal grainstones, and other sedimentary structures include nodular bedding, horizontal and wavy lamination, ripples, and thin to thick beds, with some beds having a lenticular to almost wedge-shaped character.

Of note is that at both the Red Mountain Expressway and Tidwell Hollow sections, small mud-rich bioherms are present, and they consist of a diverse assemblage of bryozoans, sponges, brachiopods, corals and stromatoporoids, and some calcareous algae.

The Deicke and Millbrig K-bentonites, with their distinctive phenocrystic mineralogical assemblages, are also present at both sections, and provide time lines for correlation (Fig. 5-7).

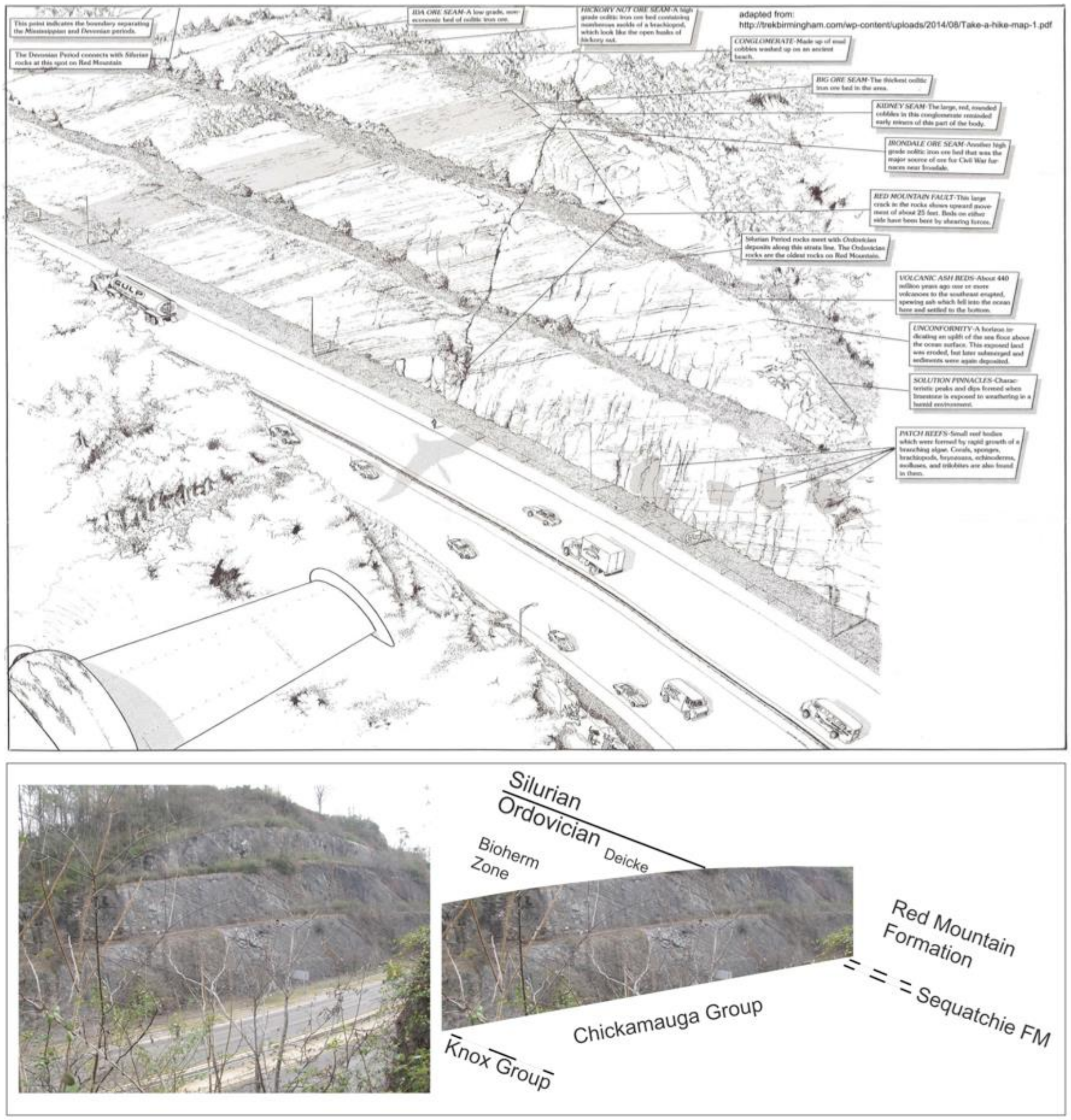



**Figure 5.—The Red Mountain Expressway roadcut in Birmingham, Alabama. Top: sketch of major features that can be seen in the south side of the roadcut. Bottom: view of the north side of the cut, which is Stop 1-1, where we will examine Ordovician carbonates and the Deicke and Millbrig K-bentonites. The Ordovician-Silurian boundary at this stop is an angular unconformity with an angle of 1.6° between the Upper Ordovician Sequatchie Formation and the Lower Silurian Red Mountain Formation.**

At the Red Mountain Expressway both occur in the nodular bedded argillaceous limestones of the uppermost Chickamauga Limestone. The Deicke is a distinct bed but the Millbrig is a biotite-rich bentonitic zone (Haynes, 1994), suggesting that the Millbrig tephra was either deposited and then reworked, most likely by scouring from the deeper wave base associated with storms on the shelf, or, that the Millbrig is in fact comprised of multiple and separate tephras (Huff et al., 2004). By contrast, both K-bentonites are discrete beds at Tidwell Hollow, where

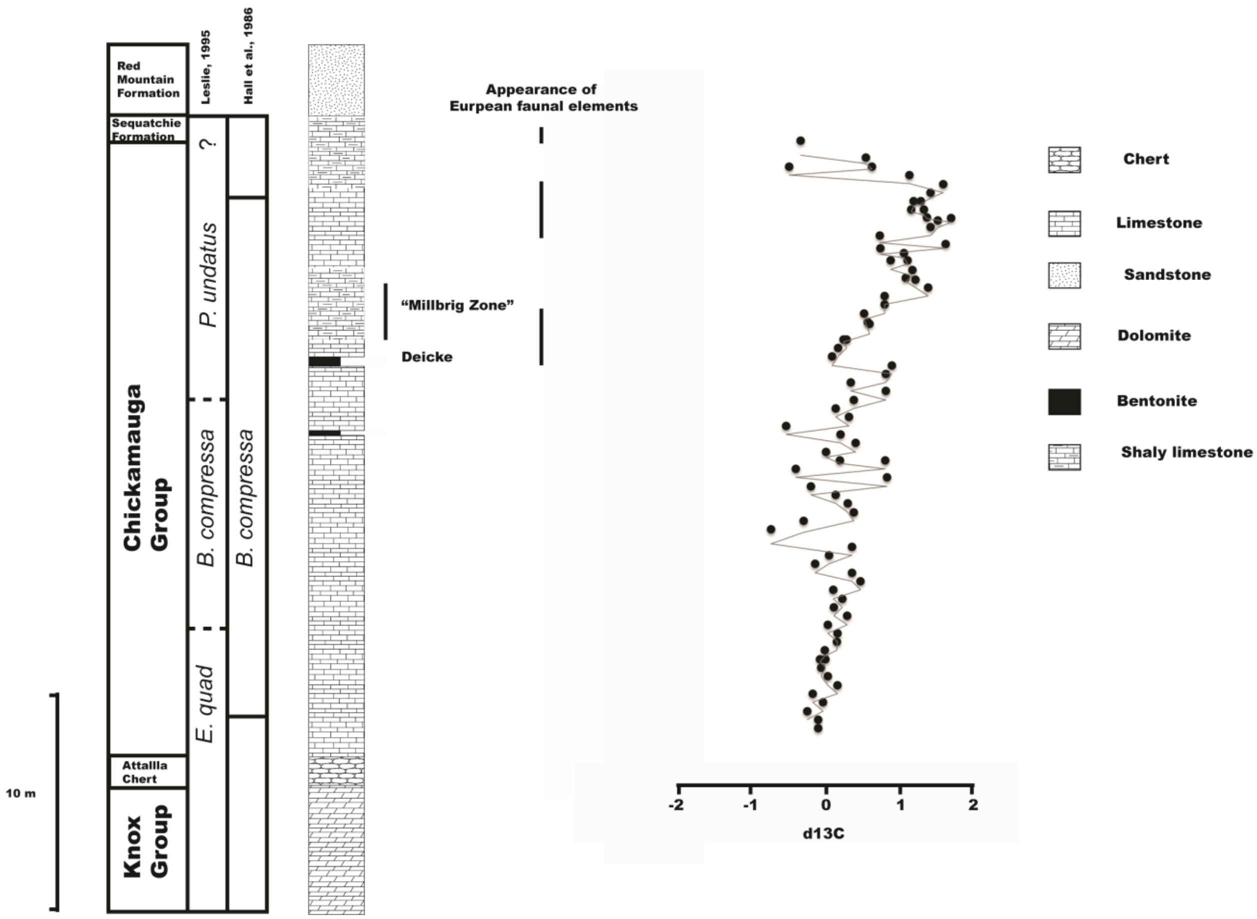



**Figure 6.—Lithology, stratigraphy and carbon isotope data at the Red Mountain Expressway. Carbon isotopes from Quinton et al. (in review). 3-point average. Lithology and European faunal data from Raymond et al. (1986).**

they occur in the upper few meters of the Stones River Limestone, with the Millbrig occurring right at the contact of the Stones River and Nashville Limestones. This contact would seem to correlate with the M4-M5 sequence boundary of Holland and Patzkowsky (1996) as defined in the cratonic interior sections of the Nashville and Jessamine Domes of Tennessee and Kentucky, respectively. Yet at the Red Mountain Expressway, there is no obvious lithologic break that would likewise seem to correlate with the M4-M5 boundary, nor can an obvious M4-M5 boundary be identified at Alexander Gap. Difficulties associated with identifying sequence boundaries across the midcontinent have been addressed and scrutinized previously by Pope and Read (1997) and Kolata et al. (1998), and the problem of locating any of the sequence boundaries of Holland and Patzkowsky (1996) in the Blount foreland basin sections, when the various boundaries were originally defined at cratonic sections, will be addressed at a number of the stops on this trip. We suggest that perhaps eustatic sealevel changes influenced stratal architecture far less in the flysch and molasse deposits of the Blount foredeep than in the cratonic

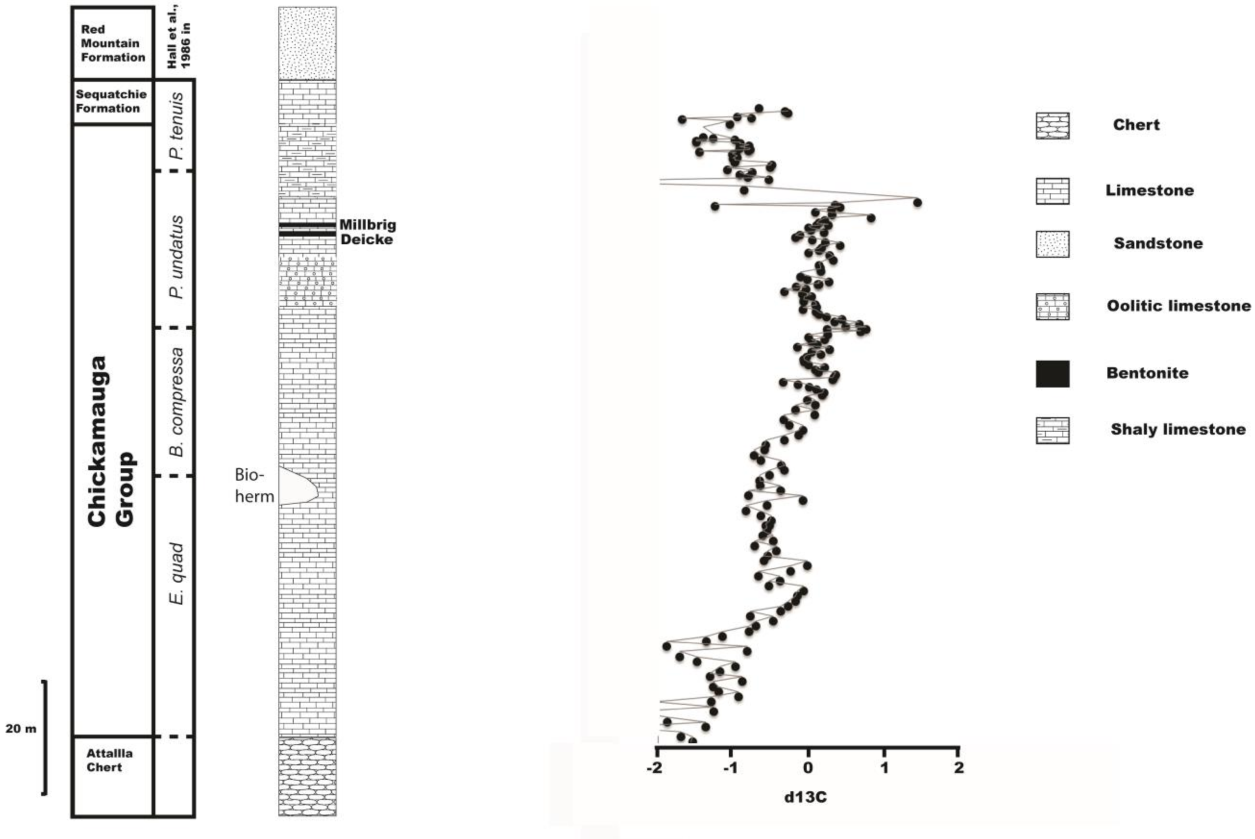



**Figure 7.—Lithology, stratigraphy, and carbon isotopes at Tidwell Hollow. Carbon isotopes from Quinton et al. (in review). 3-point average. Location of Millbrig from Haynes (1994). Location of Deicke based on field observations of Haynes and Herrmann.**

sequences, because in the depositional environments that were most proximal to the Blount orogenic highlands tectonic influences may have very likely overwhelmed the eustatic signals in the depositional sequence, but in the distal cratonic sequences, the eustatic signals were dominant.

Recently, Quinton et al. (in review) measured bulk carbonate $\delta^{13}C$ and $\delta^{18}O$ as well as organic carbon $\delta^{13}C$ values from four locations in Alabama (in addition to Tidwell Hollow, Red Mountain Expressway, and Fort Payne, samples from an exposure north of Gadsden at Big Ridge were analyzed, but we will not visit that outcrop on this trip). The Deicke and Millbrig K−bentonites have been identified in these sections (Haynes, 1994), and they can be used for precise correlation between sections and to evaluate the exact timing of the isotope curve among the different sites. $\delta^{13}C$ results from Fort Payne and Gadsden record an ~1‰ positive excursion following the Millbrig K−bentonite. The other two sites, Tidwell Hollow and Red Mountain expressway, both located near the continental margin, a ~2‰ negative excursion follows the Millbrig K-bentonite. Currently, the lack of a GICE signature is attributed to a hiatus spanning the GICE interval. The presence of a hiatus is also suggested by the conodont biostratigraphy of the different sites (Table 1 and 2; personal communication S. Leslie, 2015).

| | *Drepanoistodus suberectus* | *Panderodus Gracilis* | *Curtognathus sp.* | *Erismodus sp. cf E. radicans* | *Phragmodus undatus* | *Belodina compressa* | *Dapsilodus aff. D.mutatus* | *Plectodina/Aphelognathus?* | *Aphelognathuss ap. Aff. A. grandis* | *Yaoxianognthus abruptus* | *Apheognathus kimmswickensis* | *Oulodus subundulatus* | *Plectodina sp* | *Oulodus sp.* | *Plectodina tenuis* | *Rhipidognathus symmetricus* | *Oulodus oregonia* | *Apheognathus politis* | Bio-zone |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TH 25m | | | | | x | | | | | | x | | | | x | x | x | x | *P. tenuis* or higher |
| TH 22.85 | | | | | | | | | | | x | | | | x | x | x | x | |
| TH 20m | | | | | | | | | | | | | | | x | x | ? | ? | |
| TH 18.5 m | | | | | | | | | | | | | x | | x | ? | x | x | |
| TH 16m | | x | | | | | | | | | x | | | x | | ? | | | |
| TH 11m | x | | | | | | | | | | x | x | x | | | | | | |
| TH 10.5 m | | x | | | x | | | x | x | x | | | | | | | | | *P. undatus* Zone |
| TH 8m | | x | x | x | | | | x | | | | | | | | | | | |
| TH 0m | x | x | x | x | x | x | x | | | | | | | | | | | | |

**Table 1.—Conodont fauna distributions for Red Mountain Expressway (from Quinton et al., in review).**

| | *Drepanoistodus suberectus* | *Panderodus gracilis* | *Phragmodus undatus* | *Belodina compressa* | *Oistodus venustus* | *Dapsilodus aff. D.mutatus* | *Plectodina sp.* | *Yaoxianognthus abruptus* | *Icriodella superba* | Zone |
|---|---|---|---|---|---|---|---|---|---|---|
| RM 10.5 | | x | x | | | | | | x | |
| RM 10 | x | | x | | | | | | | |
| RM 9.5 | x | | x | | | | | | x | |
| RM 8.97 | x | x | x | | | | | ? | x | |
| RM 8.5 | x | | x | | | x | | | | |
| RM 8 | x | x | x | | | x | | ? | | |
| RM 7.5 | | | | | | | | | | |
| RM 7.05 | | | x | | | | | | | |
| RM 7 | x | | x | | | | | x | x | |
| RM 6 | x | | x | | | | | | x | P. undatus |
| RM 5.25 | x | x | x | x | | | | x | x | |
| RM 5 | x | x | x | x | | | | x | x | |
| RM 4.55 | | | x | | | | | | | |
| RM 4 | x | | x | x | | | | | x | |
| RM 3.55 | | | x | x | | | | | x | |
| RM 3.5 | | | x | | | | | x | x | |
| RM 3.45 | x | x | x | x | | | | x | x | |
| RM 2 | x | x | x | x | | x | | x | | |
| RM 1.5 | x | x | x | x | | | | x | | |
| RM 1 | x | x | x | x | | | | x | | |
| RM 0.9 | x | | x | ? | | | | x | | |
| RM 0.5 | | | | x | | | | | | |
| RM 0 | x | x | x | x | x | x | x | | | |

**Table 2.—Conodont data for Red Mountain Expressway (from Quinton et al., in review).**

**STOP 1-1: Red Mountain Expressway section, Birmingham AL; 8:30 – 10:30 am (120 mins)**

At this stop (Fig. 5), trip participants will be introduced to some of the important ideas regarding Ordovician strata in the Southern Appalachians, with an ~15-20 minute overview of litho-, bio-, chrono-, and sequence stratigraphy, isotope geochemistry, paleoclimate, facies relations, carbonate buildups, K-bentonites, and paleoecology. We will discuss this exposure in particular, as well as regional Ordovician relationships in general. As we walk upsection along the walkway, we will point out the changes in lithology that occur, while also highlighting the ongoing isotopic work to identify isotope excursions (Fig. 6), as well as various aspects of paleoclimate, the Taconic orogeny, Ordovician volcanism and the tephras that have become the Deicke and Millbrig K-bentonites including an overview of their mineralogy and petrology, and then finally, the extreme thinness of the Sequatchie? Fernvale? Formation here. Participants are also encouraged to walk upsection to view and collect the world-famous ironstones of the Silurian Red Mountain Formation, in addition to any Ordovician samples.

**STOP 1-2: Tidwell Hollow section along Blount County Highway 15, ~5 miles SW of Oneonta, AL; 12:30 – 2:30 pm (120 mins)**

At this exposure, we will focus more provincially on a sequence of primarily platform carbonates that were deposited along the Laurentian margin. The first stop will be at the Attalla Chert Conglomerate, near the base of the section, to see limited exposures of the cherty rubble that accumulated over a wide area of the paleokarst surface of the Knox unconformity. From there we will go upsection into the younger strata that are far more extensively exposed. We will be able to examine small buildups of bryozoans, sponges, corals, and stromatoporoids, along with other facies that accumulated in the shelf and peritidal environments that were prevalent in this area. Discussion will center on the isotopic and paleoclimate work currently being done (Fig. 7), which includes the search for the Guttenberg Isotopic Carbon Excursion (GICE). The importance of the Deicke and Millbrig K-bentonites as reference horizons for that work will be discussed (Fig. 2), and we will see the distinctive biotite-rich middle zone of the Millbrig and discuss how crystal-rich (vs. vitric-rich) the original tephra was as compared to many or most other K-bentonites in this region and elsewhere. We will also discuss the similarities and differences of the Tidwell Hollow section and sections to the north on the Nashville Dome, especially regarding the sequence boundaries of Holland and Patzkowsky (1996), i.e., the M3, M4, M5 etc., and the problems that arise when attempts to extend cratonic sequence architecture into proximal, molasse deposits of the Taconic foredeep, vs. more distal, flysch deposits in the Taconic foredeep, where eustatic signals have been recognized and correlated (Joy et al., 2000; Brett et al., 2004; Mitchell et al., 2004). The Ordovician – Silurian boundary is not exposed here, but we note that the very thick ironstones of the Silurian Red Mountain Formation that we saw at

Stop 1-1 are here reduced in thickness to just a 6-8 cm thick ironstone that is exposed to the northwest along the road (Fig. 8).

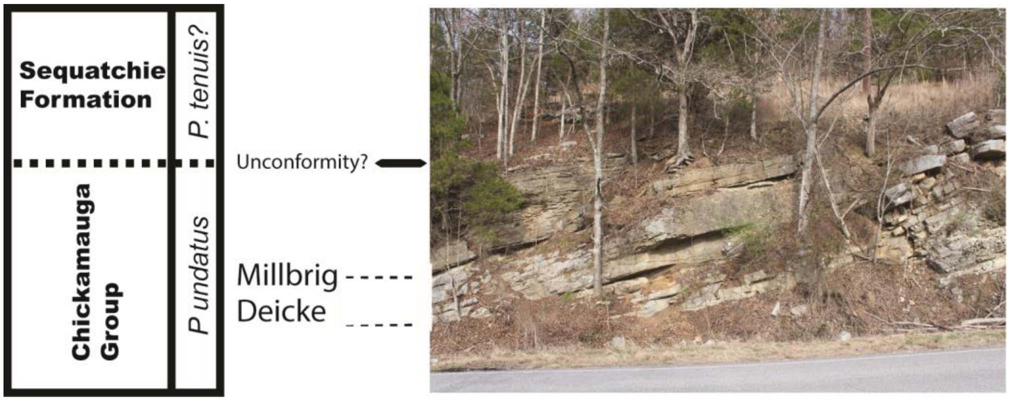



**Figure 8.—The stratigraphic interval in which the Deicke and Millbrig K-bentonites occur at Tidwell Hollow. Based on lithologic change and conodont zones, it appears that an previously unidentified unconformity is present, and as a result the GICE interval is missing at the Tidwell Hollow section.**

### *The Ordovician siliciclastic succession southeast of the Helena Thrust*

On a regional scale, carbonate sedimentation persisted throughout what is now the southern Appalachians until the onset of tectonic activity associated with the Taconic orogeny (Read and Repetski, 2012), when the southeastern edge of the Laurentian carbonate shelf began to subside and foreland basins developed on what had been shallow continental shelf margin environments. The collision of Laurentia with the Taconic microplates and terranes occurred first in the southern Appalachians from Alabama northeastward to west-central Virginia in what is widely referred to as the Blountian phase of the Taconic orogeny, a deformational event that produced the Blount foredeep (Rodgers, 1971; Drake et al., 1989). In Alabama, development of the Blount foredeep occurred in late Darriwilian to early Sandbian time. The change is evident in sections south and east of Birmingham, where shelf limestones of the Lenoir, Pratt Ferry, and Little Oak Limestones are overlain by black graptolitic mudrocks of the Athens and Columbiana Shales (Fig. 3, not seen on this trip) that were deposited in basinal environments.

When the Blount foredeep filled with these flysch deposits, a molasse sequence of redbeds and quartz arenites prograded west and northwest from the perimeter of the Blount highlands across the now-filled foredeep, and these marginal marine to transitional and non-marine sediments of the Bays Formation and its lateral equivalents extend from north-central Alabama to west-central Virginia. At Alexander Gap, we will see the Colvin Mountain Sandstone, a sequence of mature quartz arenites, some pebbly zones as well as some prominent cross-bedded intervals. These quartz arenites are underlain and overlain by redbeds, which include siltstones and shales, some of which are calcareous.

**STOP 1-3: Alexander Gap, and roadcut through Colvin Mountain along the E side of northbound US Highway 431, Glencoe, AL; 3:45– 4:45 pm (60 mins)**

This stop will introduce the group to the redbeds and quartz arenites and conglomerates of the molasse that prograded over the now-filled Blount foredeep, and which represent the first pulse of siliciclastic sediments deposited in various fluvial-deltaic-beach-coastal environments. The gradational contact of the upper several meters of Greensport Formation redbeds (primarily mudrocks) with the coarser and more mature quartzose beds of the overlying ~20 m thick Colvin Mountain Sandstone will be observed, as will both the Deicke and Millbrig K-bentonites in the upper several meters of the quartz arenites of the Colvin Mountain Sandstone (Table 3). The presence of quartz sandstones both above and below the Deicke and Millbrig is an important stratigraphic relationship (Fig. 9), and one that will be referred to at other stops in the next couple of days where the two K-bentonites occur in the Blount molasse. Diagenetic alteration of the tephras in the sandstone has occurred along a different pathway than in the carbonate sections to the northwest (Haynes, 1994); the feldspars are extensively kaolinized, and the biotite in the Millbrig is gone, but the ilmenites in the lower Deicke are little altered, and as discussed below in more detail at Stop 2-2, that is the case in the Deicke throughout the region where it occurs in the redbeds and quartz arenites of the Blount molasse (Haynes and Melson, 1997).

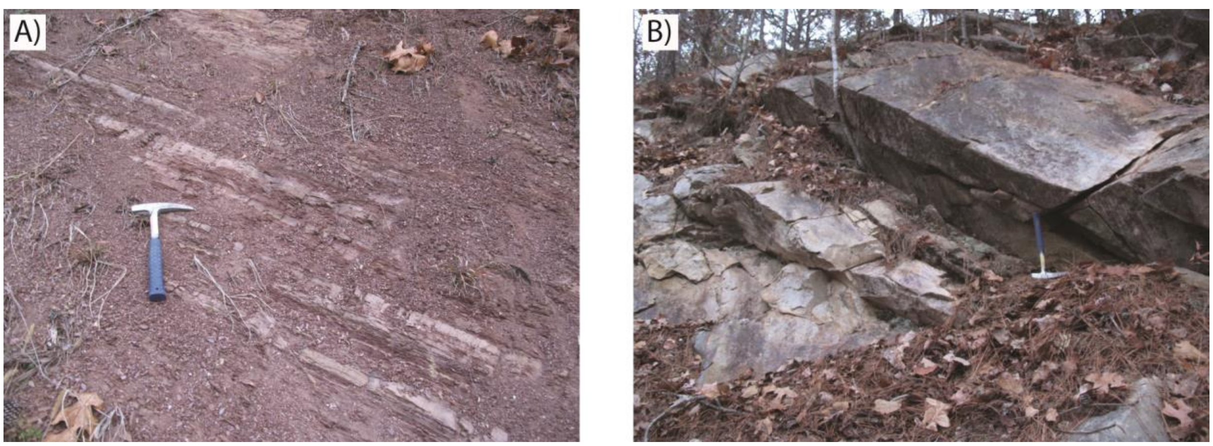



**Figure 9.—(A) Redbeds of the Greensport Formation at Alexander Gap. (B) The Deicke K-bentonite as identified by Haynes (1994) in the cross-bedded quartz arenites of the Colvin Mountain Sandstone at Alexander Gap.**

Underlying the quartz arenites of the Colvin Mountain Sandstone are several meters of the red mudrocks that comprise the Greensport Formation, which in this region ranges in thickness from 60 to 75 m, with a variety of sedimentary structures (ripple marks, flaser bedding, burrows, desiccation cracks) that point to deposition in peritidal environments ranging from shallow shelf to supratidal mud flats (Benson and Mink, 1983). The sandstones of the Colvin Mountain include planar and trough cross-bedding, planar laminae that are bedding parallel to

**Table. 3.—Measured section of Colvin Mountain Sandstone Member at Alexander Gap along the east side of the cut through the gap along northbound U.S. Highway 431, Calhoun Co., Ala. Alexander Gap section: measured top down beginning at uppermost quartz arenite bed "Sequatchie" Formation. 1436 Measurements made by J. Haynes in 2003.**

**Bed**

43 Some redbeds above the uppermost quartz arenites (we agree with the speculation of J. Dennison, which is that this actually not the Sequatchie, but the upper redbeds of the Bays Formation, and that there is no unconformity at the top of the Colvin Mountain: "the redbed sequence may be Middle Ordovician, analogous to the upper redbed sequence of the Bays Mountains of Tennessee, where redbeds underlie the Martinsburg Shale (Reedsville Formation of some authors) and overlie a middle whitish sandstone of the Bays Formation, which in turn overlies a lower redbed sequence of the Bays Formation.") ............ .not measured

**Colvin Mountain Sandstone Total estimated thickness: 63.25 ft.**

Unless noted otherwise, all cross bedding is tangential, S to N paleocurrent direction

42 Med. bedded yellowish med. ss., planar lamination ............ .5 in
41 Med. ss., cross beds and some planar lamination ............ 1 ft 4 in
40 Med. ss, planar lamination ............ 7 in
39 Med. ss., planar lamination ............ 6 in
38 Med. ss., cross beds............ 7 in
37 Med. ss, planar lamination ............ 1 ft 1 in
36 Med. ss., cross-bedded 5 in. above base ............ 2 ft
35 Med. ss., cross bedding in lower 6 in., with sharp top to cross beds,
rusty oxidation color to bed (photo # 3243) ............ 11 in
34 Med. ss., planar lamination ............ 6 in
33 Med. ss., planar lamination (photo # 3242) ............ 8 in
32 Millbrig K-bentonite ............ 3 ft 4 in
Pale blue gray coarse tuffaceous zone, but no obvious biotite ............ 4 in
Pale blue gray clay, no obvious structure ............ 3 ft
31 Med. ss., planar lamination ............ 8 in
30 Med. ss., cross bedding in 8 in. to 16 in. interval above base ............ 2 ft 1 in
29 Med. ss., planar lamination ............ 10 in
28 Med. ss., splits into a 12 in. and 5 in. bed along outcrop ............ 1 ft 5 in
27 Massive yellowish white med. to crs. ss ............ 4 ft 4 in
26 Massive yellowish white med. to crs. ss ............ 1 ft 10 in
25 Massive yellowish white med. to crs. ss ............ 1 ft 5 in
24 Massive yellowish white med. to crs. ss ............ 8 in
23 Massive yellowish white med. to crs. ss ............ 1 ft 6 in
22 Massive yellowish white med. to crs. ss., rusty oxidation zone at base............ 1 ft 4 in
21 Massive yellowish white med. to crs. ss., lowest sandstone in the exposure
that is not obviously white on the weathered surface............ 1 ft 3 in
20 Massive white med. to crs. ss, trough cross bedded............ 6 in
19 Deicke K-bentonite ............ 1 ft 2 in

Pale blue gray clay with small shiny black ilmenite grains and small bright green zones, medium gray and heavily pyritized at ditch level but not higher up on exposure
18 Massive very hard silicified and rusty oxidized med. ss........................................................................1-2 in
17 Massive white cross-bedded med. ss. ........................................................................................... 6 in
16 Massive white cross-bedded med. ss., with channel? form .............................................................1 ft 6 in
15 Massive white med. ss., light gray 13 in. zone 21 in. below top; cross-beds
with microslump? (photo # 3246) in 5 in. oxidized zone 7 in. above base .........................................5 ft 6 in
14 Massive white med. ss .......................................................................................................................2 ft
13 Massive white med. ss ....................................................................................................................3 ft 4 in
12 Massive white med. ss., cross bedded...........................................................................................2 ft 11 in
11 Massive white med. ss., distinct cross-bedding pattern (photo # 3236)............................................ 3 ft 8 in
10 Blocky white med. ss. with rusty spots............................................................................................ 18 in
9 Thin to medium bedded white med. ss ..........................................................................................1 ft 8 in
8 Massive white med. ss ...................................................................................................................... 7 in
7 Massive fn. to med. ss., basal 3 in. is remarkably porcelaneous, quartzite-like ....................................... 10 in
6 Massive white crs. ss., less indurated than overlying bed, but still hard.................................................... 7 in
5 Massive white med. ss., cross-bedded .................................................................................................1 ft
4 Massive white v. crs. ss., slightly crumbly, planar lamination ................................................................. 7 in
3 Massive white crs. ss., with granules in lenses 5 to 6 in above
base (photo # 3234)........................................................................................................................ 1 ft 5 in
2 Massive white v. crs. ss., with granules in basal 6 in.............................................................................2 ft
1 Massive white med. to crs. ss., both planar and cross bedding; some heavy
mineral laminae? outlining laminations .........................................................................................2 ft 4 in
Greensport Formation (or Shale Mbr. of Bays?) .......................................................................... not measured

[Jenkins (1984) measured the Greensport, which here is/was very well exposed for quite some distance along the road, and consists of red shale with noticeable yellow laminae and thin beds throughout (e.g. photo # 1987, 1988, 3250, 3251, 3252, & 3253), but the upper 5+ feet is noticeably transitional with the Colvin Mountain Sandstone (photo # 3247, 3248, and 3249) and maybe ought to be included in the Colvin Mountain, as it is thin bedded and silty to fine sandstones, but NOT RED. Low-angle cross-laminated, *Skolithos*, and some ripple marks including oscillation ripples, leading Benson and Mink (1983), and Bayona and Thomas (2003, 2006) to interpret the Colvin Mountain as a sequence of shoaling shallow-marine sand bars.]

---

Overlying the Colvin Mountain Sandstone is another redbed sequence that we will also examine because there is yet some controversy as to the stratigraphic assignment (age and position) of these younger redbeds (Fig. 9a). They have been identified variously as the Sequatchie Formation (Benson and Mink, 1983; Carter and Chowns, 1989) or as redbeds that are older than the Sequatchie and which are equivalent to the redbeds of the upper Bays Formation farther northeast in Tennessee and Virginia (Dennison, 1991). If these redbeds above the Colvin Mountain Sandstone are the Sequatchie Formation, then an unconformity occurs at the top of the

Colvin Mountain Sandstone that cuts out the intervening pre-Sequatchie age Ordovician strata, which would include equivalents of the "Trenton" and Reedsville Formations, as well as the regionally extensive *Orthorhynchula* zone at the Reedsville – Sequatchie contact.

The lack of any obvious unconformable relations between the uppermost bed of the Colvin Mountain Sandstone and the redbeds that overlie it, along with the presence of the Deicke and Millbrig K-bentonites in the upper few meters of the Colvin Mountain Sandstone, suggest to us that these overlying redbeds are in fact NOT the Sequatchie Formation, but are as Dennison (1991) suggested instead, a lateral equivalent of the upper Bays Formation farther north. In the Bays Mountains of Tennessee and farther north along Big Walker Mountain in Virginia, redbeds of the Bays Formation sandwich one or several white quartz arenites of varying thickness, and the upper redbeds are overlain by the bioclastic grainstones and packstones of the "Trenton" Limestone or its equivalents (Haynes, 1994). Fossils are very scarce in these redbeds, but brachiopods of Trenton character occur in similar redbeds along Rocky Face Mountain in Georgia at Stop 2-3 (R. Neuman, pers. comm.), which is about 120 km NNE of Alexander Gap.

At this stop, we will also expand on our dialog about the uncertain nature of how the sequence stratigraphic framework from cratonic sections (M4-M5 etc. of the Nashville Dome area; Holland and Patzkowsky, 1996) might be recognized – or not – in the molasse deposits of the Blount foredeep.

## DAY 2. ORDOVICIAN CARBONATE AND CLASTIC DEPOSITS ACROSS STRIKE FROM ALABAMA TO GEORGIA

### Introduction

At today's stops we will examine four exposures of Ordovician strata, one in Alabama, and three in Georgia. The first stop (Ft. Payne, Stop 2-1) is essentially along strike with the Red Mountain Expressway and Tidwell Hollow stops (Stops 1-1 and 1-2) that we saw yesterday. However, at Ft. Payne we will examine in greater detail a critical stratigraphic interval in the carbonate platform sediments in the several meters below and above the contact of the upper laminated lime mudstones of the Stones River and the overlying fossiliferous grainstones to wackestones of the Nashville Group (Fig. 10). This stratigraphic interval includes the Deicke and Millbrig K-bentonites in the upper Stones River, and our discussion will emphasize new isotopic data obtained from analyses of samples collected across the contact, as well as continued discussion on this contact being equivalent to the M4-M5 sequence boundary in the Nashville area of central Tennessee. This will be a good opportunity to examine and collect some of the corals that thrived in the more open marine environments that characterized the Nashville Limestone (Fig. 10). These fossiliferous beds are in contrast to the underlying more restricted peritidal laminated limestones of the upper Stones River Limestone, which themselves are quite a contrast from the bioclastic grainstones and packstones that occur at the equivalent

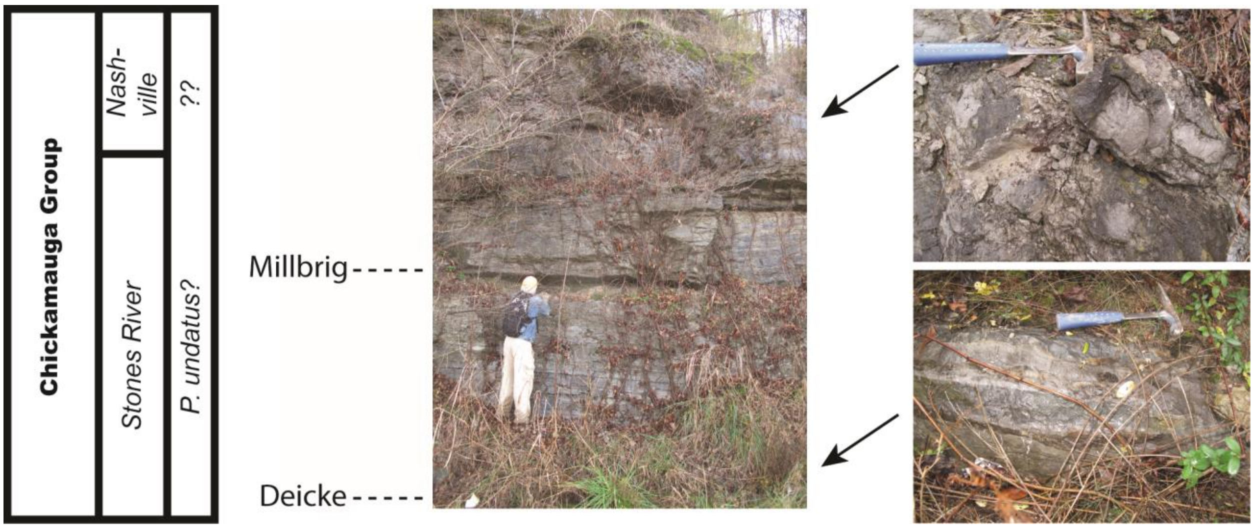



**Figure 10.—The Deicke K-bentonite, which here is underlain by black chert up to 8-10 cm thick (lower right), is at the base of this outcrop. At this location, unlike at the Red Mountain Expressway farther south (Stop 1-1), the Chickamauga Group can be subdivided into two distinct formations, the Stones River Formation and the Nashville Formation. The contact between the two is perhaps correlative with the M4-M5 sequence boundary. There is a distinct lithologic change from the underlying laminated lime mudstones of the upper Stones River to the bioclastic packstones, grainstones, and boundstones of the lower Nashville, which here is fossil rich including several corals (*Tetradium? sp.*; upper right).**

stratigraphic horizon in the Red Mountain Expressway exposure, as determined by using the Deicke and Millbrig K-bentonite beds as isochrons. The stops at Horseleg Mountain, near Rome, Georgia (Stop 2-2) and along Reed Road north of Dalton (Stop 2-4) are in the redbeds and quartz arenites of the Blount molasse, which we saw at Alexander Gap (Stop 1-3) at the end of the day yesterday. Important differences are the much thinner quartz arenites at both stops, the coarser grain size of the quartz arenites at Reed Road, and perhaps most significantly, the stratigraphic relations of the quartz arenites and the Deicke and Millbrig K-bentonites. At Alexander Gap (Stop 1-3), the K-bentonites were enclosed by thick cross-bedded quartz arenites of the Colvin Mountain Sandstone (Fig. 9), whereas at Horseleg Mountain, the Deicke is immediately beneath the Colvin Mountain Sandstone and it overlies the uppermost redbeds of the Greensport Formation (Fig. 11), and at Reed Road, both the Deicke and Millbrig are in redbeds downsection from the oldest pebbly quartz arenites that are tentatively correlated with the Colvin Mountain Sandstone on the basis of petrographic analysis. The Millbrig has not been definitively identified at Horseleg Mountain, but it may be a very weathered clay-rich zone in the redbeds upsection from the prominent ledge of the Colvin Mountain Sandstone. Again, as at Alexander Gap, the redbeds above the Colvin Mountain Sandstone are questionably correlated with the Sequatchie Formation (Chowns and Carter, 1983), but those redbeds may in fact be correlative instead with the upper redbeds of the Bays Formation farther north, as discussed yesterday at Alexander Gap.

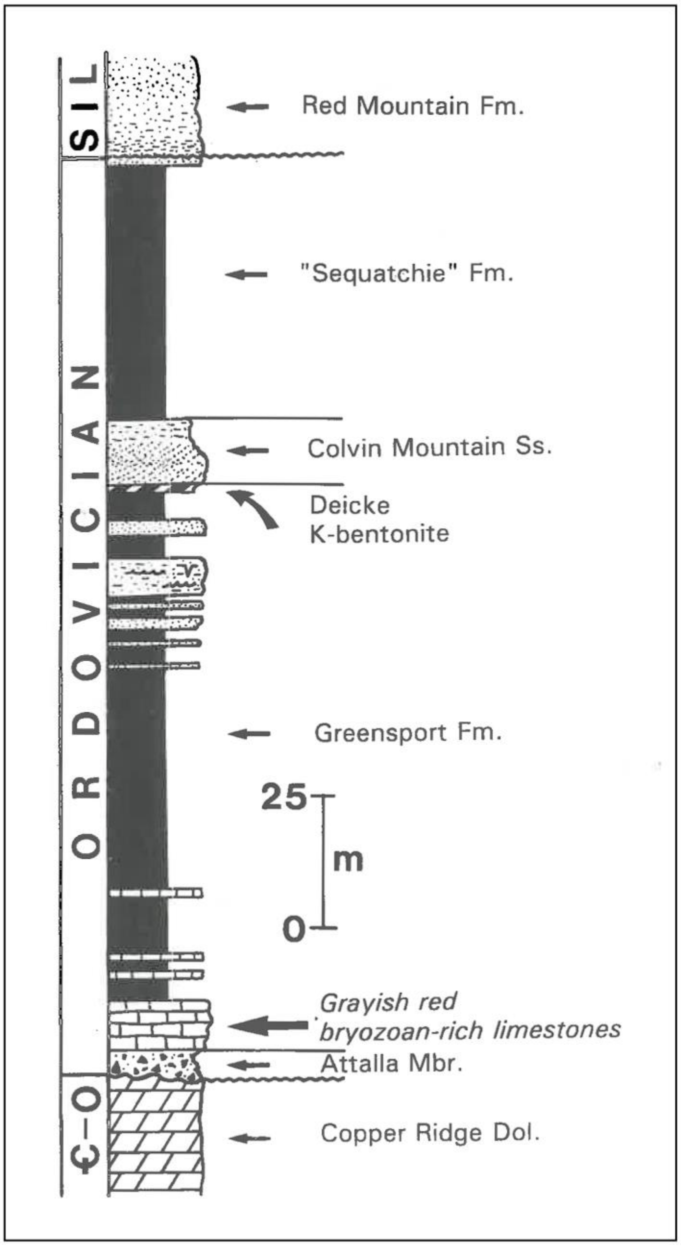



**Figure 11.—Composite stratigraphic column of exposures on Horseleg Mountain, Stop 2-3, near Rome, GA.**

The section at Horseleg Mountain will be our first look at the thin limestones that underlie the Greensport Formation redbeds and overlie the Attalla Chert Conglomerate. These may be correlative with the Lenoir Limestone, or as shown in Figure 2, they may be limestone beds within the Greensport Formation. The limestones are reddish brown from hematite that coats most of the framework grains and is also pervasive in the patchy micritic matrix. Most samples are skeletal packstones and grainstones that contain an abundance of bryozoans, with lesser calcareous red algae, and some brachiopods and trilobites as well.

The Deicke K-bentonite here at the Horseleg Mountain section yields appreciable quantities of ilmenite phenocrysts that are little altered (Fig. 12). Visually, they are still weakly magnetic, black, and shiny, with a metallic luster (Fig. 12C, D), and thus quite unlike the highly altered (to leucoxene) ilmenites in the Deicke obtained from exposures where that K-bentonite is in a carbonate sequence, such as at Tidwell Hollow and Fort Payne. The leucoxene pseudomorphs of ilmenite from Deicke samples in those and other carbonate sections are various shades of light brown, are non-magnetic, and they exhibit a more dull luster (Fig. 12E, F), but there is a continuum of textures between nearly unaltered ilmenites to the leucoxene pseudomorphs. Data obtained from electron microprobe analysis of several ilmenites from the Deicke here at Horseleg Mountain are compared with ilmenites separated from the Deicke at the Thorn Hill section in Tennessee and the Rockdell (Hayters Gap) section in Virginia (not seen on this trip), and with an ilmenite standard of Jarosewich et al. (1980). Our results (Fig. 13) show that although the ilmenites in the Deicke are compositionally different from the ilmenite standard that

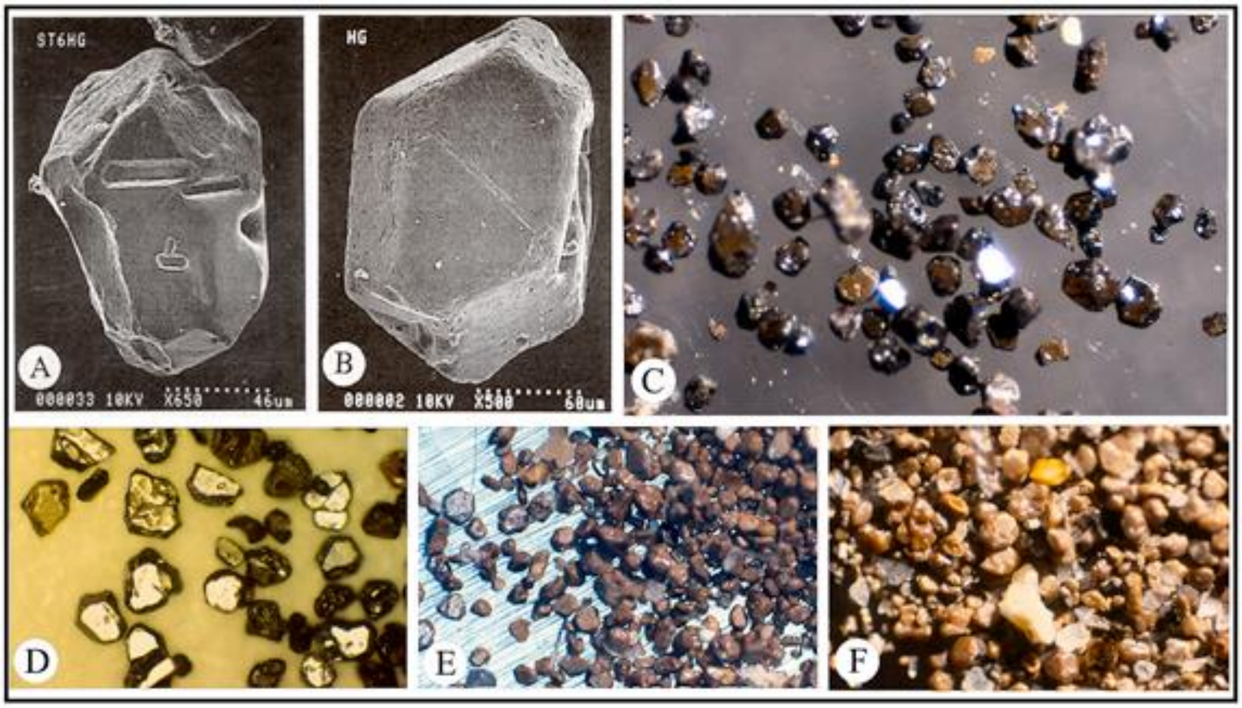



**Figure 12.—Ilmenite grains from the Deicke K-bentonite that exhibit some of the distinguishing textures observed in many samples. (A) Grooves in ilmenite where other mineral crystals, probably apatite, were originally present in the magma chamber and possibly during and after eruption of the tephra as well. Hayters Gap, near Rockdell, Virginia, (B) Euhedral ilmenite that, like the grain in (A), exhibits the hexagonal crystal shape that is common in ilmenite phenocrysts. Hayters Gap. (C) Reddish brown to dark brown to black weakly magnetic ilmenite grains, several of which exhibit a shiny metallic luster on the larger crystal faces. Hayters Gap. (D) Ilmenite grains that are very similar in texture to those from Hayters Gap in (C), with their metallic luster, black color, and weak movement in a magnetic field. Horseleg Mountain, near Rome, Georgia. (E) Ilmenite grains now partly altered to leucoxene. Citico Beach, Tennessee. (F) Ilmenite grains that are entirely altered to leucoxene, as evidenced by their dull luster, light brown color, and lack of response to a magnet. Frankfort, Kentucky.**

was used to monitor analytical precision, the Deicke ilmenites are nonetheless relatively consistent compositionally between this exposure near Rome, Georgia, the Thorn Hill exposure northwest of Knoxville, Tennessee, and the Hayters Gap exposure southeast of Rockdell, Virginia. So within limits, the ilmenite in Deicke samples from the Blount molasse has value as a correlation tool, along with other phenocrysts including feldspar and biotite (Haynes, 1994; Haynes et al., 1995, 1996), and apatite (Samson et al., 1988, 1995; Emerson et al., 2004; Sell and Samson, 2011; Sell et al., 2015).

It is worth noting that either phenocrystic ilmenite, or leucoxene pseudomorphs of original ilmenite phenocrysts, was obtained and analyzed from samples of the Deicke at 29 of the sections that were studied by Haynes (1994) throughout the eastern midcontinent, and in none of those samples was any evidence observed that would support the suggestion of Samson et al. (1988) that leucoxene in the Deicke might be an alteration product of biotite. Rather than invoking a biotite-to-leucoxene alteration process that “must be complex to remove most of the Al, Si, Fe, and K from the biotite” (Samson et al., 1988), we suggest a simpler explanation, that the leucoxene is the product of an alteration process that starts with phenocrysts of ilmenite in the original Deicke tephra, which are far more abundant, and far larger, than the biotite grains in the Deicke of that region (Haynes, 1994; Haynes et al., 1995; Haynes and Melson, 1997), rather than with phenocrysts of biotite. Diagenetic removal of $Fe^{2+}$ from originally volcanogenic ilmenite is a far less complex chemical process overall (Morad, 1988; Morad and AlDahan, 1986) than any of the alteration pathways suggested by Samson et al. (1988). In many phenocrystic ilmenite and authigenic leucoxene grains that we obtained from samples of the Deicke, embedded apatite crystals or rodlike grooves are present (Fig. 12A; Haynes and Melson, 1997, Fig. 3). These embedded apatites (or the grooves where embedded crystals had been present) are a petrographic characteristic that Samson et al. (1988) referenced as evidence that the authigenic leucoxene in Deicke samples was derived from alteration of biotite grains. Whereas it is true that some biotite grains in the Deicke (and the Millbrig) do contain apatite inclusions, as well as zircon inclusions (Haynes, 1994, Fig. 10), we nevertheless favor the much simpler chemical alteration process of primary ilmenite to authigenic leucoxene. That alteration pathway adequately explains the abundance of leucoxene in Deicke samples from dozens of sections throughout Kentucky, Tennessee, Alabama, Georgia, and Virginia (Haynes, 1994), and it is a pathway that is consistent with the abundance of nearly unaltered ilmenite phenocrysts in Deicke samples from the Blount molasse including samples from Alexander Gap and Horseleg Mountain (Haynes, 1994; Haynes and Melson, 1997).

The stop at Dug Gap (Stop 2-3) will be our first stop that is focused on the youngest Ordovician strata of this region. We will see what may be one of the most, or even the most, southerly occurrences of the regionally widespread *Orthorhynchula* biozone (known informally as just the *Orthorhynchula* zone), which separates the underlying Reedsville? Formation here from the overlying Sequatchie Formation (Fig. 14). This biozone, characterized by many densely clustered molds and casts of brachiopods including the large brachiopod *Orthorhynchula sp*., especially *Orthorhynchula linneyi*, extends northward to Pennsylvania (Bretsky, 1969, 1970), and is a very useful stratigraphic marker horizon. The measured section of Dug Gap by Zeigler (1988) does not note the presence of any *Orthorhynchula*, and in fact our review of the literature indicates that the only mention of *Orthorhynchula* in Georgia are these two citations:
(1) Butts & Gildersleeve (1948, p. 33), who noted it in the “Maysville Fm” which they describe as a soft, tawny, clayey siliceous rock, and that *Orthorhynchula linneyi* was found on the road east of Trion at Narrows Gap on Taylor Ridge (that location is southwest of Dug Gap); Butts and Gildersleeve also state (p. 34):

> “The Sequatchie is known to be present wherever its horizon crops out as far east as the northwest slope of White Oak Mountain, and its southward continuation, Taylor Ridge. It has not been observed, however, in the ridges carrying the Red Mountain formation east and south of Tunnel Hill to and including Lavender Mountain. It may be present in those areas, however, although unobserved.”

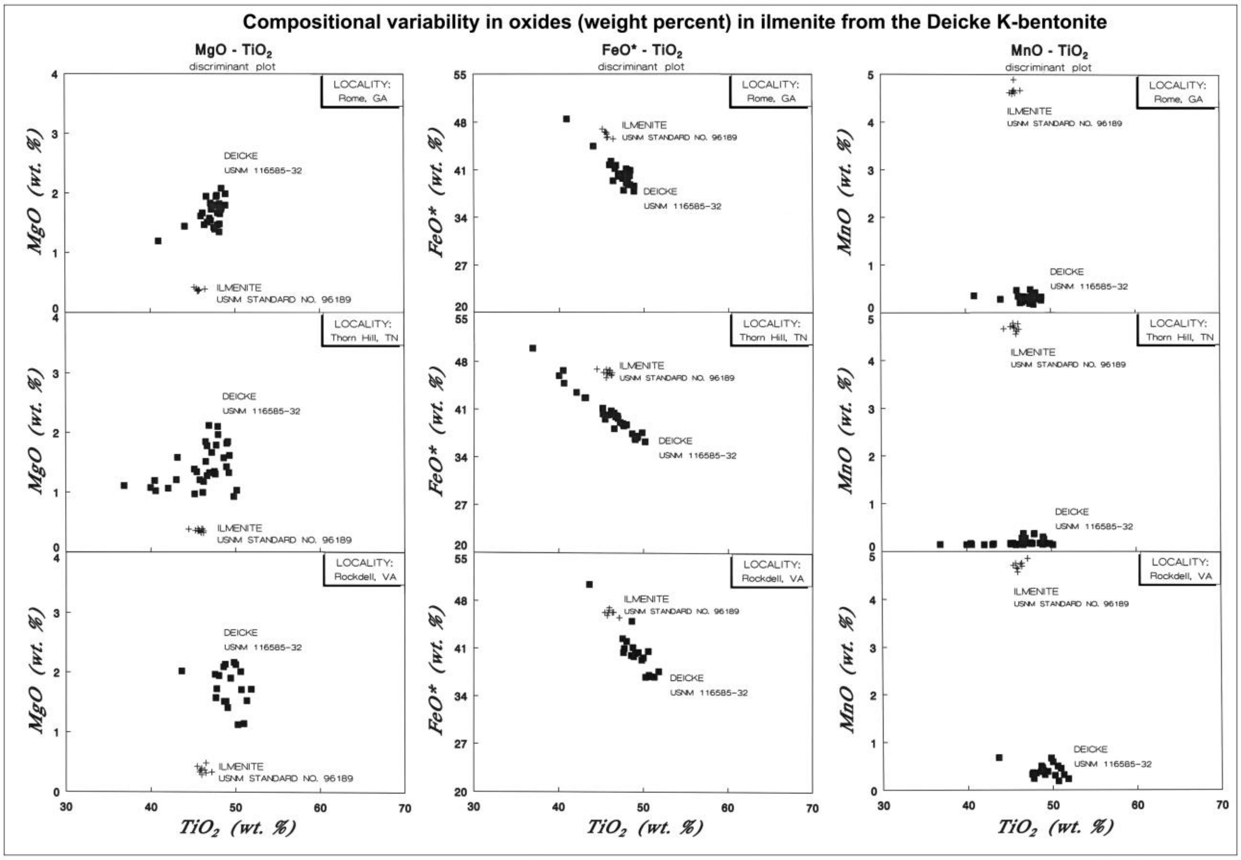



**Figure 13.—Electron microprobe analyses of major elements (as oxides) in nearly unaltered ilmenite phenocrysts from samples of the Deicke K-bentonite at 3 localities: Horseleg Mountain, near Rome, Georgia, Thorn Hill, Tennessee, and Hayters Gap, near Rockdell, Virginia. Horseleg Mountain and Hayters Gap are about 420 km apart, and yet the compositional trends in the ilmenites are quite constant over that distance, which represents about ¾ of the along-strike extent of the Blount foredeep.**

And this comment suggests to us that the exposure of the *Orthorhynchula* zone here at Dug Gap was not seen by Butts and Gildersleeve:

(2) Allen and Lester (1957, p. 17, 19, 51), who list *Orthorhynchula* in an exposure at Dunaway Gap on Horn Mountain, to the south of Dug Gap, and in many of the carbonate sections to the northwest. Unfortunately, Allen and Lester (1957) did not list which fossils came from which specific exposures, so their faunal lists are now of somewhat limited value.

Uphill and upsection from the exposure of the *Orthorhynchula* zone is an exposure of the Sequatchie Formation that we will examine. We will note how the Sequatchie differs from what we saw in the equivalent stratigraphic interval at Stop 1-1 in the Red Mountain Expressway exposure, as well as what we saw above the Colvin Mountain Sandstone at Alexander Gap. In addition, we will discuss the relationship of the Sequatchie to the Juniata and Oswego Formations farther north. This exposure will be our introduction to the significance of these three stratigraphic units in the Ordovician of the Appalachians from New York and Pennsylvania

**Figure 14.—The *Orthorhynchula* zone at Dug Gap, with the characteristic dense abundance of brachiopods, both molds and casts, along discrete bedding planes. Inset at upper left shows the exposure at Dug Gap. Inset at lower right shows several brachiopod molds from samples collected at this location, which we will see at Stop 2-3.**

southward to right here at Dug Gap, specifically to the importance of those units as principal components of the younger Queenston molasse that prograded over the main Taconic foredeep, which had by that time shoaled to near sea level. The Sequatchie-Oswego-Juniata interval records the second pulse of fluvial-deltaic-coastal molasse clastics associated with the Taconic orogeny, and sediment generated thusly (the aforementioned Queenston molasse) was dispersed over a far larger area than the earlier Blount molasse, which, as we have already seen yesterday at Stops 1-2 and 1-3, did not even reach across the width of the present-day folded Appalachians of the Valley and Ridge province. By contrast, the Sequatchie-Oswego-Juniata sediments extend west of the Valley and Ridge and into the subsurface of the Appalachian basin. We will be highlighting the presence of strata associated with the Blount molasse and of younger strata associated with the Queenston molasse at Dug Gap and the preceding stop at Horseleg Mountain (Stop 2-2) as well as the final stop of the day at Reed Road (Stop 2-4) just north of Dalton (Fig. 15).

**STOP 2-1: Ft. Payne, AL, at Exit 222 on I-59; exposures along entrance ramp to northbound I-59 and just to north on E side of I-59 N; 8:30 – 10:00 am (90 mins)**

At this stop we will begin with a recap of what we have seen thus far regarding stratigraphy, isotope geochemistry, paleoclimate, facies relations, carbonate buildups, K-bentonites, and paleoecology of the Ordovician carbonates in this region. As we did at Tidwell Hollow (Stop 1-2), this stop will also include discussion of current and ongoing isotopic work on carbon isotope excursions, and on various aspects of climatic changes in the later Ordovician. We will examine excellent exposures of the upper few meters of the Stones River Limestone, and the associated outstanding exposures of relatively thick sections of both the Deicke and Millbrig K-bentonites, as well as one or two thinner K-bentonites, in the Stones River (Fig. 10). The contact of the

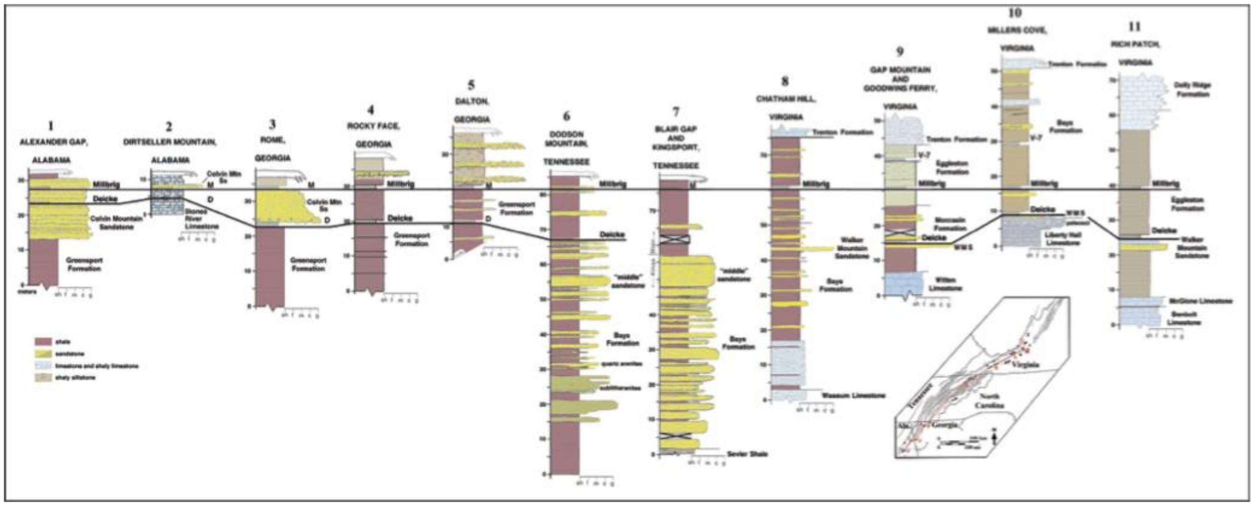


**Figure 15.—Correlation of sections in the Blount molasse along depositional strike from Alexander Gap, Alabama to Rich Patch, Virginia. The stratigraphic relationships of the quartz arenites in these sections to the Deicke and Millbrig K-bentonites show that these quartz sands and gravels were being delivered to the depositional basin before (Sections 6 to 11 in Tennessee and Virginia, including Section 6, Dodson Mountain, which is Stop 3-3 of this trip), during (Alexander Gap and Rome, which are Stops 1-3 and 2-2 of this trip, respectively), and after (Sections 2, 4, and 5, including Section 5, Dalton, which is Stop 2-4 of this trip) the times that the Deicke and Millbrig tephras were erupted.**

Stones River Limestone and the overlying Nashville Limestone, which is perhaps the M4-M5 sequence boundary? is superbly exposed here, as are the overlying several meters of the Nashville Limestone, which is a sequence of open marine and more extensively fossiliferous carbonate strata. This will be one of the best exposures to collect samples of both K-bentonites, including the ilmenite (now leucoxene) bearing zone of the lower Deicke, and the biotite-rich middle zone of the Millbrig. In addition, we will continue to discuss the sequence stratigraphic framework, and how the M4-M5 sequence boundary is recognized in the carbonate sections like this one throughout the region.

### STOP 2-2: Horseleg Mountain, along Radio Springs and Mont Alto Roads, crest of Horseleg Mountain, just south of Rome, GA; 11:15 am – 1:00 pm (105 mins incl. lunch)

The initial parking place at this stop is underlain by float of the Attalla Chert Conglomerate, and as we walk a short distance down the road, we go upsection into an exposure of thin-bedded, reddish brown bioclastic grainstones of the Greensport (or Lenoir?) Formation that is only a few meters thick. After examining these interesting limestones, we will drive a little farther up the road to see the 80-120 cm thick Deicke K-bentonite and the overlying ~6 m thick ledges of Colvin Mountain Sandstone that are cross-bedded, including herringbone cross-bedding (Chowns and Carter, 1983) where we will continue our discussion about the stratigraphic relations of the quartz sandstones, the redbeds both below and above the Colvin Mountain Sandstone, the K-bentonites, and the M4-M5 sequence boundary.

**STOP 2-3: Dug Gap, cuts along State Highway 52 across Rocky Face Mountain, just west of Dalton, GA; 2:20 pm – 3:45 pm (85 mins)**

We will first examine here what is likely the southernmost described exposure of the *Orthorhynchula* zone in the Appalachians (Fig. 14). This typically 3-4 m thick stratigraphic interval "consists of an irregularly bedded, lumpy, brown sandstone that is almost incredibly filled with fossils which break out and weather out in molds and casts. The rock is gray and solid when fresh, but turns brown and crumbles rapidly on surface exposures. A few zones have become slightly calcareous because of their fossils." (Woodward, 1951). The *Orthorhynchula* zone separates the Reedsville? Formation here (the "Maysville Fm" of Butts and Gildersleeve (1948)) from the overlying Sequatchie Formation, and its distinctive texture looks very much the same here as it does in sections 100s of km to the north, in the Virginias and Pennsylvania, which is worth noting for reference when we see the *Orthorhynchula* zone again during the conference field trip to Germany Valley in West Virginia on June 10$^{th}$.

Just up the road toward the summit at Dug Gap we will stop to see a second exposure that is stratigraphically upsection in the sequence of exposures along the Dug Gap road. This is an exposure of part of the Sequatchie Formation, and we will note the reddish color of some of the beds, a textural feature that led Chowns (1972) to in fact refer to these strata at this exposure as Juniata rather than Sequatchie, but since then Zeigler (1988) and others have considered these strata to be the Sequatchie Formation. We will also take this opportunity to discuss the weathering profile of this exposure of the Sequatchie vs. the appearance of the Sequatchie? redbeds at the Alexander Gap and Horseleg Mountain sections, where the redbeds above the Colvin Mountain Sandstone may or may not be correlative with the strata here, which by all accounts are indeed unequivocally Sequatchie.

At the summit of Rocky Face Mountain, the Silurian Red Mountain Formation and its characteristic resistant quartz arenites overlie the Sequatchie, in what looks much like the same stratigraphic relationship that exists farther north in Tennessee, Virginia, West Virginia, Maryland, and Pennsylvania, where the Clinch or Tuscarora Sandstone overlies the Juniata Formation.

**STOP 2-4: Reed Road, low cut along the east side of the road where it parallels Hamilton Mountain between West Haig Mill/Caprice/Raindance Roads (south of cut) and Battle Way (north of cut), north of Dalton, GA; 4:00 – 4:30 pm (30 mins)**

At this exposure, which does not look like much compared to the grand outcrops like those we have seen at the Red Mountain Expressway and Tidwell Hollow, and will see at Hagan and Dodson Mountain, we will examine THE coarsest sandy conglomerates and pebbly sandstones of the Colvin Mountain Sandstone? (or is it the Bays Formation?) that JTH has found to date in the Blount molasse anywhere in the southern Appalachians, AND we will see that both the Deicke and Millbrig K-bentonites are in redbeds of the Greensport Formation? Bays Formation? a few meters ***downsection*** from the stratigraphically oldest of three conglomeratic zones (Fig. 16). This stratigraphic relationship makes for an important contrast with the Alexander Gap and Horseleg Mountain sections that we have already seen, the now inaccessible Dirtseller Mountain quarry section in Alabama (not seen on our trip), and the Dodson Mountain section (Stop 3-3) that we will see tomorrow, where the Deicke and Millbrig are ***upsection*** from all the quartz sandstones and which is stratigraphically representative of all the exposures in northeast Tennessee and southwest Virginia where the Walker Mountain Sandstone occurs downsection from the Deicke and Millbrig. Also at this stop, we will pose these questions again: Where is the M4-M5 boundary? How could we tell it if we saw it in this sedimentary sequence of redbeds, pebbly sandstones, and as yet no known fossils? Why is it so difficult to identify a sequence boundary in these strata that elsewhere is evidently so readily recognized? What is the evidence for the presence of an unconformity beneath many of the quartz arenites in the Blount molasse? as well as other questions related to sequence stratigraphy in the Ordovician of the entire southern Appalachians, not just those exposures comprised of carbonate strata.

## DAY 3. ORDOVICIAN CARBONATE AND CLASTIC DEPOSITS ACROSS STRIKE FROM VIRGINIA TO TENNESSEE VIRGINIA TO TENNESSEE

### Introduction

At today's stops we will examine three exposures of Ordovician strata, one in Virginia, and two in Tennessee. As we have done on the previous two days, we will be following a route that takes us on an across-strike transect from the carbonate facies in the northwestern Valley and Ridge to the siliciclastic facies in the southeastern Valley and Ridge. This will again allow us to see various aspects of sedimentation in the Ordovician that were governed by the Taconic orogeny in the southern Appalachians. The first stop (Hagan, Stop 3-1; Fig. 17)) is in the westernmost Valley and Ridge, on the west limb of the Powell Valley anticline, and the eastern edge of the Cumberland Plateau rises immediately west of the Hagan section as the prominent escarpment formed by erosion of the nearly horizontal Pennsylvanian sandstones that comprise the caprock of the Plateau. Like the Tidwell Hollow section, which had several features in common with the cratonic exposures around the Nashville Dome in central Tennessee, the Hagan section shares many sedimentologic and stratigraphic features with the time-equivalent carbonate strata in the cratonic exposures around the Jessamine Dome in central Kentucky, as first noted by Huffman (1945). At Hagan we will examine a long section that is over 310 m thick and is mostly continuous from the base of the Hardy Creek Limestone to the contact of the Sequatchie Formation and the overlying Clinch Sandstone, which is the Ordovician – Silurian boundary (see Miller and Brosgé 1954).


**Figure 16.—Exposure along Reed Road on the west wide of Hamilton Mountain north of Dalton, in 1994, which we will examine at Stop 2-4. The Deicke and Millbrig K-bentonites are in red mudrocks of the Bays? Greensport? Formation, and just a couple of meters above the Millbrig is the oldest of three polymictic pebble conglomerates (inset, upper right), which share several petrographic features with the other quartz arenites and conglomerates in the Blount molasse, but which are the youngest of those coarse clastics in the southern Appalachians, as shown in Fig. 14.**

The second stop (Dandridge, Stop 3-2) will provide us with our first look at the Knox unconformity in this region, and the several meters of strata below and above it. The Douglas Lake Member that discontinuously overlies the unconformity has some features in common with the roughly equivalent Attalla Chert Conglomerate Member in Alabama and Georgia that we saw at Tidwell Hollow. Both units contain cherty regolith and rubble that accumulated in topographic lows on the subaerially exposed karst surface that became the Knox unconformity, and the thickness of both units commonly varies abruptly in all directions. At Dandridge we will in fact see a pinch out of the Douglas Lake Member along strike, such that the overlying Lenoir Limestone overlies the Knox Group carbonates just a short distance from a location where the Douglas Lake Member is approximately 6 m thick.

The third stop (Dodson Mountain, Stop 3-3) will be our introduction to the Bays Formation in its type region of the Bays Mountains (although no type section has yet been described and formally proposed). The exposure at Dodson Mountain is the best and most complete exposure of the redbeds and the interbedded and prominent quartz arenites of the Bays Formation, which here is over 220 m thick. The Bays Formation is the molasse facies of the Blount phase of the Taconic orogeny in northeast Tennessee and southwest Virginia, and it is equivalent to the Greensport Formation, the Colvin Mountain Sandstone, and quite possibly the redbeds ("Sequatchie"?) that overlie the Colvin Mountain Sandstone at Alexander Gap, Horseleg Mountain, and other exposures in that region. At this stop we will yet again emphasize the stratigraphic position of the quartz arenites relative to the Deicke and Millbrig K-bentonites, which are both present here, and are ***upsection*** from all of the major quartz arenites, in contrast to what we saw in Georgia and Alabama (Fig. 15). We will also discuss Ordovician paleoclimate and the presence of what may be paleosols in the redbeds of the Bays Formation, and we will yet again ponder how the M4-M5 sequence boundary, and other eustatically-driven sequence boundaries, might be recognized in the Bays Formation, and whether or not we would even expect them to be present. The exposure at Dodson Mountain is very accessible because of the near-vertical dip of the beds and the width of shoulder, such that one is easily able to walk the entire length of the exposure and see all beds. There is unfortunately no exposure of the stratigraphic contacts with either the underlying Sevier Shale or the overlying "Martinsburg" or "Trenton" Formation.

**STOP 3-1: Hagan, outcrops along railroad at Hagan, VA; 9:30 – 11:30 am (120 mins)**

At this outstanding exposure (Fig. 17) we will examine several hundred meters of, from oldest to youngest, middle and upper Ordovician carbonates of the upper Ben Hur, Hardy Creek, and Eggleston Limestones, the interbedded thick bioclastic limestones and thinner shales of the overlying "Trenton" (Dolly Ridge) Formation, and the shalier strata of the Reedsville and Sequatchie Formations that are themselves separated by the *Orthorhynchula* zone (Miller and Brosgé, 1954). Being in the far western (Lee confacies) belt of the Valley and Ridge makes this section similar in some ways to Tidwell Hollow, with minimal evidence here for the Blount phase of the Taconic orogeny in such a western location (we are about at the longitude of Detroit, Michigan here). But by contrast, the shales of the Reedsville Formation, and the coarser clastics of the Sequatchie and of the overlying Silurian Clinch Sandstone are evidence for expansive deposition of siliciclastic sediments associated with the Queenston phase of the Taconic orogeny.

Of particular note at the Hagan section is the overall deepening upward sequence from the ~130 m thick upper Ben Hur, Hardy Creek, and Eggleston Limestones that are variably open shelf to peritidal deposits, upsection into the "Trenton" (Dolly Ridge) Formation that was deposited on a deeper, storm-dominated shelf, and then into the deeper shelf or slope deposits of the Reedsville Formation, which represent the deepest environments of this sequence. The *Orthorhynchula* zone is interpreted as recording deposition in a nearshore setting (Bretsky, 1969, 1970), which implies regional shallowing from the middle to the uppermost Reedsville to explain the transition from the shales of the lower and middle Reedsville that were deposited in shelf edge to slope settings, to the muddy sandstones of the *Orthorhynchula* zone with their abundant and diverse community of robust brachiopods and other marine organisms, which were deposited in shallow shelf to nearshore environments. The Sequatchie Formation here, with its variable but appreciable quantities of siliciclastic muds, silts, and fine sands in addition to beds of fossiliferous limestone (Miller and Brosgé 1954), contrasts with the underlying Reedsville. The Sequatchie overlies the *Orthorhynchula* zone here, as it does at Dug Gap and throughout much of the southern Appalachians. The limestones of the Sequatchie were deposited in shallow marine shelf to nearshore settings, and the siliciclastics were deposited in environments ranging from marine to transitional coastal and supratidal environments that were subaerially exposed at times as evidenced by the desiccation cracks in some beds.

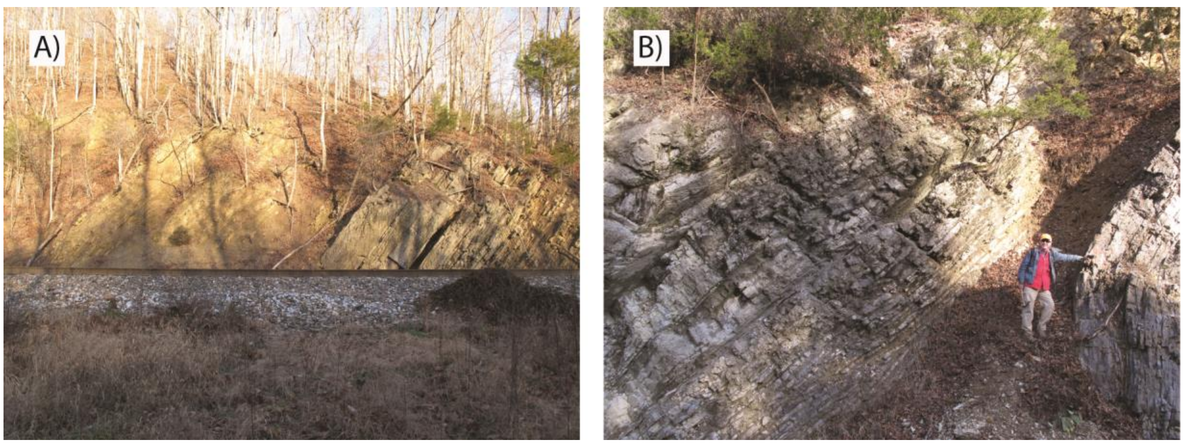



**Fig. 17.—STOP 3-1: Hagan, VA. A) Reedsville Shale and Dolly Ridge Limestone (transition about middle of picture) and B) Deicke K-bentonite in the Egglestone Formation. John Haynes for scale.**

Another characteristic that the exposure at Hagan shares with the cratonic exposures of central Kentucky is that several of the eustatically-generated sequence boundaries identified and named by Holland and Patzkowsky (1996) in the cratonic exposures (e.g., M2-M3, M3-M4, M4-M5, and M5-M6) can be recognized here at Hagan. Others who have studied the exposures in and around the Hagan area, however, including Pope and Read (1997) and Kolata et al. (1998) have suggested that there is more complexity to the unconformities and the sequence boundaries that may be present here at Hagan. At least some of that complexity seems attributable in part to our previous findings regarding correlations of the Deicke and Millbrig K-bentonites into the Blount molasse, where, as we have seen already on this trip, problems surrounding the identification of unconformities and their correlative conformities occur in not only a Cincinnati

Arch-to-eastern Valley and Ridge direction, but in the opposite direction as well. Therefore, as we have been discussing each day thus far, the correlation of sequence stratigraphic boundaries identified from detailed study of cratonic carbonate sections might not be so readily demonstrated with the coarser siliciclastic deposits of molasse in foredeep sections, and unconformities that are prominent and widespread in the molasse may not persist into the cratonic sections (Haynes, 1994; Haynes and Goggin, 1993, 1994, 2011).

**STOP 3-2: Dandridge Municipal Park, sections along shoreline of Douglas Lake just off of Chestnut Hill Road (State Highway 92), at Dandridge, TN; 1:00 – 2:30 pm (90 mins; bathroom stop at park facilities)**

Some of the key features of interest at this series of exposures along the lakeshore (Fig. 18) that we will be able to examine in detail are (1) the Knox unconformity (Fig. 19) and associated paleokarst surface; (2) regolith breccias with clasts up to 3.0 m long diameter in the overlying Douglas Lake Member of the Lenoir Limestone, which accumulated in lows on the Knox paleokarst surface; (3) the Lenoir itself, many beds of which are fossiliferous; (4) the overlying condensed section in the Fetzer Member of the Whitesburg Formation, with its phosphatic and metalliferous horizons; and (5) the overlying graptolitic gray to black shales of the main body of the Whitesburg Formation, one of the classic flysch units of the Blountian phase of the Taconic orogeny. This outstanding set of exposures shows evidence for the abrupt and perhaps rapid(?) deepening of the carbonate platform that had been developed and widespread along the Laurentian shelf margin since the Cambrian but which sagged and developed into a foreland basin as a result of Taconic, i.e., Blountian, orogenic activity along the Laurentian continental margin. This abrupt deepening, presumably caused by crustal downwarping much more so than by eustatic sealevel rise, ultimately resulted in drowning of the shallow shelf environments, and subsequent deposition of great thicknesses of graptolitic muds on top of those formerly shallow carbonate sediments. One of the most significant aspects of a visit to these exposures is that the complete depositional sequence from shallow shelf to drowning shelf to deep basin margin is readily seen just by walking upsection through only a few meters of the dipping ledges.

The base of the exposures here consists of about 55 m of the upper Knox Group, and most of that interval consists of peritidal deposits of stromatolitic (planar and wavy laminated to domal) microbial mat carbonates, with some supratidal dolomites, as well as beds of ribbon limestone, all of which are very typical lithologies of the thick Cambro-Ordovician carbonate sequence throughout nearly the entire Appalachian region (Read and Repetski, 2012).

Above the unconformity is the Lenoir Limestone, with its basal Douglas Lake Member, a discontinuous unit that is restricted to topographic lows on the Knox unconformity. This member includes regolithic breccias and conglomerates (Fig. 16), some of which may have been transported short (?) distances, and medium to very coarse lithic sandstones, some with extensive bioturbation. These sandstones contain much chert as framework grains in addition to mono- and polycrystalline quartz, all of which are cemented by a ubiquitous reddish brown and

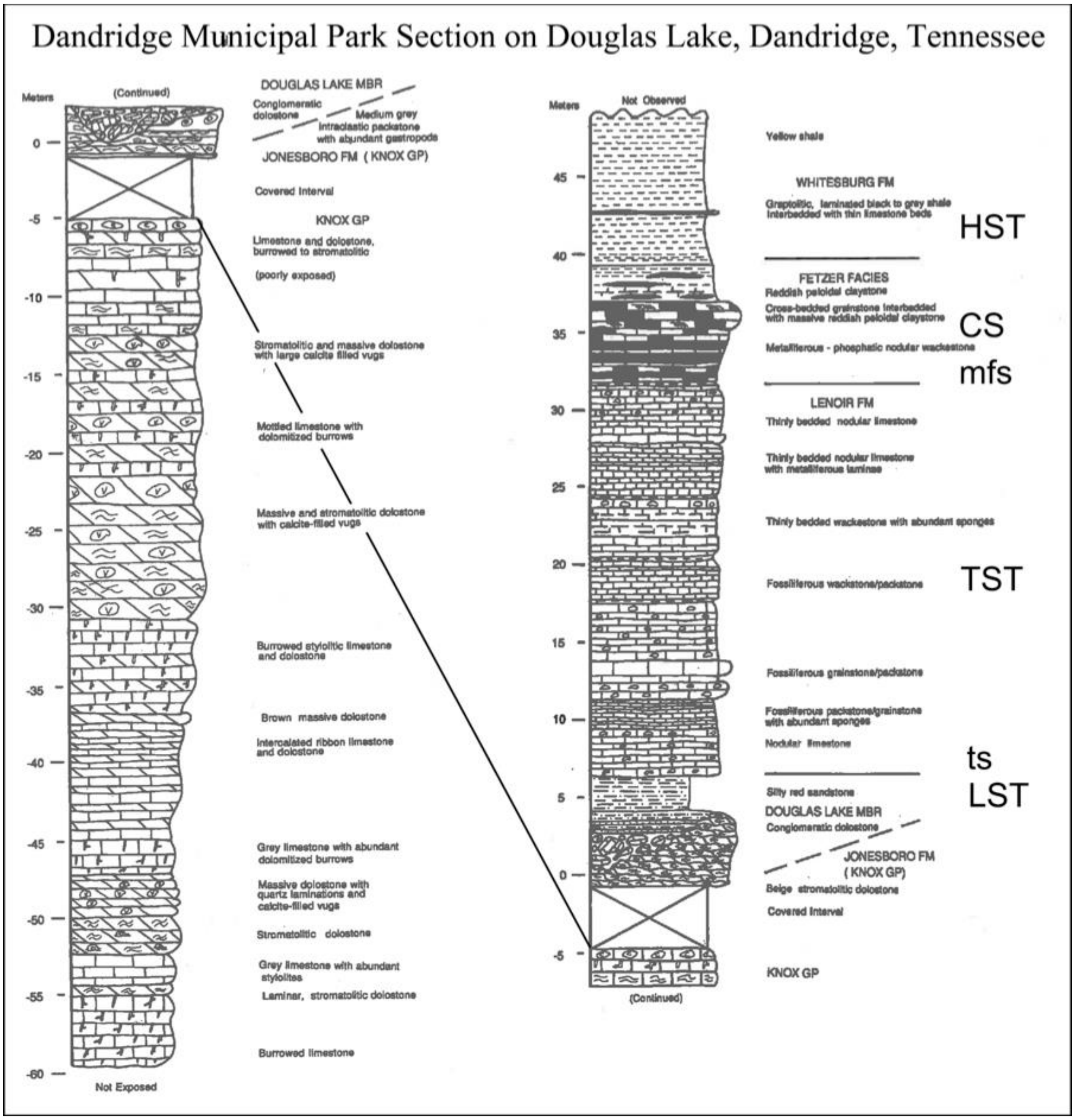



**Figure 18.—Stratigraphic section along Douglas Lake at Dandridge, Tennessee, including outstanding exposures of the Knox unconformity and the overlying Douglas Lake Member, an accumulation of regolith that collected in topographic lows on the unconformity surface, and that is now a mixture of lithologies including breccia, lithic sandstones, and argillaceous dolomites. Modified from Steinhauff and Roberson (1989).**

presumably hematitic matrix that has nevertheless incompletely reduced the primary interparticle pore spaces, thus the porosity of these sandstones is low to moderate. The overlying main sequence of the Lenoir Limestone varies in thickness here from a thinner western section that is about 12 m thick to a thicker eastern section that is about 24 m thick; this difference over a short distance is attributed to variable topography on the Knox paleokarst surface (Steinhauff and

Roberson, 1989). The Lenoir represents a more open marine accumulation that consists primarily of skeletal grainstones and packstones with an abundant and diverse assemblage of marine fauna, including whole and fragmental bryozoans, brachiopods, trilobites, and crinoids, with some sponges, calcareous algae, and oncoids.

**Figure 19.—The Knox unconformity at Dandridge (Stop 3-2), with regolithic breccias of limestone and chert clasts in paleotopographic lows on the paleokarst surface. Ledges in the background are reddish sandstones of the Douglas Lake Member of the Lenoir, and the overlying limestones of the main body of the Lenoir. Staff is marked in decimeters.**

The dark colored Fetzer Member of the Whitesburg Formation contrasts markedly with the much lighter colored Lenoir carbonates, and the darker color results from metal oxide staining of the argillaceous matrix in the carbonates and mudrocks of the Fetzer, which are relatively phosphatic and manganiferous (Steinhauff and Roberson, 1989). A more limited fauna of echinoderms, ostracodes, and trilobites has been identified in some of the Fetzer beds here, and the character of the bedding is more nodular and laminated compared to the underlying Lenoir carbonates.

Above the Fetzer Member are monotonous exposures of interbedded fissile graptolitic black shales and silty lime mudstones of the Whitesburg Formation and possibly the Blockhouse Shale above that, which collectively tend to weather into thin shaley plates. These mudrocks are the uppermost unit exposed here, and these shales are at least 40 m thick here, but true thickness is difficult to determine because of structural complications in these incompetent and ductile strata. Some beds in the Whitesburg/Blockhouse have sole markings on their undersides, suggesting deposition by turbidity currents on a slope.

From a sequence stratigraphic perspective, we interpret the Douglas Lake Member as a Lowstand Systems Tract (LST), the basal bed of the Lenoir Limestone as the transgressive surface (ts), the main body of the Lenoir as a Transgressive Systems Tract (TST), the sharp contact of the uppermost limestone of the Lenoir with the overlying basal bed of the Fetzer Member as a maximum flooding surface (mfs), the main body of the Fetzer Member itself as a Condensed Section (CS, as was likewise suggested by Steinhauff and Roberson, 1989), and then at least the lowest shales of the main body of the Whitesburg/Blockhouse itself as perhaps a Highstand Systems Tract (HST). If these sequence surfaces and systems tracts identifications are correct, this exposure is one of the best, and perhaps THE best, known to us where such an outstanding example of this sequence progression can be seen in the Southern Appalachians in such a relatively thin stratigraphic interval.

There is a chance that the water level in Douglas Lake will be high enough such that some of the exposure along the western part of the section is inaccessible, but we expect that the eastern section (Fetzer Member and Whitesburg) will be exposed and accessible at normal lake level.

**STOP 3-3: exposure along north side of State Highway 70 in gap between Dodson and Kite Mountains in the western Bays Mountains synclinorium, southeast of Rogersville, TN; 3:30 – 5:00 pm (90 mins)**

This is the best and most complete exposure of the Bays Formation, with its redbeds and associated prominent quartz arenites, in the Bays Mountains (Table 5), which is the type area of the Bays Formation (Fig. 20). At this stop we will emphasize the stratigraphic position of the quartz arenites relative to the Deicke and Millbrig K-bentonites, which here are both upsection from the major quartz arenites, in contrast to what we saw in Georgia and Alabama (Fig. 15). We will discuss the sedimentary structures and burrows that are present in these rocks, paleoclimate and the presence of up to 15? paleosols (as tentatively identified in Table 4), the M4-M5 sequence boundary relative to the Deicke and Millbrig K-bentonites throughout this region, and the difficulty of identifying cratonic sequence boundaries here in the Bays Formation, which comprises the bulk of the Blount molasse in Tennessee and Virginia, and possibly in northern Georgia, as we have discussed at earlier stops.

Because of the near-vertical dip of the beds, and the generous width of the shoulder along SH 70, it is a relatively easy walk along the entire length of exposure to see all the beds, but there is no exposure of stratigraphic contacts with either the underlying (Sevier Shale) or overlying ("Martinsburg" Formation) units.

**Table 4.—Measured section of Bays Formation along Tenn. State Hwy. 70 at SW end of Dodson Mountain, Hawkins Co., Tenn. Dodson Mountain section: measured top down, with 15 possible paleosols identified. Measurements made by J. Haynes in 2002.**

**Trenton Formation**

**Bed**

117 Not exposed here, but the basal several 10s of feet are present at Charles Mtn.
    Bays Formation Total estimated thickness: ........................................ 730 ft.
116 Estimated distance to base of Trenton ("Martinsburg") based on measurements
    at the Charles Mtn. section, along strike to the north of this section, where
    the Bays – Trenton contact interval is completely exposed ........................................ ~56 ft
115 Red shale/siltstone to covered zone, E. end of exposure along S.H. 70 ........................................ 18 ft
114 Red siltstone/v. fn. ss., blocky weathering........................................ 2 ft
113 Millbrig K-bentonite ........................................ 1 ft 8 in
    Red shaly bentonite to bentonitic shale........................................ 8-10 in
    Biotite zone, red and grayish red to gray bentonitic clay ........................................ 8-10 in
    Red clay........................................ 2 in
112 Red siltstone/v. fn. ss., blocky weathering........................................ 9 in
111 Red shale/siltstone ........................................ 7 ft 3 in
110 Red siltstone/v. fn. ss., blocky weathering........................................ 2 ft
109 Red shale/siltstone ........................................ 20 ft
108 **Paleosol**? of red shale; 9 in. blue-gray shale 15 in. above base........................................ 3 ft 7 in
107 Sandstone, fn. to med. gr., lt. olive brown, blocky weathering........................................ 9 ft 11 in
106 **Paleosol**? of red shale with thin olive drab beds at top........................................ 1 ft 11 in
105 Red shale, thin blue-gray beds at base ........................................ 13 ft 10 in
104 Siltstone, olive drab, blocky weathering........................................ 4 in
103 Red shale........................................ 1 ft 9 in
102 Deicke K-bentonite ........................................ 1 ft 3 in
    Red and orange-red claystone/shale, bentonitic........................................ 8 in
    White clay with ilmenite as dark specks in red shale........................................ 7 in
101 Siltstone, red, blocky weathering, top 2-3 in. fractured, top 1/4 in. green, chert-like........................................ 1 ft 5 in
100 **Paleosol**? of red shale, noticeably gullied........................................ 9 in
99 Sandstone, f. to med. gr., lt. olive brown ........................................ 2 ft 10 in
98 Red shale/siltstone ........................................ 3 ft 3 in
97 Red shale with discontinuous blue-green mudrock interbeds........................................ 10 in
96 Sandstone, f. to med. gr., lt. olive brown ........................................ 2 ft 10 in
95 Red shale/siltstone ........................................ 5 ft 5 in
94 Red shale with lenses of blue-green shale ........................................ 1 ft 6 in
93 Sandstone, f. to med. gr., lt. olive brown ........................................ 5 ft 4 in
92 Red shale/siltstone ........................................ 8 ft
91 Sandstone, f. to med.gr., olive brown ........................................ 7 ft 2 in
90 Sandstone, v. fn. gr., first noticeably massive bed above bed # 80........................................ 8 ft
89 Red shale/siltstone ........................................ 5 ft 7 in
88 **Paleosol**? of red shale, gullied, with olive and blue gray layers........................................ 21-24 in

87 Red shale/siltstone, rare blue gray blebs = reduction zones? ........................................................6 ft 6 in
86 Red and olive shale/siltstone to red and blue-gray in upper 6 in ...................................................2 ft 8 in
85 **Paleosol**? of red shale .......................................................................................................... 9 in
84 Red shale/siltstone, blocky weathering, with olive beds..............................................................1 ft 1 in
83 **Paleosol**? of red shale with olive beds at top ........................................................................... 9 in
82 Olive siltstone, blocky weathering ................................................................................................. 4 in
81 **Paleosol**? of red shale with olive beds at base and top ................................................................ 5 in
80 Sandtone, med. gr., lt. olive brown, blocky weathering (bed 31 of Herg)............................................3 ft
79 Red shale/siltstone, 2 beds may be paleosols? ........................................................................8 ft
78 Sandstone, med. gr., white to yellow-gray, med. bdd ...............................................................5 ft
77 **Paleosol**? of red shale ...........................................................................................................1 ft 10 in
76 Sandstone, med. gr., white to yellow-gray, med. to thk. bdd, "**middle sandstone member**", poss. equival. to Walker Mtn. Ss. (bed 27 of Herg)...............................................26 ft 10 in
75 Red and olive interbeds at top of red shale paleosol? ...................................................................4-6 in
74 **Paleosol**? of red shale ............................................................................................................ 11 in
73 Sandstone, f. gr., x-bdd., current from SE, thickens at road level...............................................25-40 in
72 Red and olive interbeds at top of red shale paleosol? ...................................................................2-3 in
71 **Paleosol**? of red shale ............................................................................................................1 ft 4 in
70 Red and olive shale/siltstone ......................................................................................................... 9 in
69 Siltstone/v. fn. ss., olive brown .....................................................................................................1 ft 2 in
68 **Paleosol**? of red shale .............................................................................................................. 6 in
67 Red shale and interbdd. olive shale/siltstone ................................................................................1 ft 8 in
66 Olive shale/siltstone, blocky weathering ........................................................................................1 ft 7 in
65 Sandstone, med. gr., white to v. lt. gray, med. to thk. bdd. (bed 25 of Herg).............................10 ft 8 in
64 **Paleosol**? of red shale with10 in. of interbdd. olive and red shale at top .....................................5 ft 7 in
63 Sandstone, med. gr., lt. greenish gray, med. bdd ..........................................................................3 ft 8 in
62 Olive and red shale/siltstone interbdd ........................................................................................... 10 in
61 **Paleosol**? of red shale ...............................................................................................................3 ft 8 in
60 Red shale/siltstone ..........................................................................................................................20 ft
59 Sandstone, v. fn.gr., siltstone at top ...............................................................................................3 ft 1 in
58 **Paleosol**? of red shale .............................................................................................................3 ft 11 in
57 Sandstone, med. gr., v. lt. gray, med. bdd.....................................................................................10 ft 7 in
56 Red shale/siltstone .......................................................................................................................27 ft 6 in
55 Sandstone, f. gr., lt. olive brown, thn. to med. bdd, some red shale laminae.................................8 ft 6 in
54 Red shale/siltstone .............................................................................................................................2 ft
53 Siltstone, red and olive, blocky weathering ....................................................................................... 9 in
52 Red shale/siltstone, with interbdd. olive siltstone ...............................................................................3 ft
51 Sandstone, v. fn. gr., lt. olive brown .............................................................................................12-15 in
50 Red shale/siltstone ..........................................................................................................................2 ft 5 in
49 Sandstone, v. fn. gr, olive and blue-gray ........................................................................................... 9 in
48 Red shale/siltstone (below ravine that drains into grated culvert) ............................................15 ft 10 in
47 Sandstone, med. gr., lt. greenish gray (5GY8/1), med. bdd. (first sandstone west of the grated culvert) ..........................................................................................................10 ft 2 in
46 **Paleosol**? of red shale with 1 in. olive bed at base and 0-3 in at top ............................................2 ft 1 in

45 Red shale/siltstone with olive interbdds....3 ft
44 Red shale/siltstone ....5 ft
43 Sandstone, v. fn. gr., lt. olive brown, thin "spine" up the exposure.... 11 in
42 Red and olive shale/siltstone.... 8 in
41 Siltstone, red and olive.... 11 in
40 Red shale/siltstone ....7 ft 9 in
39 Siltstone, red and olive....3 ft 8 in
38 Olive shale/siltstone....1 ft 1 in
37 Sandstone, v. fn. gr., olive brown ....1 ft 11 in
36 Olive shale .... 5 in
35 Red shale/siltstone ....10 ft 7 in
34 Siltstone, olive....1 ft 8 in
33 Sandstone, v. fn. gr., olive, 1 massive bed at road, splits into two with bedding plane halfway up cut ....3 ft 4 in
32 Olive yellow-brown siltstone/v.fn. ss ....3 ft 9 in
31 Sandstone, fn. gr., white to pale yellow, channel fill at road, thins up slope ....14-21 in
30 Red shale/siltstone ....4 ft 10 in
29 Siltstone/v. fn. ss., olive to blue-gray, med. bdd....1 ft 2 in
28 Sandstone, v. fn. gr., olive to blue gray, blocky....1 ft 2 in
27 Red shale/siltstone, thin blue-gray interbdds. at base, top, and 8 ft. above the base....16 ft 8 in
26 Sandstone, med. gr., greenish gray, med. bdd....7 ft 2 in
25 Olive brown siltstone/shale....5 ft 7 in
24 Sandstone, med. gr., lt. greenish gray, med. bdd ....3 ft 10 in
23 Olive brown siltstone/shale.... 10 in
22 Sandstone, med. gr., blueish-gray, med. bdd., superficially like Oswego at Brocks Gap ....5 ft 1 in
21 Sandstone, fn. gr., olive brown, thn. to med. bdd ....11 ft 3 in
20 Olive brown shale ....2 ft 11 in
19 Sandstone, silty to v. fn. gr., olive brown, med. bdd....3 ft 6 in
18 Red shale/siltstone with interbdd. olive and blue-gray shale/siltstone....1 ft 6 in
17 Sandstone, v. fn. gr., olive brown .... 6 in
16 Olive and blue-gray shale/siltstone....1 ft 5 in
15 Sandstone, v. fn. gr., olive brown ....2 ft 2 in
14 Red shale/siltstone with interbdd. olive and gray green shale ....12 ft 5 in
13 Sandstone, fn. gr., olive, notably massive and resistant compar. w. surrounding mudrocks .... 5 in
12 Red shale/siltstone, interbdd. olive shale in lower 8 in....2 ft
11 Sandstone, fn. gr., olive, resistant like # 13 .... 8 in
10 Red shale/siltstone ....2 ft 3 in
9 Olive siltstone ....2 ft
8 Red shale/siltstone/v. fn. Ss ....1 ft 11 in
7 Sandstone, med. to crs. gr., greenish gray (5GY 7/1), med. bdd ....20 ft
6 Olive siltstone/v. fn. Ss....10 ft

5 Red shale/siltstone ........................................8 ft 8 in
4 Sandstone, fn. gr., olive gray, med. bdd........................................10 ft 11 in
3 Red shale/siltstone ........................................41 ft
2 Red shale/siltstone/v. fn. ss, to covered zone at W. end of exposure........................................90+ ft

**Sevier Formation**

1 Micrite and calcareous shale, not exposed in July ’02,
but observed by Hergenroder in 1964........................................not measured

**Figure 20.—Vertical beds of red mudrocks, including what may be several paleosols, and white quartz arenites in the Bays Formation at Dodson Mountain, Stop 3-3. As seen in the inset (lower right), some of the redbeds are moderately to extensively burrowed, with the burrows being highlighted by the color differences, which are probably the result of oxidation differences.**

## DAY 4. ORDOVICIAN PROXIMAL CARBONATE AND CLASTIC DEPOSITS OF THE BLOUNT FOREDEEP IN TENNESSEE AND VIRGINIA VIRGINIA TO TENNESSEE

## Introduction

At today's stops we will examine our final two exposures of Ordovician strata, one in Tennessee and one in Virginia, and then we will head north along Interstate 81 to Harrisonburg, and James Madison University and the kick-off of the 2015 ISOS meeting. Our first stop (South Holston Dam, Stop 4-1) will be to see some of the coarsest and most proximal conglomeratic sediments of the Tellico Formation that are a part of the flysch deposits that accumulated as distal to proximal submarine fan deposits along the eastern margin of the Blount foredeep. The exposures below South Holston Dam, which include over 200 m of coarse conglomerates both matrix and clast supported (Fig. 21), pebbly sandstones, turbidite sandstones and shale, should be thought of as being linked to the section we examined yesterday at Dandridge (Stop 3-2) as well as to the shales that we will drive by enroute to the South Holston Dam, because they are stratigraphically upsection from the graptolitic shales of the Whitesburg and Blockhouse Formations that represent the deepest and most distal deposits that accumulated in the nascent Blount foredeep. The Tellico Formation, however, is of course younger and more proximal than the older graptolitic shales, and the clasts in the Tellico provide important information about their provenance in the Taconic orogenic highlands that were sourcing these sediments.

**Figure 21.—Cobble and pebble conglomerates in the Tellico Formation at the South Holston Dam (Stop 4-1) deposited in submarine fan channels. These submarine fans were developed along the east margin of the Blount foredeep and were receiving sediment brought into the foredeep from the Blount tectonic highlands along the southeastern margin of Laurentia (Bowlin et al., 1989). Staff is marked in decimeters.**

Our second and final stop (Rich Valley, Stop 4-2) will provide us with the opportunity to see a vertical sequence that records initial downwarping of the Laurentian shelf and the subsequent growth and development of a downslope buildups of the Effna Limestone, which has abundant small bryozoan colonies, followed by continued deepening of the shelf, which ultimately led to drowning of the Effna buildup by black graptolitic mudrocks of the Rich Valley Shale. This sequence is yet again similar to the section at Dandridge, where in a few meters we could see the flooding of the Knox paleokarst, development of the open marine deposits of the Lenoir, and then abrupt drowning and deposition of the metalliferous Fetzer Member and finally by the accumulation of great thicknesses of graptolitic muds that became the Whitesburg and Blockhouse Formations. A main difference at Stop 4-2 is that we will actually be able to see a bioherm that developed during the relative sealevel rise that accompanied the development of the Blount foredeep throughout much of the southern Appalachians.

**STOP 4-1: exposures along Holston Dam/Ruthton Roads below South Holston Dam, TN; 8:50 – 9:50 pm (60 mins)**

At these exposures below the dam, we will have the opportunity to look at coarse polymict conglomerates, turbiditic sandstones, and shales of the Tellico Formation that collectively record a prograding submarine fan complex into a more proximal part of the Blount foredeep. The conglomerates we will focus on at this stop have been interpreted as an incised channel-fill deposit on a prograding submarine fan (Bowlin et al., 1989), and it should be possible to see a variety of textures and fabrics including clast-supported conglomerates with no visible grading or imbrication, clast-supported conglomerates with inverse to normal grading and distinct imbrication, and even some indistinct cross-bedding, as well as matrix-supported conglomerates with only very few areas where imbrication, or bedding, either normal or inverse, is evident. Clasts were derived from Precambrian, Cambrian, and older Ordovician units, and it should be possible to find clasts of quartzose and arkosic sandstone, chert of various colors, vein quartz, and maybe some rhyolites from the late Precambrian Mt. Rogers Formation to the east-northeast of us, along with abundant clasts of limestone and dolomite. Bowlin et al. (1989) speculate that perhaps an 8-10 km thick sequence of Precambrian to Lower Paleozoic strata was present in the Taconic highlands and was being eroded during the later Ordovician to provide the polymictic population of clasts that are present here.

**STOP 4-2: Cuts along State Highway 107 in Rich Valley northwest of Chilhowie, VA; 10:45 am – 12 Noon (75 mins), lunch following the stop in Marion at the Black Rooster Restaurant in the General Francis Marion Hotel.**

Here we will walk along exposures of the deep ramp downslope buildup of the Effna Formation with its bryozoan thickets, and the overlying Rich Valley Shale that is a sequence of graptolitic black shales and limestones which record the relative sealevel rise that ultimately resulted in drowning of the buildup. The work of Read (1980, 1982) elucidated the stratigraphic and paleogeographic relations of the shelf margin and downslope buildups in the Ordovician of Virginia, and their diversity relative to each other. These deeper water buildups are part of a larger trend of buildups that includes the Holston buildups in the Knoxville area of Tennessee and elsewhere in that region to the south (Walker and Ferrigno, 1973), possibly extending as far south as the Pratt Ferry Beds in Alabama, as well as the Murat buildups to the north of here near Lexington and Stuarts Draft, Virginia. In addition, there were generally contemporaneous buildups along the shelf edge that developed in the Rockdell and Ward Cove Limestones (Read, 1980, 1982).

Read (1982) notes that these downslope buildups of the Effna share some similarities with the Waulsortian-type buildups of the later Paleozoic, but because the buildups in Virginia have calcareous algae throughout them, Read (1982) suggests that buildups like this one we will see developed in deeper water, but water that was still in the lower reaches of the photic zone. The core of the Effna buildups is a massive lime wackestone to lesser lime mudstone, and it is enclosed by flanking deposits of crinoid-bryozoan sands and coarser gravels of bioclastic debris, with some thickets of bryozoan bafflestones (Read, 1982). The drowning of the buildups evidently occurred rather abruptly, and there may be some hardgrounds, with metalliferous crusts discontinuously present, similar to the beds of the Fetzer Member at Dandridge (Stop 3-2).

From here we will go into Marion for lunch, and then we will drive to Harrisonburg, the end point of our field trip.

**END OF TRIP**

## ACKNOWLEDGEMENTS

We thank Stacey Law and Katie Meierdiercks at JMU and Claire Jones, Bryan Mogrovejo, John Michael Callen, and Cody Schulte at LSU for assistance with fieldwork. NSF EAR 1324954 supported this research. The ilmenite analyses were made while JTH was a post-doc at the Smithsonian Institution in the Department of Mineral Sciences working with W.G. Melson, whose support and advice over the years is gratefully acknowledged. This is a contribution to "IGCP 591: The Early to Middle Paleozoic Revolution."

## REFERENCES

ALLEN, A.T., and LESTER, J.G., 1957, Zonation of the Middle and Upper Ordovician strata in northwestern Georgia: *Georgia Geological Survey Bulletin* 66, 110 p.

BAYONA, G., and THOMAS, W.A., 2003, Distinguishing fault reactivation from flexural deformation in the distal stratigraphy of the Peripheral Blountian Foreland Basin, southern Appalachians, USA: *Basin Research*, v. 15, p. 503-526.

BAYONA, G., and THOMAS, W.A., 2006, Influence of pre-existing plate-margin structures on foredeep filling: Insights from the Taconian (Blountian) clastic wedge, Southeastern USA: *Sedimentary Geology*, v. 191, p. 115-133.

BEAUCHAMP, B., and DESROCHERS, A., 1997, Permian warm- to very cold-water carbonates and cherts in northwest Pangea, in James, N.P., and Clarke, J.A.D., eds., Cool-Water Carbonates: Tulsa, SEPM (Society for Sedimentary Geology), p. 327–347.

BENSON, D.J., and MINK, R.M., 1983, Depositional history and petroleum potential of the Middle and Upper Ordovician of the Alabama Appalachians: *Transactions Gulf Coast Association of Geological Societies*, v. 33, p. 13-21.

BOWLIN, B.K., KELLER, F.B., and WALKER, K.R., 1989, Stop 9 – Incised submarine channel-fan deposits in the Tellico Formation, South Holston Dam, Tennessee, in Walker, K.R., Read, J.F., and Hardie, L.A., (leaders), Cambro-Ordovician carbonate banks and siliciclastic basins of the United States Appalachians: Washington DC, *28th International Geological Congress, Field Trip Guidebook T161*, p. 28-33.

BRETSKY, P. W., 1969, Ordovician benthic marine communities in the central Appalachians: *Geological Society of America Bulletin*, v. 80, p. 193-212.

BRETSKY, P. W. 1970: Upper Ordovician Ecology of the Central Appalachians: *Yale University Peabody Museum of Natural History Bulletin* 34, p. 1-150.

BRETT, C.E., MCLAUGHLIN, P.I., CORNELL, S.R., and BAIRD, G.C., 2004, Comparative sequence stratigraphy of two classic Upper Ordovician successions, Trenton Shelf (New York–Ontario) and Lexington Platform (Kentucky-Ohio): Implications for eustasy and local tectonism in eastern Laurentia: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 210, p. 295–329.

BROOKFIELD, M.E., and BRETT, C.E., 1988, Paleoenvironments of the Mid-Ordovician (Upper Caradocian) Trenton limestones of southern Ontario, Canada: Storm sedimentation on a shoal-basin shelf model: Sedimentary Geology, v. 57.

BROOKFIELD, M.E., and ELGADI, M., 1998, Sedimentology and paleocommunities of the Black River and Trenton Limestone groups (Ordovician), Lake Simcoe area, Ontario, p. 35.

BUGGISCH, W., JOACHIMSKI, M.M., LEHNERT, O., BERGSTRÖM, S.M., REPETSKI, J.E., and WEBERS, G.F., 2010, Did intense volcanism trigger the first Late Ordovician icehouse?: Geology, v. 38, p. 327–330, doi:10.1130/G30577.1.

BUTTS, C., and GILDERSLEEVE, B., 1948, Geology and mineral resources of the Paleozoic area in northwest Georgia: *Georgia Geological Survey Bulletin* 54, 176 p.

CARTER, B.D., and CHOWNS, T.M., 1989, Stratigraphic and environmental relationships of Middle and Upper Ordovician rocks in northwest Georgia and northeast Alabama, in KEITH, B.D., ed., The Trenton Group (Upper Ordovician Series) of eastern North America: *American Association of Petroleum Geologists Bulletin Studies in Geology* no. 29, p. 17-26.

CHOWNS, T.M., 1972, Depositional environments in the Upper Ordovician of northwest Georgia and southeast Tennessee, in CHOWNS, T.M., ed., Sedimentary environments in the Paleozoic rocks of northwest Georgia: *Georgia Geological Society*, 11th Annual Field Trip Guidebook, p. 3-12.

CHOWNS, T.M., and CARTER, B.D., 1983, Stratigraphy of Middle and Upper Ordovician redbeds in Georgia, in Chowns, T.M., ed., Geology of Paleozoic rocks in the vicinity of Rome, Georgia: *Georgia Geological Society*, 18th Annual Field Trip Guidebook, p. 1-15.

DENNISON, J.M., 1991, Sea level drop contrasted with peripheral bulge model for Appalachian basin during Mid-Ordovician: *Geological Society of America Abstracts with Programs*, Northeast and Southeast Sections, v. 23, p. 21.

DRAKE, A.A. JR., SINHA, A.K., LAIRD, J., and GUY, R.E., 1989, The Taconic orogen, in Hatcher, R.D. Jr., Thomas, W.A., and Viele, G.W., eds., The Appalachian – Ouachita orogen in the United States: Boulder, *Geological Society of America, The Geology of North America*, v. F-2, p. 101-177

ECKERT, J.D., 1988, Late Ordovician extinction of North American and British crinoids: Lethaia, v. 21, p. 147-167.

EMERSON, N.R., SIMO, J.A., BYERS, C.W., and FOURNELLE, J., 2004, Correlation of (Ordovician, Mohawkian) K-bentonites in the upper Mississippi Valley using apatite chemistry: implications for stratigraphic interpretation of the mixed carbonate-siliciclastic Decorah Formation: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 210, p. 215-233.

FREY, R.C., 1995, Middle and Upper Ordovician nautiloid cephalopods of the Cincinnati Arch region of Kentucky, Indiana, and Ohio, 1-126 p.

HATCH, J.R., JACOBSON, S.R., WITZKE, B.J., RISATTI, J.B., ANDERS, D.E., WATNEY, W.L., NEWWLL, K.D., and VULETICH, A.K., 1987, Possible late Middle Ordovician carbon isotope excursion: evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and East-Central United States: AAPG Bulletin, v. 71, p. 1342-1354.

HAYNES, J.T., 1994, The Ordovician Deicke and Millbrig K-bentonite beds of the Cincinnati Arch and the southern Valley and Ridge province: *Geological Society of America Special Paper* 290, 80 p.

HAYNES, J.T., and GOGGIN, K.E., 1993, Field guide to the Ordovician Walker Mountain Sandstone Member: Proposed type section and other exposures: *Virginia Minerals*, v. 39, p. 25-36.

HAYNES, J.T., and GOGGIN, K.E., 1994, K-bentonites, conglomerates, and unconformities in the Ordovician of southwestern Virginia, in Schultz, A., and Henika, W., eds., *Field guides to southern Appalachian structure, stratigraphy, and engineering geology*, Virginia Tech Department of Geological Sciences Guidebook Number 10: Blacksburg, Virginia Tech, p. 65-93.

HAYNES, J.T., and GOGGIN, K.E., 2011, Stratigraphic relations of quartz arenites and K-bentonites in the Ordovician Blount molasse, Alabama to Virginia, southern Appalachians, USA, in GUTIERRIEZ-MARCO, J.C., RABANO, I., and GARCIA-BELLIDO, D. (eds.), *Ordovician of the World*: Cuadernos del Museo Geominero, 14, p. 221-228.

HAYNES, J.T., and MELSON, W.G., 1997, SEM and EMX study of titaniferous minerals in the Ordovician Deicke K-bentonite of southwestern Virginia: *Virginia Minerals*, v. 43, p. 1-7.

HAYNES, J.T., MELSON, W.G., and GOGGIN, K.E., 1996, Biotite phenocryst composition shows that the two K-bentonites in the Little Oak Limestone (Ordovician) at the Old North Ragland Quarry, Alabama, are the same structurally repeated tephra layer: *Southeastern Geology*, v. 36, p. 85-98.

HAYNES, J.T., MELSON, W.G., and KUNK, M.J., 1995, Composition of biotite phenocrysts in Ordovician tephras casts doubt on the proposed trans-Atlantic correlation of the Millbrig K-bentonite (United States) and the Kinnekulle K-bentonite (Sweden): *Geology*, v. 23, p. 847-850.

HERRMANN, A.D., HAUPT, B.J., PATZKOWSKY, M.E., SEIDOV, D., and SLINGERLAND, R.L., 2004, Response of Late Ordovician paleoceanography to changes in sea level, continental drift, and atmospheric pCO2: potential causes for long-term cooling and glaciation: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 210, p. 385-410.

HERRMANN, A.D., MACLEOD, K.G., and LESLIE, S.A., 2010, Did a volcanic mega-eruption cause global cooling and a regional extinction during the Late Ordovician?: Palaios, v. 25, p. 831-836, doi: 10.2110/palo.2010.p10069r.

HOLLAND, S.M., and PATZKOWSKY, M.E., 1996, Sequence stratigraphy and long-term paleoceanographic change in the Middle and Upper Ordovician of the eastern United States, in WITZKE, B.J., LUDVIGSON, G.A., and DAY, J., eds., Paleozoic sequence stratigraphy: Views from the North American craton: *Geological Society of America Special Paper* 306, p. 117-129.

HOWE, H. J., 1979. Middle and Upper Ordovician plectambonitacean, rhynchonellacean, syntrophiacean, trimerellacean, and atrypacean brachiopods. *United States Geological Survey Professional Paper* 1066-C, p. C1-C18.

HUFF, W.D., MUFTUOGLU, E., BERGSTROM, S.M., and KOLATA, D.R., 2004, Comparative biotite compositions in the Late Ordovician Deicke, Millbrig and Kinnekulle K-bentonites: a test of consanguinity, in Hints, O., and Ainsaar, L. (eds): *WOGOGOB-2004 Conference Materials*, Tartu University Press, Tartu, p. 47-48.

HUFFMAN, G.G., 1945, Middle Ordovician limestones from Lee County Virginia to central Kentucky: *Journal of Geology*, v. 53, p. 145-174.

JAROSEWICH, E., NELEN, J.A., and NORBERG, J.A., 1980, Reference samples for electron microprobe analyses: *Geostandards Newsletter*, v. 4, p. 43-47.

JENKINS, C.M., 1984, Depositional environments of the Middle Ordovician Greensport Formation and Colvin Mountain Sandstone in Calhoun, Etowah, and St. Clair Counties, Alabama [M.S. thesis]: Tuscaloosa, Univ. Alabama, 156 p.

JOY, M.P., MITCHELL, C.E., and ADHYA, S., 2000, Evidence of a tectonically driven sequence succession in the Middle Ordovician Taconic foredeep: *Geology*, v. 28, p. 727–730.

KOLATA, D.R., HUFF, W.D., and BERGSTRÖM, S.M., 1998, Nature and regional significance of unconformities associated with the Middle Ordovician Hagan K-bentonite complex in the North America midcontinent: *Geological Society of America Bulletin*, v. 110, p. 723-739.

KOLATA, D.R., HUFF, W.D., and BERGSTRÖM, S.M, 2001, The Ordovician Sebree Trough: An oceanic passage to the Midcontinent United States: Geological Society of America Bulletin, v. 113, p. 1067-1078.

LAVOIE, D., and ASSELIN, E., 1998, Upper Ordovician facies in the Lac Saint-Jean outlier, Québec (eastern Canada): palaeoenvironmental significance for Late Ordovician oceanography: Sedimentology, v. 45, p. 817-832.

LAVOIE, D., 1995, A Late Ordovician high-energy temperate-water carbonate ramp, southern Quebec, Canada: implications for Late Ordovician oceanography: Sedimentology, v. 42, p. 95 - 116.

LUDVIGSON, G.A., JACOBSON, S.R., WITZKE, B.J., and GONZÁLEZ, L.A., 1996, Carbonate component chemostratigraphy and depositional history of the Ordovician Decorah Formation, Upper Mississippi Valley, in WITZKE, B.J., LUDVIGSON, G.A., and DAY, J., eds., Paleozoic Sequence Stratigraphy: Views from the North American Craton, Volume Geological Society of America Special Paper 306, p. 67-86.

LUDVIGSON, G.A., WITZKE, B.J., GONZÁLEZ, L.A., CARPENTER, S.J., SCHNEIDER, C.L., and HASIUK, F., 2004, Late Ordovician (Turinian-Chatfieldian) carbon isotope excursions and their stratigraphic and paleoceanographic significance: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 210, p. 187-214.

MILLER, R. L., and BROSGÉ, W.P., 1954, Geology and oil resources of the Jonesville district, Lee County, Virginia: *United States Geological Survey Bulletin* 990, 240 p.

MITCHELL, C.E., ADHYA, S., BERGSTRÖM, S.M., JOY, M.P., and DELANO, J.W., 2004, Discovery of the Ordovician Millbrig K-bentonite bed in the Trenton Group of New York State: Implications for regional correlation and sequence stratigraphy in eastern North America: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 210, p. 331–346.

MORAD, S., 1988, Diagenesis of titaniferous minerals in Jurassic sandstones from the Norwegian Sea: *Sedimentary Geology*, v. 57, p. 17-40.

MORAD, S., and ALDAHAN, A.A., 1986, Alteration of detrital Fe-Ti oxides in sedimentary rocks: *Geological Society of America Bulletin*, v. 97, p. 567-578.

PATZKOWSKY, M.E., and HOLLAND, S.M., 1993, Biotic response to a Middle Ordovician paleoceanographic event in eastern North America: Geology, v. 21, p. 619-622.

PATZKOWSKY, M.E., and HOLLAND, S.M., 1996, Extinction, invasion and sequence stratigraphy: Patterns of faunal change in the Middle and Upper Ordovician of the eastern United States, in WITZKE, B.J., LUDVIGSON, G.A., and DAY, J., eds., Paleozoic Sequence Stratigraphy: Views from the North American craton: Boulder, CO, Geological Society of America Special Paper 306, p. 131-142.

PATZKOWSKY, M.E., and HOLLAND, S.M., 1999, Biofacies Replacement in a Sequence Stratigraphic Framework: Middle and Upper Ordovician of the Nashville Dome, Tennessee, USA: Palaios, v. 14, p. 301-323.

POPE, M., and READ, J.F., 1997, High-resolution surface and subsurface sequence stratigraphy of late Middle to Late Ordovician (Late Mohawkian – Cincinnatian) foreland basin rocks, Kentucky and Virginia: *American Association of Petroleum Geologists Bulletin*, v. 81, p. 1866-1893.

POPE, M.C., and READ, J.F., 1997, High-resolution stratigraphy of the Lexington limestone (Late Middle Ordovician), Kentucky, U.S.A.: A cool-water carbonate-clastic ramp in a tectonically active foreland basin, in Noel, P., and Clarke, J.A.D., ed., Cool-water carbonates, Volume 56: Special Publication - SEPM, p. 410-429.

READ, J.F., 1980, Carbonate ramp-to-basin transitions and foreland basin evolution, Middle Ordovician, Virginia Appalachians: *American Association of Petroleum Geologists Bulletin*, v. 64, p. 1575-1612.

READ, J.F., 1982, Geometry, facies, and development of Middle Ordovician carbonate buildups, Virginia Appalachians: *American Association of Petroleum Geologists Bulletin*, v. 66, p. 189-209.

READ, J.F., and REPETSKI, J.E., 2012, Cambrian – lower Middle Ordovician passive carbonate margin, southern Appalachians, in J. R. DERBY, R. D. FRITZ, S. A. LONGACRE, W. A. MORGAN, and C. A. STERNBACH, eds., The great American carbonate bank: The geology and economic resources of the Cambrian – Ordovician Sauk megasequence of Laurentia: *American Association of Petroleum Geologists Memoir* 98, p. 357 – 382.

RODGERS, J., 1971, The Taconic Orogeny: *Geological Society of America Bulletin*, v. 82, p. 1141-1178.

ROSENAU, N., HERRMANN, A.D., and LESLIE, S., 2012, Conodont apatite δ18O values from a platform margin setting, Oklahoma, USA: Implications for initiation of Late Ordovician icehouse conditions, Palaeogeography, Palaeoclimatology, Palaeoecology. doi:10.1016/j.palaeo.2011.12.003

SAMANKASSOU, E., 2002, Cool-water carbonates in a paleoequatorial shallow-water environment: The paradox of the Auernig cyclic sediments (Upper Pennsylvanian, Carnic Alps, Austria-Italy) and its implications: Geology, v. 30, p. 655-658.

SAMSON, S.D., KYLE, P.R., and ALEXANDER, E.C. Jr., 1988, Correlation of North American Ordovician bentonites by using apatite chemistry: *Geology*, v. 16, p. 444-447.

SAMSON, S.D., MATTHEWS, S., MITCHELL, C.E., and GOLDMAN, D., 1995, Tephrochronology of highly altered ash beds: The use of trace element and strontium isotope geochemistry of apatite phenocrysts to correlate K-bentonites: *Geochimica et Cosmochimica Acta*, v. 59, p. 2527-2536.

SCOTESE, C.R., and MCKERROW, W.S., 1990, Revised world maps and introduction, in MCKERROW, W.S., and SCOTESE, C.R., eds., Palaeozoic palaeogeography and biogeography: Oxford, United Kingdom, p. 1-21.

SCOTESE, C.R., and MCKERROW, W.S., 1991, Ordovician plate tectonic reconstructions, in Barnes, C.R., and Williams, S.H., eds., Advances in Ordovician geology: Geological Survey of Canada Paper 90-9, p. 225-234.

SELL, B.K., and SAMSON, S.D., 2011, Apatite phenocryst compositions demonstrate a miscorrelation between the Millbrig and Kinnekulle K-bentonites of North America and Scandinavia: *Geology*, v. 39, p. 303-306, doi: 10 .1130 /G31425 .1.

SELL, B.K., SAMSON, S.D., MITCHELL, C.E., MCLAUGHLIN, P.I., KOENIG, A.E., and LESLIE, S.A., 2015, Stratigraphic correlations using trace elements in apatite from Late Ordovican (Sandbian-Katian) K-bentonites of eastern North America: *Geological Society of America Bulletin*, v. 127, in press, doi: 10.1130/B31194.1.

STEINHAUFF, D.M., and Roberson, K.E., 1989, Stop 7 – Uppermost Knox Group, the Knox unconformity, and the Middle Ordovician transition between shallow shelf and deeper basin near Dandridge, Tennessee, in WALKER, K.R., READ, J.F., and HARDIE, L.A., (leaders), Cambro-Ordovician carbonate banks and siliciclastic basins of the United States Appalachians: Washington DC, *28th International Geological Congress, Field Trip Guidebook T161*, p. 24-27.

WALKER, K.R., AND FERRIGNO, K.F., 1973, Major Middle Ordovician reef tract in east Tennessee: *American Journal of Science*, v. 273-A, p. 294-325.

WEBBY, B.D., COOPER, R.A., BERGSTROM, S.M., and PARIS, F., 2004, Stratigraphic framework and time slices, in Webby, B.D., Paris, F., Droser, M.L., and Parcival, I.G., eds., The Great Ordovician Biodiversification Event: New York, Columbia University Press, p. 41-47.

WOODWARD, H. P., 1951, The Ordovician System of West Virginia: W. Va. Geol. Survey, v. 21, 627 p.

YOUNG, S.A., SALTZMAN, M.R., and BERGSTRÖM, S.M., 2005, Upper Ordovicain (Mohawkian) carbon isotope (d13C) stratigraphy in eastern and central North America: Regional expression of a perturbation of the global carbon cycle: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 222, p. 53-76.

ZEIGLER, E.L., 1988, Sedimentary petrology and depositional environments of the Upper Ordovician Sequatchie and Lower Silurian Red Mountain Formations, northwestern Georgia [Ph.D. dissertation]: Atlanta, Emory University, 288 p.