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Structural and Stratigraphic Framework of the Ozarks Uplift:

A "Show-Me" Perspective of the Mississippi Lime Play

Structural and Stratigraphic Framework of the Ozarks Uplift: A "Show-Me" Perspective of the Mississippi Lime Play

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"When ideas fail, words come in handy." — Johann Wolfgang von Goethe

PREFACE

Understanding the geology of an entire subsystem on the leading edge of an active, convergent margin is a monumental task. Recent focus on the Mississippian strata of the midcontinent region with publication of AAPG Memoir 122 (Grammer et al., eds., 2019) has provided some welcome additions to the literature. A few of the articles contributed to that volume have dealt with surface exposures in the Ozarks (Childress and Grammer, 2019; Godwin et al., 2019; Godwin and Puckette, 2019; Mazzullo et al., 2019; Miller et al., 2019; Price and Grammer, 2019; Sessions et al., 2019; Shelley and Grammer, 2019; Unrast et al., 2019), and a few of these address Missouri biostratigraphy and sequence stratigraphy. Some of the latter acknowledge the idea that tectonism was active during the Mississippian and that it affected sedimentation; however, most of the papers have ignored the structural geology, and none addresses the integrated surface and subsurface geology of Missouri. For example, where explanations were difficult, terms were invented, such as the so-called "Kanoka Ridge" (Mazzullo et al., 2019, Fig. 14A, p. 44, 50). We consider that understanding of Mississippian syntectonic features on the Bella Vista, Bentonville-Pea Ridge, Greasy Creek, Brush Creek, and other fault systems provide a more plausible explanation of anomalous accumulations in southwestern Missouri and northwest Arkansas. Additionally, new lithostratigraphic terms, previously proposed by Mazzullo et al., (2013), were applied for many of the well-known and long-established stratigraphic units of Missouri. Sadly, there is no recourse for comment and reply in the AAPG Memoir series. It seems that one result of this is, as Rudyard Kipling might opine, we are left with a volume that includes a few "just-so" stories.

This field trip guidebook aims to clarify some of the nomenclature issues and fill in some of the tectono-stratigraphic gaps to provide a more comprehensive view of the Mississippian from the perspective of at least a few Missouri geologists. We do not intend to diminish the broad and impactful efforts of our colleagues from adjoining states, but we seek to preserve the historic and long-standing nomenclature that has worked well for geologists of Missouri and provide insight into the factors controlling sedimentation. Chapter one of this guidebook concerns lithostratigraphic nomenclature. Chapter two discusses the overall structure of the Ozarks, timing of the Ozarks uplift, nuances in syntectonic sedimentation, and discovery of anomalous fossil micro-reefs in the Reeds Spring Formation.

CHAPTER ONE

Revisions to Mississippian Stratigraphic Nomenclature in Southwest Missouri

ABSTRACT. At its core stratigraphy remains a multi-dimensional scientific discipline based on careful examination of stratigraphic successions in outcrop and in the subsurface, with the complicating factors of time and tectonic movements. This complex set of variables requires testing and deliberation prior to acceptance or adoption of proposed new names. The names Elsey Formation, Burlington-Keokuk Limestone (undivided), Warsaw Formation, and Baird Mountain Member, a minor but biostratigraphically significant lithologic marker unit, were proposed for abandonment in southwestern Missouri. Strata mapped as the Elsey Formation were included with the underlying Reeds Spring Formation. New names, such as Bentonville Formation and Ritchey Formation were proposed as replacements for the Burlington-Keokuk Limestone (undivided) and Warsaw Formation, even though unit boundaries essentially remained the same, with exception that the combined Reeds Spring Formation rather than Elsey Formation was recognized below the Bentonville Formation. Additionally, new group names were proposed to elevate the rank of two units that commonly are used as member and formational names in Arkansas.

We contend that new formal names simply are not needed, and that traditional and conventional names for stratigraphic units should be retained for a variety of reasons that are elaborated herein. We argue that the "Pineville Tripolite Facies" and "Bentonville Limestone Facies" rightly should be recognized as important diagenetic and depositional facies, respectively. We recommend that the name Ritchey Formation should be abandoned, and name Warsaw Formation retained. We also consider that the Elsey Formation, a widely mapped lithostratigraphic unit in southwestern Missouri should be retained. We also recognize additional informal units we refer to as "Springfield Facies" (lower part) and "Phenix Facies" (upper part) as informal depositional units in the Burlington-Keokuk Limestone (undivided) on the main part of the Burlington Shelf north of the Arkansas-Missouri state line.

***Keywords**: Mississippian Subsystem, Burlington-Keokuk Limestone (undivided), Elsey Formation, Reeds Spring Formation, Warsaw Formation.*

INTRODUCTION

A few of the well-established stratigraphic names for Mississippian rock units in southwestern Missouri have been proposed for abandonment, and new replacement names have been proposed for some (Mazzullo et al., 2013). Recent publication of AAPG Memoir 122 (Grammer et al., eds., 2019) has nearly uniformly followed that treatment, except for Price and Grammer (2019). Publication of AAPG Memoir 122 (Grammer et al., eds., 2019) has led to confusion of the lithostratigraphic nomenclature, and the implications for adopting new names has hindered communications for geologists who live and work in Missouri and Arkansas. Therefore, we do not recognize the formal names proposed by Mazzullo et al., (2013), and we argue for retention of conventional stratigraphic nomenclature for use in the State of Missouri for the following reasons:

1. **Priority and long-standing use of traditional names.** The North American Stratigraphic Code, hereafter referred to as the Code (NACSN, 2021, Part II, Article 7(c), p. 170), states that well-established names should not be changed or abandoned lightly. The names Burlington Limestone, Keokuk Limestone, and Warsaw Formation were proposed in the 1850s (Owen 1852; Hall 1857). Notably, the first two names ("Burlington" and "Keokuk") have been used for more than a century across Missouri without confusion or controversy. These names clearly have priority. In southwestern Missouri, the names collectively are mentioned in thousands of geologic maps, well logs, reports, and other publications. Identification of these combined units is recorded even in the subsurface of northwesternmost Missouri (See Fig. II-4). Continued use of the traditional names helps to facilitate communications. Moreover, these strata retain the characteristic features of the type Burlington and Keokuk Limestone in southeast Iowa. Hall (1857, quoted in Thompson, 1986, p.90) stated,

> "The encrinital limestone of Burlington, or, hereafter we shall term it, the *Burlington Limestone*, is characterized by its great number of crinoids, of which Drs. D.D. Owen and B.F. Shumard have described numerous species. The rock is in a great measure composed of the broken and comminuted remains of this family of fossils: large masses of the rock consist almost entirely of the separated but unbroken joints of the columns of various species."

It would be difficult to write a more accurate and succinct description of the Burlington Limestone in southwest Missouri. The Keokuk Limestone likewise is highly crinoidal at both its type section and in southwest Missouri.

Historic uses of the Burlington-Keokuk Limestone (undivided) and Warsaw Formation, and their cultural importance in southwestern Missouri cannot be overemphasized. the upper part of the Burlington-Keokuk limestone (undivided), is mined in the Phenix quarry, near Ash Grove, Missouri; among other famous buildings, it was used as building stone in construction of the Missouri State Capitol (Hannibal and Evans, 2010), and it currently is being used in renovation of Kansas City International Airport. At Carthage, the Warsaw Formation was quarried and marketed as *Napoleon Gray*, *Gray Veined*, and *Ozark Fleuri* varieties of marble. The Burlington-Keokuk Limestone (undivided) and Warsaw Formation are part of the fabric of Missouri. They are the named rock units that middle school and secondary education science teachers in Missouri learn to convey to their students the importance of protecting fresh groundwater resources in the karstic Springfield aquifer.

Mazzullo and colleagues (2013, Fig. 2, column 3, p. 416) have illustrated a very close approximation to the long established nomenclature for Missouri that we propose to retain (Fig. I-1), with a few exceptions, in that the top of the Keokuk should be marked by the Short Creek Oolite (Thompson, 1986, p. 96) and illustrated as a disconformity as shown in the proposed revisions in that figure (Mazzullo et al., 2013, column 4, Fig. 2, p. 416). We agree that the upper part of the Short Creek Oolite, and several units in the Meramecian and Chesterian, can be interpreted as bounded by unconformities, based on successions of shallow-water carbonate facies or progradation of overlying siliciclastic facies. Also, the Osagean-Meramecian boundary is recognized within the Warsaw Formation (Kammer et al., 1990).

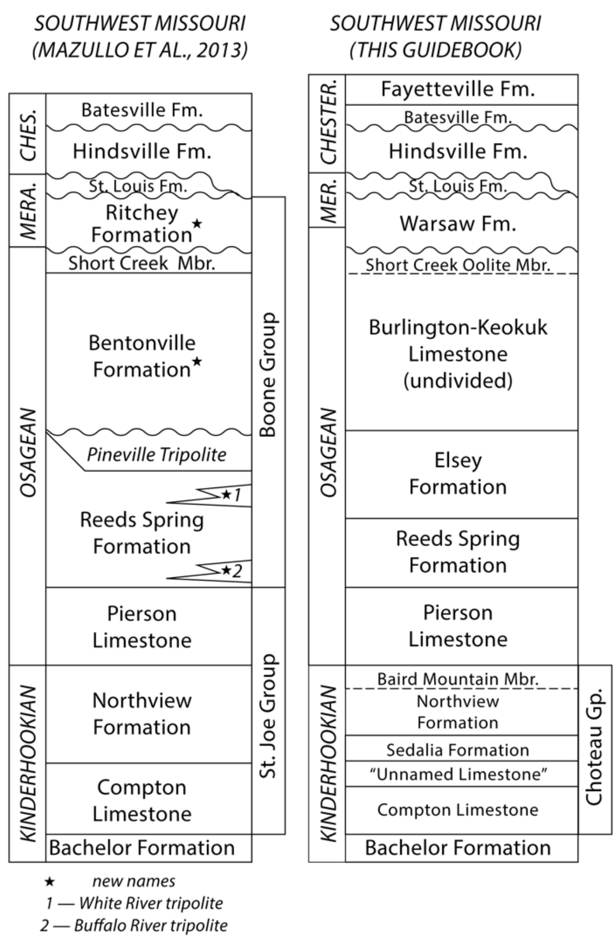

Figure I-1. *Stratigraphic names and facies proposed by Mazzullo et al., (2013) for Mississippian strata in the southwestern Ozarks (left column), and lithostratigraphic names preferred by the authors of this guidebook (right column). Abbreviations include CHES. and CHEST. for the Chesterian Stage, and MER. and MERA. for the Meramecian Stage.*

2. **Improper abandonment of long-established names**. Ostensibly the Burlington-Keokuk Limestone (undivided) and Warsaw Formation, were abandoned because these units differ from their respective type sections and type areas (Mazzullo et al., 2013). Undoubtedly, there are differences in depositional facies, but such variation is expected in lithostratigraphic units and does not constitute grounds for abandonment of the traditional names. The proposed Bentonville Formation and Ritchey Formation show expression of variation in age as well as depositional setting. If use of the name Burlington-Keokuk Limestone (undivided) is viewed as overly cumbersome to use by some geologists, the Code (NACSN, 2021, Part II, Article 30 (a)), allows for referring to compound names with shortened names for convenience, for example, "the Burlington-Keokuk " for Burlington-Keokuk Limestone (undivided). Use of the name Burlington-Keokuk is no more cumbersome than Bentonville. In this portion of the field trip guidebook, we have retained usage of Burlington-Keokuk Limestone (undivided) for clarity.

3**. Interpretive and model-driven name changes**. Mazzullo and colleagues (2013), in their Fig. 1, illustrates a "shelf break" that more accurately portrays the northern extent of mixed chert and carbonate facies in strata assigned to the lower Osagean Stage. Elsewhere in (Mazzullo et al., 2013) and in subsequent publication (Mazzullo et al., 2019), they refer to this feature as part of a carbonate ramp (cf., Ahr, 2007). We agree that it is a distally steepened carbonate ramp, and there is no shelf break on this backstepping shelf succession (see Evans and Bassett, 2013). The margin of the Burlington Shelf as recognized by Lane and De Keyser (1980) is present across the southwesternmost part of Missouri, mostly in McDonald County. These strata overlie a lower Paleozoic peritidal carbonate succession that extended across Laurentia, known as the great American carbonate bank (Derby et al., eds., 1998). By the close of the late Osagean Age, the ramp had prograded southward beyond the Missouri-Arkansas state line.

To clarify the idea of a backstepping shelf margin more precisely, upper Devonian and Mississippian strata both constitute tectono-stratigraphic sequences deposited on the Laurentian platform, above the sub-Chattanooga and sub-Mississippian unconformities, respectively. Both unconformities were results of epeirogenesis and denudation of older platform strata due to convergence with the Ouachita allochthon on the southern margin of Laurentia. Back-stepping of the shelf margin resulted in deposition of relatively deep-water black shale facies of upper Devonian Chattanooga Shale, which unconformably is overlain by shallow-water Mississippian carbonates, and ultimately by a relatively deep-water succession of mixed carbonates and chert, prior to progradation of shallow-water, high-energy grainstone facies.

Slight variation for the pick for the top of the Keokuk Formation is based solely on occurrence of 8 ft (2.4 m) of peloidal and glauconitic carbonate in Brown Quarry in Springfield, Missouri. Thompson chose to include the unit at the top of the Burlington-Keokuk Limestone (undivided) rather than including those beds in the base of the Warsaw (Thompson, 1986, Fig. 81, p. 90), but because it is not only difficult to differentiate between the Burlington Limestone and Keokuk Limestone in southwestern Missouri, and noting that there are few key biostratigraphic markers between these units, Thompson (1986, p. 96) arbitrarily placed the Osagean-Meramecian (chronostratigraphic) boundary at a lithologic marker, the top of the Short Creek Oolite. This has helped stratigraphers and mappers identify the contact between the Burlington-Keokuk Limestone (undivided) and the overlying Warsaw Formation, even if the chronostratigraphic boundary cannot be recognized easily.

4. **Facies and structural control in type section of Bentonville Formation**. The Bentonville Formation, in its type section, is a shelf-margin carbonate that, in sequence-stratigraphic terms, we interpret as the product of highstand shedding from a paleogeographic feature long known as the Burlington Shelf. The unusual thickness of the Bentonville Formation in its type area (80 ft (24.4 m)) is a result of being deposited adjacent to the Bella Vista-Bentonville Fault on the downthrown, southeastern block (Fig. I-2, I-3). Mazzullo et al., (2013) offered that the age of the Bentonville Formation in its type section biostratigraphically is correlative only with the Keokuk Limestone. Lithologically, it is correlative only with the upper part of the Burlington-Keokuk Limestone (undivided), the Keokuk part. It is a cross-bedded crinoid grainstone. however, proposed reference sections generally span the entirety of the Burlington-Keokuk Limestone (undivided). The lower part commonly referred to as Burlington Limestone contains much more chert and lime mudstone when compared with the Bentonville Formation. Therefore, even the type section of the Bentonville Formation differs significantly from exposures in most of southwest Missouri, and it cannot be correlated confidently even with its proposed reference sections.

If correlating the Bentonville Formation with Missouri strata is viewed as problematic by the authors of this paper, we can only imagine that Arkansas geologists must have similar issues when trying to apply the same terminology with exposures of the Boone Formation in the Buffalo River area, 50 miles (80 km) to the southeast, where the main body of the Boone Formation forms 350 ft (106.7 m) cliffs between the St. Joe member at the base and Batesville Formation at the top (Fig. I-4).

5. **Inadequate type section of Ritchey Formation**. The type section for the proposed Ritchey Formation is a short (20 ft (6.1 m)), composite section near the town of Ritchey, Missouri in Newton County, where the top of the unit is overlain by residuum at the top of the weathered bedrock. In contrast, Clark (1941) mapped a unit of combined Keokuk and Warsaw, disconformably overlain by the Hindsville Formation, near Washburn, Missouri in the Cassville 15-minute quadrangle. He noted occurrences of Short Creek Oolite below the top of the combined unit, but he did not report overall thickness. According to driller logs filed with the Missouri Geological Survey, the Warsaw Formation in the subsurface is upward of 90 ft (27.5 m) thick near Carthage, Missouri, and more than 110 ft (33.5 m) thick near Nevada, Missouri. The disparity in reported thicknesses in comparison with the type section of the Ritchey Formation is a sound argument for abandoning it as a formally named lithostratigraphic unit, especially since the authors essentially exchanged names with the Warsaw Formation. We maintain that the latter name should be retained.

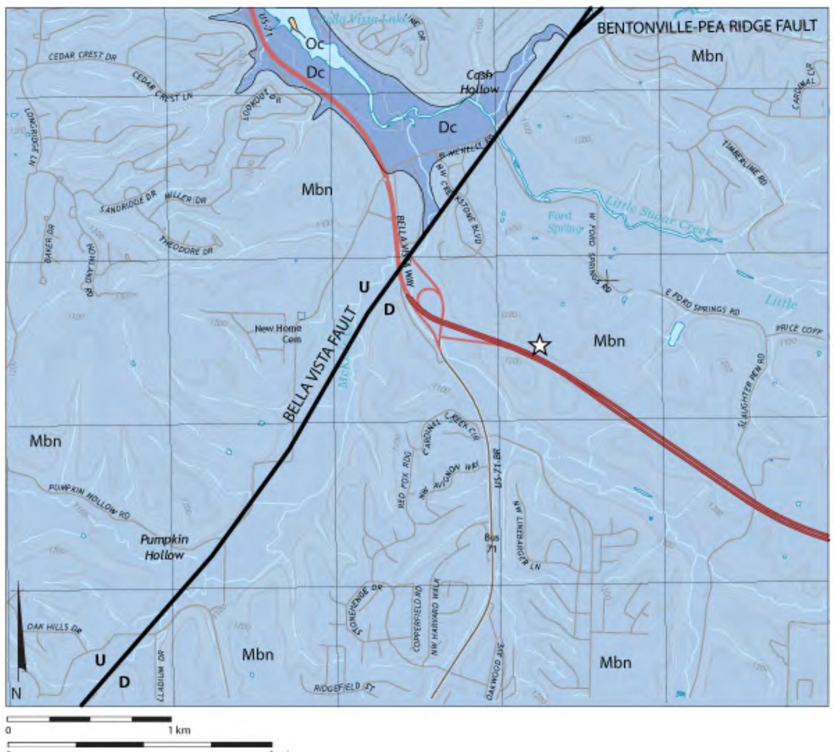

Figure I-2. *Detail of the bedrock geologic map of Bentonville North 7.5-minute quadrangle, Arkansas. Type locality of Bentonville Limestone indicated by white star, approximately 1 km southeast of the Bentonville Fault on the downthrown block (modified from geologic worksheet, Glick (1972) after Adams and Ulrich (1905)). The Bentonville Fault and its northeastern extension the Greasy Creek Fault figure prominently in regional geology of the southwestern Ozarks (see Chapter Two).*

6. **Publication of the proposed names**. While *The Shale Shaker* technically meets the requirement for adequate distribution, it is a source generally inaccessible by those who are not in the petroleum industry or by those who apply traditional names for these units on a regular basis. *The Shale Shaker* is a publication by the Oklahoma City Geological Society (OCGS) and is available with membership (for purchase) in their organization. This is the reason that all of the authors in this article were unaware of the proposed new names Bentonville and Ritchey until publication of AAPG Memoir 122 (Grammer et al., eds., 2019), which has had a much more widespread distribution. As a consequence of limited availability, Mazzullo et al., (2013) could not have received adequate review for their manuscript from the plethora of geologists from states most effected by the proposed name changes. While Mazzullo and colleagues (2013) acknowledged unspecified help from Tom Thompson, a highly esteemed paleontologist and stratigrapher now retired from the Missouri Geological Survey, Thompson was not a co-author on that publication. The only acknowledgement related to Missouri in AAPG Memoir 122 (Grammer et al., eds., 2019) was for access to Missouri Department of Natural Resources core and anonymous reviewers who may or may not have been from Missouri. Ironically, not all of the articles in AAPG Memoir 122 have expunged use of the Burling-Keokuk Limestone

(undivided) in their titles (see Price and Grammer, 2019). We consider that Arkansas and Missouri geologists should have been included in review of the proposed nomenclatural revisions as well as contributors to AAPG Memoir 122.

Figure I-3. *Type section of the proposed Bentonville Formation of Mazzullo et al., (2013) exposed in road cut north of Bentonville, Arkansas on Highway 71. The section is approximately 80 ft (24 m) thick. The lowermost exposures are tripolitic facies (photo from Evans and Bassett, 2013, Fig. II-16, p. 46). Lithostratigraphically, this exposure might be considered as Bentonville facies of the Boone Formation.*

7. **Applicability of surface to subsurface successions**. The Mississippian of northern Oklahoma and southern Kansas utilizes an informal nomenclature with Mississippian units labeled A through D in reference to the "Mississippi Lime" play (e.g., Lindzey et al., 2019). The authors of the Bentonville Formation (Mazzullo et al., 2013, p. 448) noted that the principal driving rationale for changing names was for the benefit of petroleum geologists in Kansas and Oklahoma, but they proposed that their terms should be applied in Missouri to replace traditional names,

> "In regard to stratigraphic terminology, our attempt to make the nomenclature of the rocks consistent throughout the tri-state in the study area establishes a template that can be used to recognize and subdivide correlative subsurface Mississippian stratal sections in southern Kansas and northeastern Oklahoma. Such clarification is urgently needed, and has been for decades, because of the economic significance of these rocks. We can no longer be satisfied with merely lumping these strata into meaningless categories or subdivisions just for the sake of convenience when the reality is that the lithostratigraphic architecture of the system is complex as are the petroleum reservoirs in these rocks in the subsurface (e.g., Mazzullo et al., 2010)."

This rationalization is not a valid argument for proposing new names for surface outcrops in Missouri for two reasons. The Code provides for and encourages designation of stratotype sections based on core descriptions for areas that do not have surface exposures (e.g., Hills and Hoenig, 1979). The authors of the Bentonville Formation should be encouraged to propose names appropriate for the area of the Mississippi Lime play based on core. We suspect the subsurface "Mississippi Lime" of northern Oklahoma and southern Kansas likely differ as much from the newly proposed type area as do the Burlington Limestone and Keokuk Limestone differ from the Burlington-Keokuk Limestone (undivided) in southwest Missouri from their type areas. While the goal of standardizing nomenclature for four states is laudable, it is impractical to do so in this case, because the state line between Missouri and Arkansas was essentially the shelf margin and facies relationships *are* complex across this region.

Abandonment of the Elsey Formation

Among other revisions to traditional stratigraphic nomenclature, some errors were introduced. Mazzullo et al., (2013) have argued that the Elsey Formation should be abandoned. They proposed to identify cherty limestone below the proposed Bentonville Formation as the Reeds Spring Formation. In fact, the Elsey Formation is one of the most easily mapped rock units in southwesternmost Missouri! White or light gray chert lenses and beds are the hallmark of the formation. It especially is easy to pick out in high-wall quarrying operations (Fig. I-5).

An archaeologist, Jack Ray, Missouri State University's Center for Archaeological Research, is the leading expert in identification of chert in the Ozarks. He has studied this material resource for more than 40 years and has written a comprehensive guide (Ray, 2007). Figure I-6 is modified from maps he compiled by from 7.5-minute quadrangles mapped by the late Ken Thomson, and larger-scale geologic maps. Ray (pers. comm., Sept. 21, 2022) noted that chert in the uppermost Pierson Limestone chert (above the Wolf Pen Gap Shale) and lower Reeds Spring chert are dark and mostly found in McDonald, Barry, Stone, and western Taney counties in Missouri, and in the lower Boone Formation in northern Arkansas. Middle Reeds Spring chert, a lighter color variety, is found south of the Ozark divide (roughly parallel with I-44), except at Turnback Creek adjacent to Chesapeake Fault zone. The transition to overlying, mostly bedded chert in the Elsey Formation is gradational. A cursory examination of various chert varieties might be confusing to some but clearly, the Elsey Formation is a mappable rock unit.

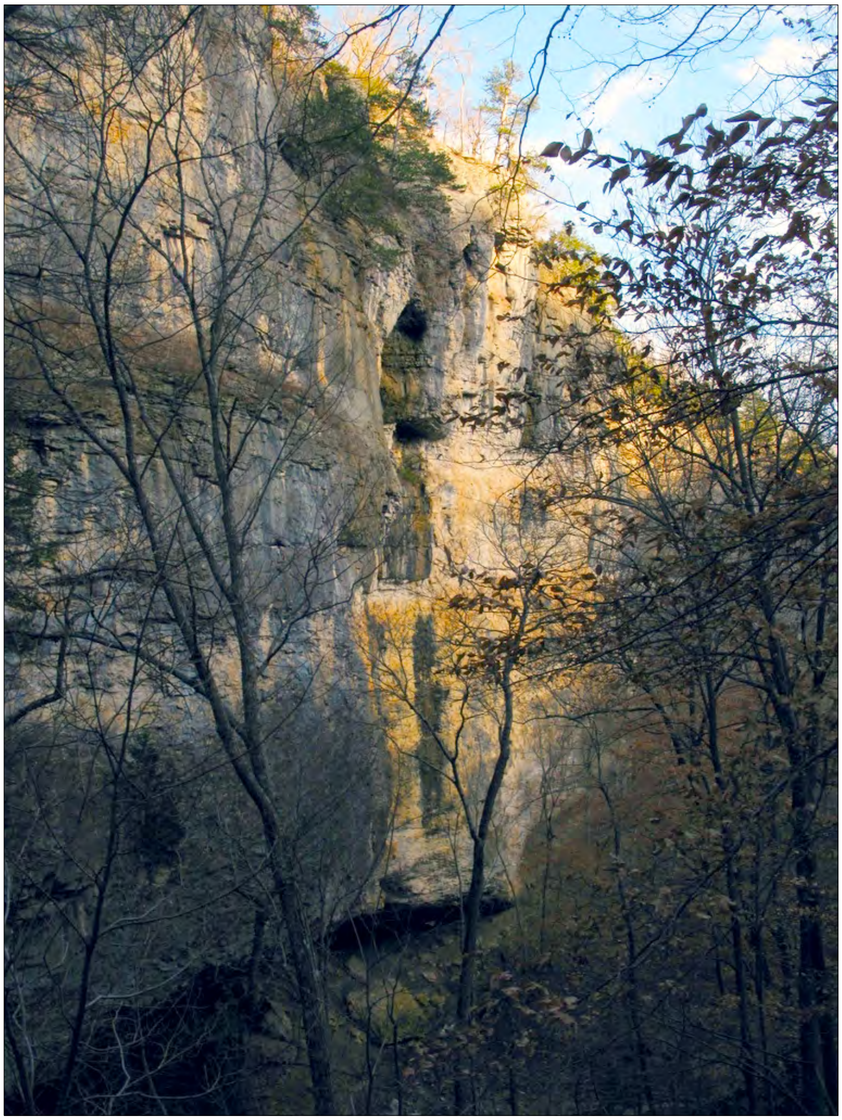

Figure I-4. *Exposure of cherty Boone Formation in Lost Valley State Park area in the Buffalo National River near Ponca, Arkansas. The St. Joe Member near the base below Cobb Cave (bottom of photo) and sandstone beds of the Batesville Formation crop out at the top of the cliff. Should this be considered Reeds Spring Formation of Mazzullo et al. (2013)?*

The upper and lower contacts of the Elsey locally are transitional above and below near Springfield, where, as Thompson (1986) noted, it is a transitional facies with the overlying Burlington-Keokuk Limestone (undivided). The 2003 AMG Field Trip Guidebook (Plymate et al., 2003) lumped the Reeds Spring Formation together with the overlying Elsey Formation as the Reeds Spring-Elsey Formation (undivided) for exposures in the Chestnut Ridge section, following the treatment of the Burlington-Keokuk Limestone (undivided). In Mazzullo et al., (2013), the ostensible justification for including rocks assigned to the Elsey Formation into the Reeds Spring Formation was based on their reference section 26 at Pickerel Creek (misspelled as Pickrell), for which they argue dolomitic Reeds Spring Formation is exposed above the Elsey Formation. That section, on I-44, is adjacent to the trace of the Republic-Sac River Fault, and the roadcut exposes Reeds Spring Formation below Burlington-Keokuk Limestone (undivided) (Figs. I-7, I-8). It is properly mapped on the Halltown NE geologic quadrangle mapped by Thomson (1982), but reasonably might be regarded as Reeds Spring-Elsey Formation (undivided), but these formations are not out of stratigraphic order. Exposures of the Elsey Formation were mapped farther north and east of Springfield, where the Reeds Spring Formation pinches out (Figs. I-9, I-10).

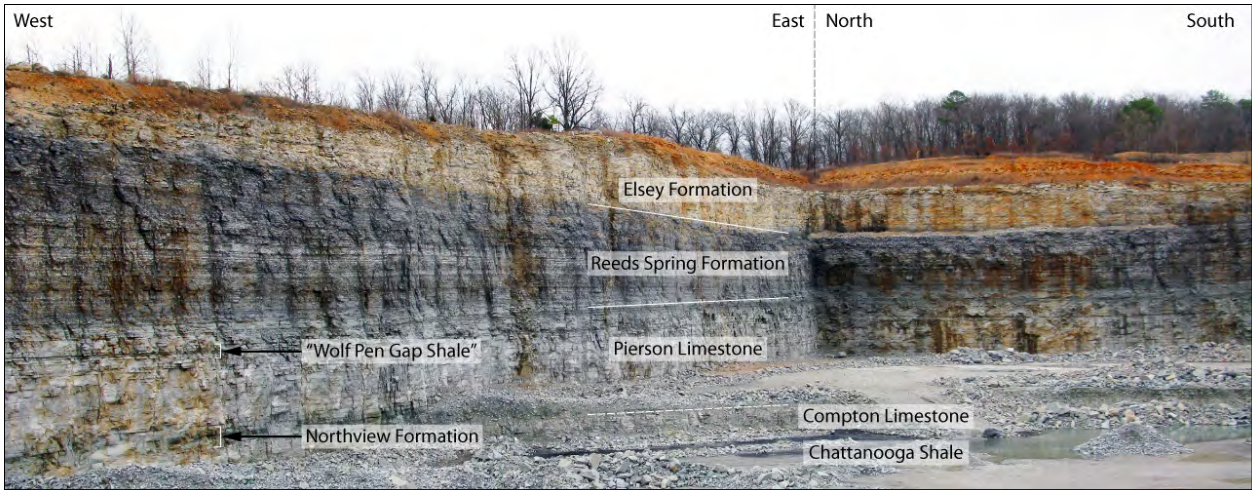

Figure I-5*. Bella Vista quarry in Caverna, Missouri. The distinctive color change from dark to light chert marks the contact between the Reeds Spring and Elsey formations (from Evans and Bassett, 2013, Fig. II-26, p. 59).*

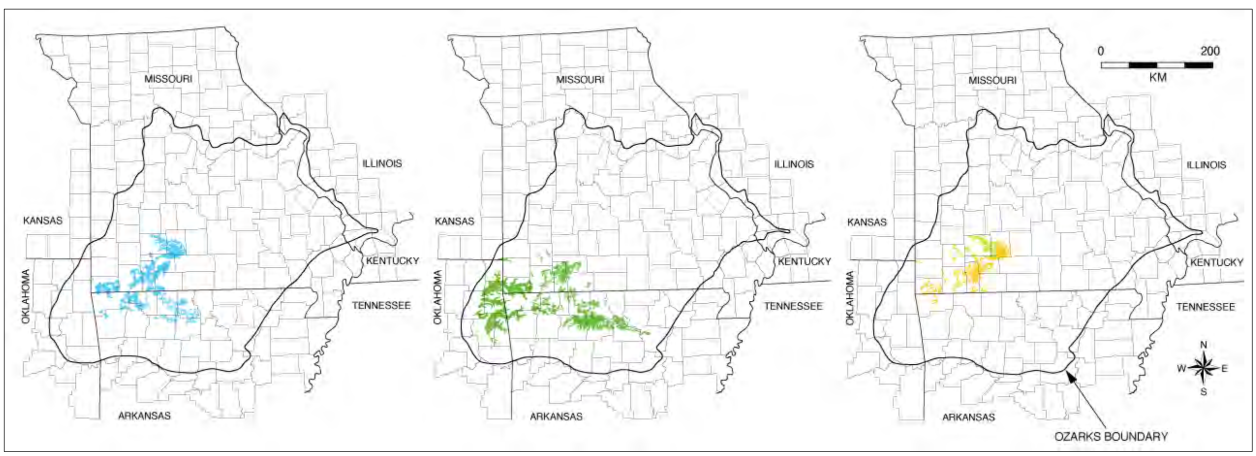

Figure I-6*. Geologic maps showing outcrops of the Pierson Limestone, Reeds Spring Formation, and Elsey Formation, respectively, from left to right (from Ray, 2007, Figs. 8.9, p. 168, 8.15, p. 179, and 8.20, p.191).*

The understanding gathered from geologic mapping and assessment of existing geologic maps should be implicit in stratigraphic studies. Publication of Mazzullo et al., (2013) undoubtedly influenced the Missouri Geological Survey's omission of the Elsey in Missouri Geological Survey's Information Circular No. 31 (Missouri Stratigraphic Committee, 2019) and Miscellaneous Publication No. 21 (Bridges and Mulvany, 2018). We accept the proposal that their Pineville Tripolite should be regarded as a diagenetic facies, but rather than being recognized as a part of the Reeds Spring Formation, it is part of the Elsey Formation although tripolite occurs in several cherty limestone intervals.

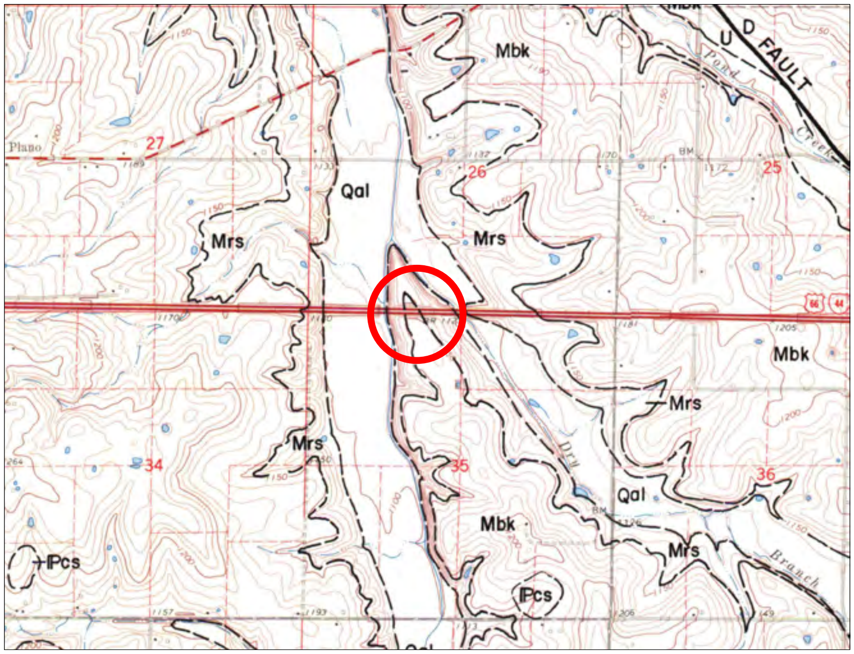

Figure I-7. *Location of Mazzullo et al., (2013) reference section 26 indicated by red circle. The geology of this area was mapped by Ken Thomson (1983; SP8332). This detail of the geology of the Halltown NE 7.5-minute quadrangle shows Burlington overlying Reeds Spring Formation. From his experience mapping more than 160 quadrangles in Missouri, Thomson recognized the difficulty in identifying Elsey and Reeds Spring formations where both consisted of white chert, whether bedded or nodular. North and east of Springfield, most of the cherty limestone below the Burlington-Keokuk Limestone (undivided) was mapped as Elsey Formation because the Reeds Spring Formation is considered to pinch out in that direction (see Fig. 6; Thompson, 1986, Fig. 58, p. 67). In the far southwestern part of the state, the distinction for identifying these units is obvious and essential for detailed mapping.*

Figure I-8. *Road cut on I-44 in Reeds Spring Formation overlain by Burlington-Keokuk Limestone (undivided). Mazzullo et al., (2013) argued that the Elsey Formation was overlain by Reeds Spring Formation at this locality, and that the Elsey Formation should be abandoned based on their suggestion that the lower Osagean cherty limestones were out of stratigraphic order. A combination of white chert bands with a fine-grain carbonate texture in the Reeds Spring Formation differs from the overlying Burlington-Keokuk Limestone (undivided), which can also have white chert bands (in lower concentrations) near the base but has a coarse crinoidal texture.*

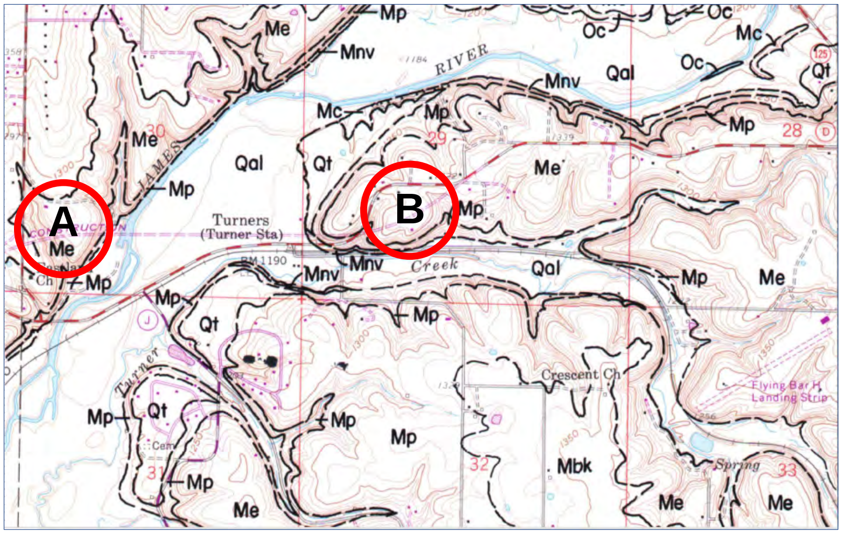

***Figure I-9**. Locations of sections of the Elsey Formation exposed in road cuts along Highway D in eastern Greene County, Missouri indicated by red circles (Thomson, 1981, SP8135). Here, the Pierson Limestone is overlain by the Elsey Formation, and the Reeds Spring Formation is missing. Locations A and B shown in Fig. I-10.*

Abandonment of the Baird Mountain Member of the Northview Formation

The Baird Mountain Member of the Northview Formation is another marker unit that was proposed for abandonment. Mazzullo et al., (2013; p. 424) claimed the member was based on biostratigraphy. While the Baird Mountain Member is characterized by upper Kinderhookian conodonts, it also is described lithologically in Thompson (1986; p. 59-61; Thompson and Fellows, 1970; p. 21) with the type section designated at Baird Mountain quarry near Table Rock Dam. Here is an excerpt of the original description:

> The Baird Mountain can usually be subdivided into two portions, a lower 1-inch to 1-foot bedded limestone with finely crystalline matrix and abundant small crinoid ossicles, and an upper foot or so of slabby bedded argillaceous limestone. Both units are brick red.

It seemingly is an insignificant unit, but biostratigraphically it marks the top of the Kinderhookian Stage, and it mostly is preserved near structures, like the Ten O'clock Run Fault, on the downthrown side. For example, exposures are found along Airport Road, the main arterial to Branson Airport near Hollister, Missouri (Fig. I-11).

Misapplied Stratigraphic Names

The names St. Joe Group and Boone Group were elevated in rank and applied to sections in Missouri (Mazzullo et al., 2013; Grammer et al., 2019). The St. Joe Limestone and Boone Chert or Boone Formation generally are names applied to strata in Arkansas. In Missouri, because formations can vary from only a few inches to a few tens of feet in thickness, we rarely use group names. We commonly consider it more significant to apply chronostratigraphic names with the general understanding of the lithostratigraphic names that tend to be assigned to these units. The St. Joe Group, as defined by Mazzullo et al., (2013), includes the Pierson Limestone, which is assigned to the Osagean Stage. Missouri geologists traditionally have recognized the name Chouteau Group for strata above the Bachelor Formation. The Chouteau Group includes four formations, two of which crop out in southwesternmost Missouri, the Compton Limestone and Northview Formation (Thompson 1986; p. 38). The name "Chouteau" shows up quite regularly in well log descriptions.

Various authors in AAPG Memoir 122 (Grammer et al., eds., 2019) have misused the name Woodford Shale in referring to the upper Devonian organic-rich shale that crops out in southwestern Missouri. Thompson (1993) expressed arguments for using the name Chattanooga Shale. Although Chattanooga, Burlington, and Keokuk are names that are appropriated from out-of-state type areas, the name Woodford is even more obscure because, according to the U.S. Geological Survey *Geolex,* it does not have a designated type section. The name Woodford Shale should be used in its outcrop area in the Arbuckle Mountains and in subsurface areas of Texas, Oklahoma, and Kansas but not in the outcrops of Missouri.

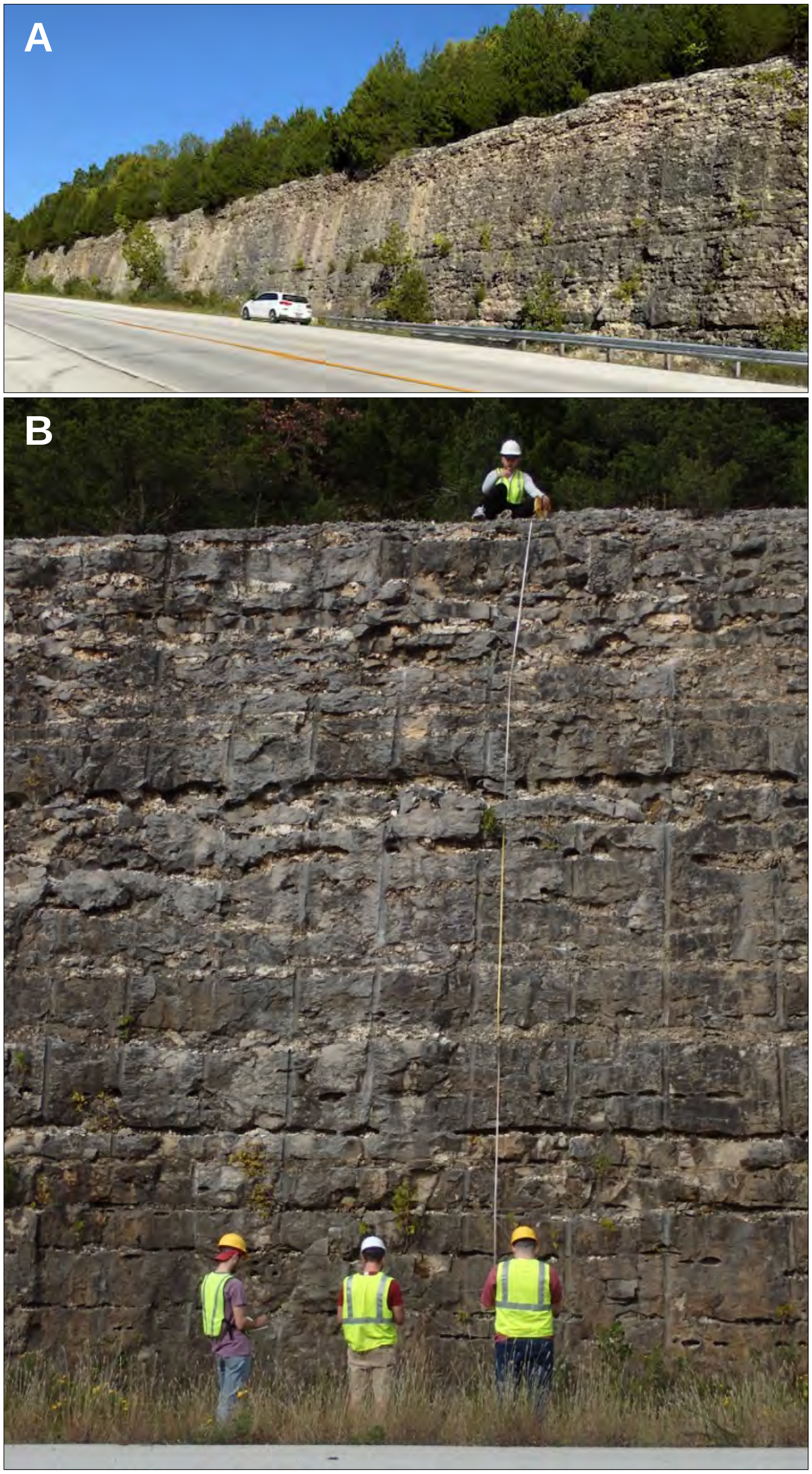

Figure I-10. *A, photo of road cut in Elsey Formation at location A from Fig. I-8. B, photo of the uppermost part of the Pierson Limestone and overlying Elsey Formation at location B from Fig. I-8. The contact between the Pierson Limestone and Elsey Formation is just above the level of three students' heads in this road cut.*

Figure I-11. *An unusual section of lower Mississippian is preserved on Airport Road, Branson Airport. The Baird Mountain Member is present at the top of mottled green and red Northview Formation. Note the occurrence of "Red Pierson". Going uphill to the right, the Pierson is exposed in a fairly thick succession. It commonly is thickened on the downthrown blocks of faults like the Ten O'Clock Run and Fair Play faults. Middle of outcrop is approximately 25 ft (8 m) high.*

For the proposed new names, even Mazzullo et al., (2019) do not consistently use the names they had proposed in Mazzullo et al., (2013). In text and figures, Mazzullo et al., (2019) refer to names like Bentonville Limestone, Reeds Spring Limestone, and Pierson Formation. Other authors in the AAPG Memoir (Grammer et al., eds., 2019) have applied the name Bentonville Formation and referenced what they term "co-type" section at Bentonville. Presumably, this refers to a principal reference section, but we find this confusing in use of terminology as well as nomenclature.

We recognize that the many authors who have been working in southwestern Missouri and who contributed to AAPG Memoir 122 (Grammer et al., eds., 2019) have helped to bring attention to the fascinating geology of our state, especially the conodont biostratigraphy, stable isotope studies, and sequence-stratigraphic re-interpretations, although we may disagree on some details of the latter (see Chapter 2). There were opportunities for collaboration, cooperation, or at least coordination between groups, especially before Darwin Boardman passed, with whom Evans had regular communications. The lack of cooperation has led a rather unfortunate instance of interstate parachute science (e.g., Stefanoudis et al., 2021), which has been compounded by citational injustice, in that some important contributions by Missouri geologists were overlooked (e.g., Evans and Bassett, 2013; Cauthon et al., 2014; Elson et al., 2014).

Proposed Facies Names for the Burlington-Keokuk Limestone (undivided)

The reference section for the Burlington-Keokuk Limestone (undivided) in southwest Missouri was designated for road cuts along Highway 65 (37.119096 °N, 93.234948 °W), south of Springfield, Missouri (Thompson, 1986). If it were considered appropriate and needed, a composite second reference section easily could be designated to supplement the existing one, Conco Quarry in Williard (37.294191 °N, 93.403348 °W) is an acceptable candidate that exposes the lower contact, and the overlying Short Creek Oolite Member of the Burlington-Keokuk Limestone (undivided) is exposed in a road cut across Highway 60 from this quarry.

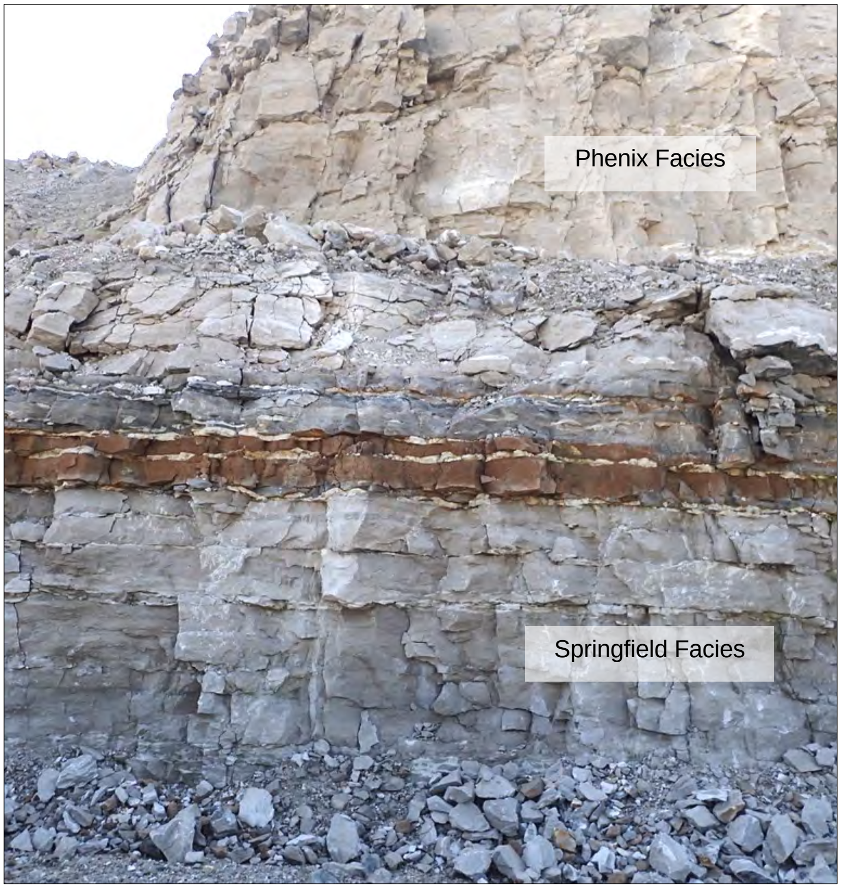

***Figure I-12**. Fresh quarry wall exposure of both Springfield and Phenix facies of the Burlington-Keokuk Limestone (undivided) in Conco quarry at Willard, Missouri. The lower bench is approximately 15 ft (4.5 m) high. The brown layer in the lower Springfield facies consists of iron-stained dolomite interbedded with thin white chert beds.,*

***Figure I-13.** Precision-sawn quarry wall exposure at Phenix Marble Company's quarry exposes Phenix facies of the Burlington-Keokuk Limestone (undivided). Note crossbedding in the crinoid-brachiopod grainstone and chert (lower right) in the fine to coarse-grain crinoid grainstone.*

In addition to retention of the conventional and traditional formation names for Missouri strata (see Fig. I-1), we recommend use of the name "Bentonville Facies" for descriptions of high-energy crinoidal grainstone units deposited in a shelf-margin setting. The Bentonville section is truly spectacular. To avoid confusion with identification of similar lithology on the main shelf, we propose two additional facies names for the Burlington-Keokuk limestone (undivided). "Springfield Facies" is introduced here to include the fine-grain darker, commonly cherty limestone beds that occur in the lower Burlington-Keokuk Limestone (undivided)(Fig. I-12). "Phenix Facies" is introduced herein to include the tan to light brown beds of the upper part of the Burlington-Keokuk Limestone (undivided) (Fig. I-13). In weathered exposures, the latter facies commonly is light gray to white with low-angle and hummocky cross-stratification, indicating deposition in relatively shallow marine setting.

Summary

Use of the proposed names Bentonville Formation and Ritchey Formation (Mazzullo et al., 2013) has led to confusion over nomenclature in the literature (e.g., Grammer et al., eds., 2019). Therefore, we recommend retention of traditional formation names for Missouri strata (see Fig. I-1). We have the goal of presenting accurate and effective communication of important concepts as well as definitive nomenclature that will withstand the test of time and allow future generations of geologists to understand the intricacies of interpretations without the conundrum of parsing nomenclatural discrepancies that potentially can become hindrances. It should be noted that the Code also recognizes,

> "Some organizations publish and distribute widely large editions of serial guidebooks that include refereed regional papers; although these do meet the tests of scientific purpose and availability, and therefore constitute valid publication..."

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CHAPTER TWO

Structural Deformation and Timing of the Ozarks Uplift: Implications for Syntectonic Sedimentation and the Origin of Lower Carboniferous Waulsortian Mounds

ABSTRACT. The timing of uplift on the Ozarks portion of the southern margin of Laurentia generally has been assumed to be Pennsylvanian in age, associated with the assembly of Pangaea, collision of the Ouachita allochthon, and development of the Arkoma foreland basin, but the Paleozoic stratigraphic record has never been fully integrated into a tectono-stratigraphic model. Evidence from regional unconformities and patterns of sedimentation indicate epeirogenic uplift began during middle Devonian time, persisted through the Mississippian, and culminated during the widely known Pennsylvanian Ouachita orogeny. Flexural uplift in the Ozarks was coupled with development of a foredeep on the Ouachita allochthon and deposition of the late Devonian to early Mississippian Arkansas Novaculite. Sinkhole fills and exotic clasts in impact structures provide a window into the unusual concatenation of sub-Devonian and sub-Mississippian unconformities across the crest of the Ozarks plateaus. We argue that these pre-Pennsylvanian epeirogenic episodes of tectonism marked a shift from passive margin to convergence with movements along re-activated Precambrian faults. Movements associated with uplift provided a framework for syntectonic sedimentation and backstepping of the shelf margin onto the platform with relatively deep-water Devonian and early Mississippian strata deposited above peritidal lower Paleozoic strata.

In addition to timing of the uplift, this paper proposes a new model for structural development of the Ozarks. Previous investigators have shown that the region is crisscrossed by conjugate sets of strike-slip faults. Much of the flexural uplift is associated with a compressional paleo-stress field with oblique convergence of the Ouachita allochthon. If the Ozarks were purely compressional, why then do we have so many grabens in Missouri? Grabens are extensional features. We propose that, like many other strike-slip provinces, the Ozarks experienced both shortening and extension in association with hard and soft linkages in transfer zones that trended obliquely to the dominant strike-slip faults. Soft linkages include development of broad anticlinal folds like the Osage-Verona Anticline (trending NNW) at Shell Knob, Horse Creek Anticline (trending E-W) in McDonald County, Washburn Syncline (trending NNE) in Barry County, and Sycamore Syncline (trending NE) near Siloam Springs, Arkansas.

On a local scale, the Wolf Pen Gap Hollow Anticline near Jane, Missouri is perpendicular to the trace of the Brush Creek Fault. The anticline was truncated prior to deposition of the basal Reeds Spring Formation, resulting in chaotic redeposition of some of the upper beds of Pierson Limestone east of the fold axis. Other examples of syntectonic sedimentation includes the emplacement of slide and slump blocks into fault-bounded intrashelf basins that developed during the early Mississippian. Slide and slump masses in the Compton Limestone were documented in an earlier field trip guidebook, but more examples include a graben-fill slump complex in the Compton Limestone, north of Noel, Missouri, slide blocks downslope of the Mt. Shira uplift, mounds in the Compton adjacent to the Lampe Fault near Dogwood Canyon in Blue Eye, Missouri, and an olistolith block of Pierson Formation adjacent to the Bella Vista Fault in northwest Arkansas.

Lastly, we note that the deepest part of the Mississippian succession in southwest Missouri is the marine flooding event that marks the base of the Reeds Spring Formation. This interval is associated with some movable hydrocarbons, and it also is associated with fine carbonate turbidites and bedded chert that locally contains abundant silicified colonial worm tubes. We suggest that these might represent micro-reefs and potentially hydrocarbon-seep communities on the up-dip margins of basinal deposits of the underlying petroleum source rock, the Chattanooga Shale.

***Keywords**: Grabens, intrashelf basins, syntectonic sedimentation, slump blocks, Waulsortian mounds.*

INTRODUCTION

The 60th meeting of the Association of Missouri Geologists was held in Joplin, Missouri on September 27-28, 2013. That meeting was well attended, and the second field trip visited a few of the localities we will visit again on this field trip. We stand behind the observations and interpretations in that field trip guidebook (Evans and Bassett, 2013). Seemingly ideas put forward in the guidebook, along with publication of Evans et al., (2011), an *AAPG Datapages Search and Discovery* article, based on a talk presented by Evans in 2010 for members of the Tulsa Geological Society, were influential on authors and editors of AAPG Memoir 122 (Grammer et al., eds., 2019). Childress and Grammer (2019) essentially followed the outline of Evans et al. (2011), repeating the mapping and investigations of the Compton Limestone slump and slide masses near Jane presented by Evans and Bassett (2013). The AMG annual field trip guidebook series is important for sharing information with the geologic community in Missouri and with geologists in neighboring states. Although we agree on the overall interpretation of these so-called mounds, if Childress and Grammer (2019) had been aware of Evans and Bassett (2013) and the USGS-funded geologic map and report on the geology of the Jane 7.5-minute quadrangle (Cauthon et al., 2014; Elson et al. 2014), it likely would have altered their interpretations to what we consider to be more accurate! Both the AAPG Memoir and 2013 AMG field trip guidebook illustrate the regional significance of the upper Devonian and Mississippian rocks of southwestern Missouri. While interpretations vary somewhat, even within AAPG Memoir 122 (Grammer et al., eds., 2019), the rocks are the same, and evidence, based on observations and in parallel arguments should be objective. We will examine some of the latter in detail.

Mississippi Lime Play

The "Mississippi Lime play" of southern Kansas and northern Oklahoma is one of the North American Midcontinent region's most prolific accumulations of exploitable hydrocarbons.[1] This petroleum play is considered a conventional play, although petroleum geologists who work extensively in this interval might argue otherwise, because of the profound heterogeneity of lithology and compartmentalization of reservoirs. The reservoir rock commonly is mixed limestone of varying carbonate textures, fractured chert, and tripolite, a porous diagenetically altered, mostly recrystallized, quartzose material. The petroleum source rock generally is regarded as Woodford Shale or its stratigraphic equivalent the Chattanooga Shale. The play extends from the Anadarko basin in western Oklahoma and Kansas, across the Nemaha ridge, and onto the Cherokee shelf, west of the Ozarks. For purposes of assessing the Nation's petroleum reserves on the Cherokee shelf province, the U.S. Geological Survey, lumps the Mississippi Lime Play together with other Paleozoic reservoirs in a total petroleum system (TPS), known as the Paleozoic Composite TPS. Production from the Mississippi Lime play ranges from the Osagean through Meramecian stages. In the subsurface, the uppermost Devonian through Mississippian informally is known as the Mississippian A through D intervals (e.g., Lindzey et al., 2019), and hydrocarbons are produced from both vertical and horizontal wells.

The southwestern Ozarks plateau of southwestern Missouri, northwestern Arkansas and northeastern Oklahoma exposes Mississippian strata that are analogues for the subsurface Mississippi Lime play (Figs. II-1–2). In fact, these rocks contain kerogens and would likely have been part of the play, except they were uplifted during the late Paleozoic and likely were not buried deeply. The Chattanooga Shale is regarded as sub-mature in this area. These rocks have been the focus of research for geologists from Arkansas, Kansas, Oklahoma, and Missouri for decades, but especially over the last fifteen years. Key questions concern controls on reservoir quality and heterogeneity, and overall predictability based on sequence-stratigraphic interpretations. Other foci include paleogeography and paleogeomorphology of the Ozarks during Mississippian time. This paper addresses some commonly overlooked or under-appreciated components of this petroleum system, the structural geology and tectonic framework of the Ozarks uplift and timing of the uplift. Evans and Bassett (2013) argued that flexural uplift began during middle Devonian time, proceeded through the late Devonian and Mississippian, and culminated during the Pennsylvanian subperiod. This paper also proposes refinement of the current tectonic model for structural development of the Ozarks (Cox, 2009) in that hard and soft linkages in transfer zones between the dominantly southeast-northwest and conjugate northeast-southwest strike-slip fault blocks formed structures that influenced depositional patterns during Mississippian time. In fact, we regard southwestern Missouri exemplary for understanding syn-tectonic sedimentation on convergent shallow shelf-margin to epicontinental settings.

The Case for Syntectonic Sedimentation

The best way to understand subtle forms of tectonism like epeirogenesis, is through evaluation of regional unconformities. Tectonostratigraphic sequences in the Ozarks region include: (1) post-rift, passive margin sedimentation of Cambrian through mid-Devonian strata of the Sauk and Tippecanoe cratonic megasequences; (2) onset of convergence, denudation of the Ozarks, and deposition of fore-deep Arkansas Novaculite in the fore-deep of the Ouachita allochthon and deep-water deposition of the late Devonian Chattanooga Shale and its lateral correlates; (3) continued convergence and denudation of much of the Ozarks and subsequent deposition of Kinderhookian, Osagean, and Meramecian strata; (4) onset of collision with deposition of Chesterian and Morrowan strata; and (5) docking of the Ouachita allochthon, with culmination of the Ozarks uplift and deepening of the Arkoma basin during the early Pennsylvanian (Atokan Stage). These snapshots of time may best be explained with illustrations.

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[1] Note "Mississippi Lime" is an informal name that should not be confused with the eponymous large corporation that produces ag-lime from carbonate deposits in Missouri and elsewhere from surface and near-surface quarries.

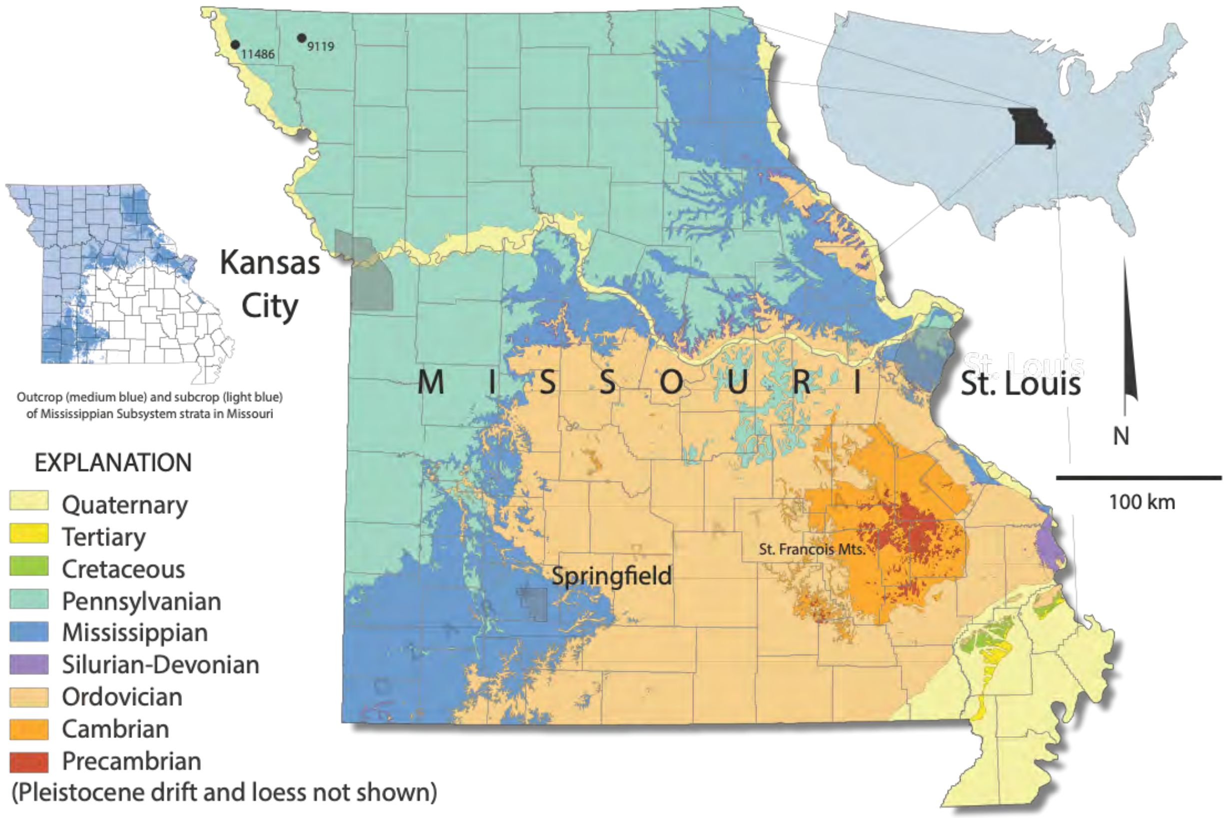


Figure II-1. *Geologic map of Missouri with insets showing location in relation to contiguous states (upper right) and outcrop and subcrop belt of strata assigned to the Mississippian subsystem (left side). In Atchison County, in the northwestern corner of Missouri, near the Missouri River, the base of the Mississippian subsystem and top of the Devonian was reported at 2345 ft (715 m) below the surface in well log no. 11486. Directly east, in Nodaway County, the base of the Mississippian and top of the Devonian was reported at 2285 ft (697 m) below the surface in well log no. 9119. Locations of both wells are indicated by black-filled circles on main map; both penetrated formations identified as Warsaw and Burlington-Keokuk. Many additional wells penetrate these units in northern Missouri (geologic map modified from Missouri Department of Natural Resources, Missouri Geological Survey, 2014).*

Neoproterozoic extension

Thomas (2012) provided a model for rifting of the Precordillera terrane from the southern margin of Laurentia (Fig. II-3). The results are expressed in features such as the Alabama promontory, the Ouachita embayment, the Texas promontory, as well as the Reelfoot rift and Oklahoma aulacogen. Many structures that underlie the Paleozoic succession were likely due to early phases of deformation during the Precambrian (Hayes, 1962). The southern margin of Laurentia subsequently experienced thermal subsidence, marine incursion, sea-level rise, and ultimately, deposition of late Neoproterozoic (?) to lower Cambrian sediments on the denuded landscape of the southern granite-rhyolite crustal province. Passive margin siliciclastic sedimentation, beginning in lower to middle Cambrian time, became dominantly carbonate or mixed carbonate and shale sedimentation during the middle Cambrian. This was the time of the Great American Carbonate Bank, or GACB (Derby et al., eds., 2012) that was associated with deposition of the Sauk megasequence of Sloss (1963).

Late Cambrian tectonism

Passive margin sedimentation should not be confused with quiescence. In the St. Francois Mountains, Cambrian strata seem to have been deformed and subjected to localized fault movements (Palmer and Seeger, 1998; Seeger and Palmer, 1998). Cambrian strata on the southern perimeter of the St. Francois Mountains also were affected by volcanic activity in structures like Furnace Creek and Dent Branch, both of which are late Cambrian features that narrowly constrain the timing of eruptive phases (McCracken, 1971).

Figure II-2. *Digital elevation map of the Ozarks region. Dark brown areas indicate higher elevations associated with Boston Mountains and leading edge of the Springfield Plateau near Cedar Gap, Missouri.*

Middle Ordovician tectonism

McCracken (1971) recognized the middle Ordovician as an episode of deformation in the Ozarks. This was coincident with the base of the Tippecanoe megasequence that saw broad emergence of Laurentia and deposition of a sheet sand across the midcontinent. In Missouri, this was the St. Peter Sandstone. Sandstone sink-fills are common on the northern slope of the Ozarks dome and smaller features dot the southern Missouri Ozarks. Such features are mapped as St. Peter Sandstone in the northern Ozarks by Missouri Geologica Survey mappers, but the age or ages of these features are not tightly constrained. In the southern Ozarks, they commonly are preserved as inverted topographic features. It is conceivable that many of these were associated with reactivation of Precambrian faults, where the St. Peter Sandstone filled karstic voids in lower Ordovician strata and subsequently the overlying main interval St. Peter Sandstone was removed by erosion. Examples around the Ten O'Clock Run Fault include Murder Rocks, south of Kirbyville, and Bear Mountain near Mincy, Missouri (Evans, 2010). The isolated blocks on Bear Mountain have deformational banding that indicates exposure to a tectonic paleo-stress field after deposition or emplacement.

The authors of this guidebook have differing interpretations on some isolated sandstone features in the Cedar Ridge section of Plymate et al. (2003) along Highway 65 north of the Saddlebrooke exit and in a former road cut along Highway 13 on Noble Hill, north of Springfield, where an angular unconformity truncated the top of the lower Ordovician Cotter Dolomite, cutting out up to 80 ft (24 m) of the Cotter. In the Noble Hill locality, two elongate, vertical lense-like bodies filled with sandstone were present in the upper beds of the Cotter (Fig. II-4). The road cut was removed during widening of the route during the middle 2000s. At Saddlebrooke, a vertical fault in the upper Cotter is filled with sandstone, approximately 20-30 cm across and minimally 10 m high (Fig. II-5, II-6). The sand either was injected from over-pressurized, underlying unlithified sandstone sources below or alternatively it was deposited *en masse* (without bedding or laminae) from above into a solution-enhanced fracture or gaping fault zone. In the former interpretation (the injection model), saturated sands would have been emplaced by compressional paleo-stress fields into this fracture. This area is in the Ponce de Leon structural zone, and a nearby road cut exposes one of the few documented thrust faults in southern Missouri. The age of that faulting is unknown, and even the sandstone-fill at Saddlebrooke shows evidence of fault reactivation with vertical slickenlines in the sandstone that parallel the walls on either side of the fault. It is unknown if there was one or two discrete movements on the fault.

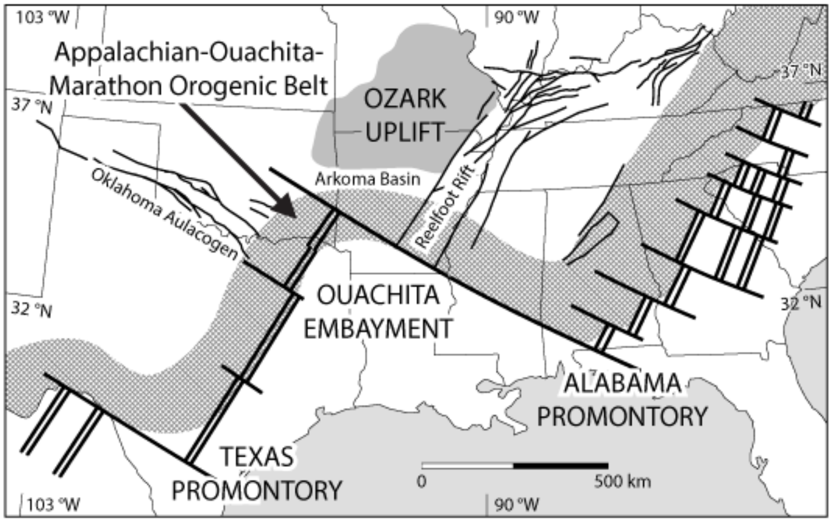


***Figure II-3**. Simplified model of Precambrian post-rift structural features of the southern margin of Laurentia (modified from Thomas, 2012).*


***Figure II-4 (left).** Vertical sandstone body at former Noble Hill road cut along Highway 13 north of Springfield, Missouri.*

***Figure II-5 (right).** Sandstone dike at Saddlebrooke road cut cuts the lower Ordovician Cotter Dolomite, which shows offset of about 20 cm. Surface irregularities on the sandstone resemble horizontal slickenlines, but vertical slickenlines are present along a fracture in the middle of the sandstone.*

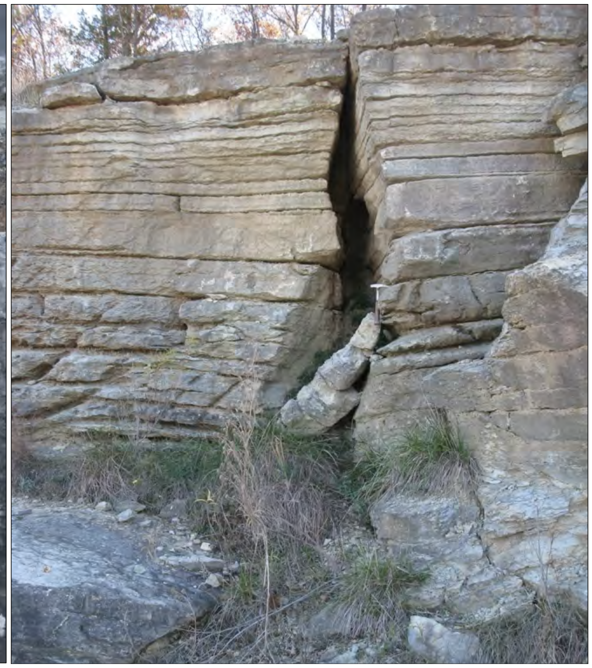


Figure II-6 (above left). *Upper surface exposure of sandstone dike at Saddlebrooke road cut.*

Figure II-7 (above right). *Solution-enhanced fault plane in Compton Limestone at Saddlebrooke road cut. Offset on the fault is only a few centimeters.*

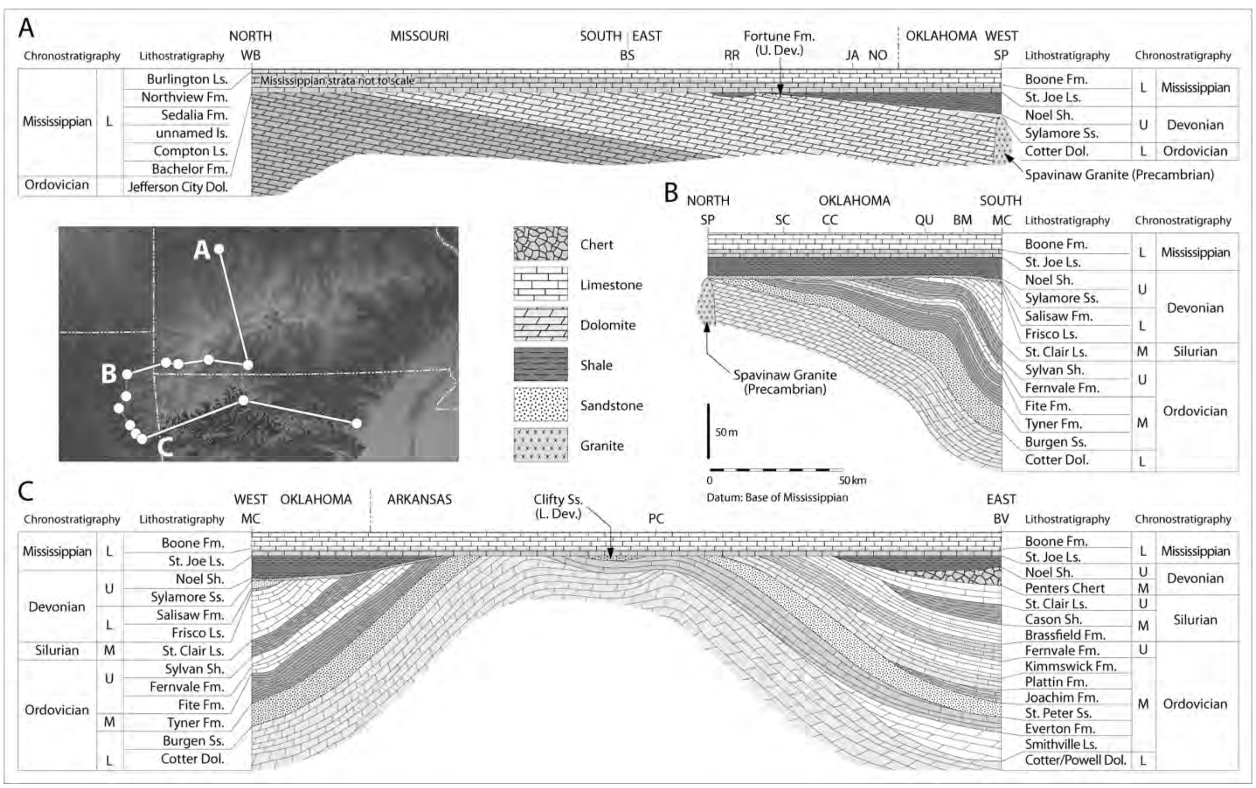


Figure II-8 (previous page)*. Stratigraphic cross sections of the western and southern Ozarks region. A, north-south and east-west composite cross section shows the progressive truncation of lower Paleozoic peritidal carbonates from shelf margin to interior and preservation of upper Devonian strata near Highlandville (modified from Jackson, 2011). B. Composite north-south stratigraphic cross section of eastern Oklahoma after Huffman (1958). C, west-to-east sketch of inferred stratigraphic relationships across northern Arkansas (Bush et al., 1977). Location abbreviations from north end of cross section A to east end of section C: BS, Branson; WB, Weaubleau; RR, Roaring River; JA, Jane; NO, Noel; SP, Spavinaw; SC, Spring Creek; CC, Clear Creek; QU, Qualls; BM, Blackgum Muntain; MC, Marble City; PC, Ponca; and BV, Batesville. Note the extensive truncation below the base of the Upper Devonian Chattanooga Shale in each.*

Figure II-9. *Road cut on Highway 65 adjacent to the Highlandville Fault exposes upper Devonian Chattanooga Shale. The Bachelor Formation here consist of sandstone and a thin green shale at the top of this recessively weathered exposure. Below the Chattanooga (below this image) is a 20 cm thick bed of conglomerate and breccia composed of dolomite and chert clasts.*

In a karst-fill interpretation, material would have infiltrated the fracture from above. The Bachelor Formation rests disconformably on the Cotter Dolomite at Saddlebrooke, but unlike the fault-fracture fill material below, it commonly contains clasts of rounded chert and phosphatic nodules derived from pre-sub-Mississippian weathering surface of the lower Paleozoic succession. No clasts of chert are found in the sandstone fill, but also no angular dolomite clasts are found along the walls of this feature. The walls appear to be relatively smooth. In the injection model sands would have had to have remained unlithified and potentially mobile while the overlying carbonates were lithified, fractured, and offset by faulting. In the infiltration model, carbonates would have been fractured, solutionally enhanced, filled with overlying sands of unknown age (older than the Bachelor Formation but younger than the Cotter Dolomite), and then faulted or re-faulted at a later date. Interestingly, the fault offset the overlying Bachelor Formation and cuts the overlying Compton Limestone (Fig. II-7), where the fault surface also was solutionally enhanced but not filled with sandstone. One thing we agree upon: *these features are products of syntectonic emplacement or deposition.* It also illustrates that although geologists may have differing views, we can work together.

Pre-Late Devonian tectonism

The Tippecanoe and underlying Sauk megasequences are cut with angular discordance in the northeast Oklahoma and northern Arkansas (Fig. II-8). Huffman (1958) and Bush et al. (1977) show truncation of the lower Paleozoic successions below a sub-upper-Devonian unconformity. In northern Arkansas, uplift and erosion may have been as early as middle Devonian. The Penters Chert is a breccia in a few localities, and it underlies the blanket of upper Devonian Chattanooga Shale present across the southwestern and southeastern Ozarks. In the Missouri Ozarks, the Chattanooga Shale and Fortune Formation are mostly found in Barry, McDonald, and Newton counties, but a few outliers are present in fault zones, such as the Highlandville Fault (Fig. II-9), and sink fills across northern Arkansas and southern Missouri, and in the Weaubleau impact structure, a rare, rounded black shale clast, about 3 cm across, is preserved in the MoDOT-SMSU Vista 1 core, along with a few Famennian conodonts (Fig. II-10; Miller et al., 2008). Weaubleau was a mid-Mississippian oblique, marine impact (Evans et al., 2003; Miller et al., 2008).

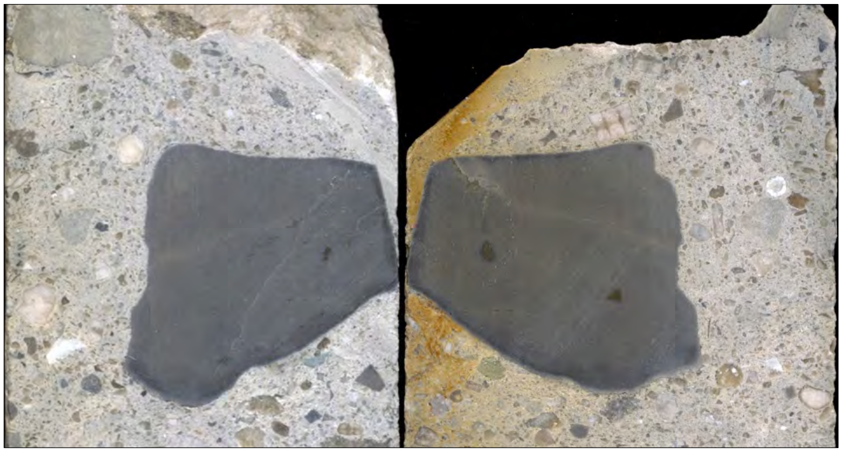


Figure II-10. *Book-matched clast of Chattanooga Shale in "Weaubleau Breccia" at 90.25 ft (27.5) depth in MoDOT-SMSU Vista 1 core from southeastern St. Clair County, Missouri.*

Interestingly, upper Ordovician to Silurian clasts are found in the Decaturville impact structure (Offield and Pohn, 1979), whereas Mississippian sandstone and coal sink-fills are present in the Crooked Creek impact structure (Hendricks, 1954; Mulvany et al., 2004). Presumably, the sub-upper Devonian or sub-Mississippian unconformities may have removed upper Ordovician and Silurian strata from the area around Decaturville because neither Devonian nor Mississippian clasts are found in impact breccias, whereas Crooked Creek was karstified prior to deposition of Mississippian sink-fill accumulations. The ages of the two impact structures are poorly constrained, but new road construction at Decaturville exposed an undeformed, relatively flat-lying body of sandstone on the northeastern perimeter of the moat region.

The timing of uplift in the Ozarks region generally has been assumed to be Pennsylvanian in age, associated with the assembly of Pangaea, collision of the Ouachita allochthon, and development of the Arkoma foreland basin (e.g., King, 1977; Cox, 2009; Hudson and Turner, 2022). Others date docking of Ouachita allochthon to the early Carboniferous Meramecian time period (Golonka et al. 2006). Clearly, evidence points toward first pre-late Devonian uplift in the western Ozarks and pre-Mississippian uplift across much of the Ozarks. Two paleo-karst features in the Jefferson City Dolomite, north of Rolla along Highway 63 are filled with mid-Devonian Grand Tower deposits and adjacent to that, Mississippian deposits (Mulvany and Davis, 2012). Collectively, these highlight the weathering, erosion, and progressive denudation of the Ozarks, down to the Jefferson City Dolomite in places, prior to a Pennsylvanian tectonic overprint. By mid-Devonian time, significant flexural movement had led to truncation of the lower Paleozoic succession.

Chattanooga Shale and Implications for the Dolomite Problem

"Absence of evidence is not evidence of absence" is a logical conundrum we commonly face in geology. Just as the St. Peter may have migrated across the Ozarks, filling sinkholes in places, widespread deposition of the Chattanooga Shale could have influenced the rocks below it. If we untether from the prevailing practical aspects of science, where hypothesis-testing is based on deductive reasoning and disproof, we venture into a hypothesis-forming framework of abductive reasoning, where we pose "what if" propositions. If the Chattanooga Shale blanketed the entirety of the Ozarks, what might be the implications? If the sub-Mississippian unconformity subsequently removed a widespread Chattanooga Shale, then although erosion has removed the physical evidence, the Chattanooga Shale could have been a confining layer that could have allowed lower Paleozoic strata to become dolomitized in the basinal brine model of Gregg (2004), prior to deposition of the largely un-dolomitized Mississippian.

Mississippian tectonism

In his studies of the Mississippian Burlington Shelf, Lane (1978; Lane and De Keyser, 1980) mapped shelf-margin facies across southwestern Missouri (Fig. II-11). There is little contention of his interpretation; relatively deep-water carbonates accumulated in the areas of northeastern Oklahoma and across northern Arkansas. The perplexing aspect is that shelf-margin strata not only were deposited above unconformities that, in Missouri, cut lower Ordovician peritidal carbonates. During the early Paleozoic, the shelf margin clearly was located farther south and likely was present below the Ouachita allochthon (Allison et al. 2012). Evans and Bassett (2013) refer to the Mississippian tectono-stratigraphic sequence as a product of backstepping sedimentation on the Laurentian platform. In the Ouachita allochthon strata show marked deepening with deposition of the Arkansas Novaculite in mid-Devonian through Osagean time. This unit was interpreted as a foredeep deposit that accumulated in front of the approaching terrane prior to docking.

Tectonic processes can be both continuous and episodic. If tectonism was active during the late Devonian and through much of the Pennsylvanian, it likely would have affected the sedimentary successions of the Mississippian as well since the collisional event was pending. Essentially, a framework exists for arguing that syntectonic sedimentation was possible. Nevertheless, to avoid "begging the question" or circular reasoning, we view anomalous features and thicknesses or strata in the Mississippian succession as evidence of tectonic movements if they are adjacent to structural features (folds or faults) that could have affected sedimentation. Features include slide and slump blocks in the Compton Limestone at many localities but especially along Highway 71, a Pierson Limestone olistolith in northwest Arkansas, and anomalous accumulations along structural features like the Bella Vista-Greasy Creek Fault.

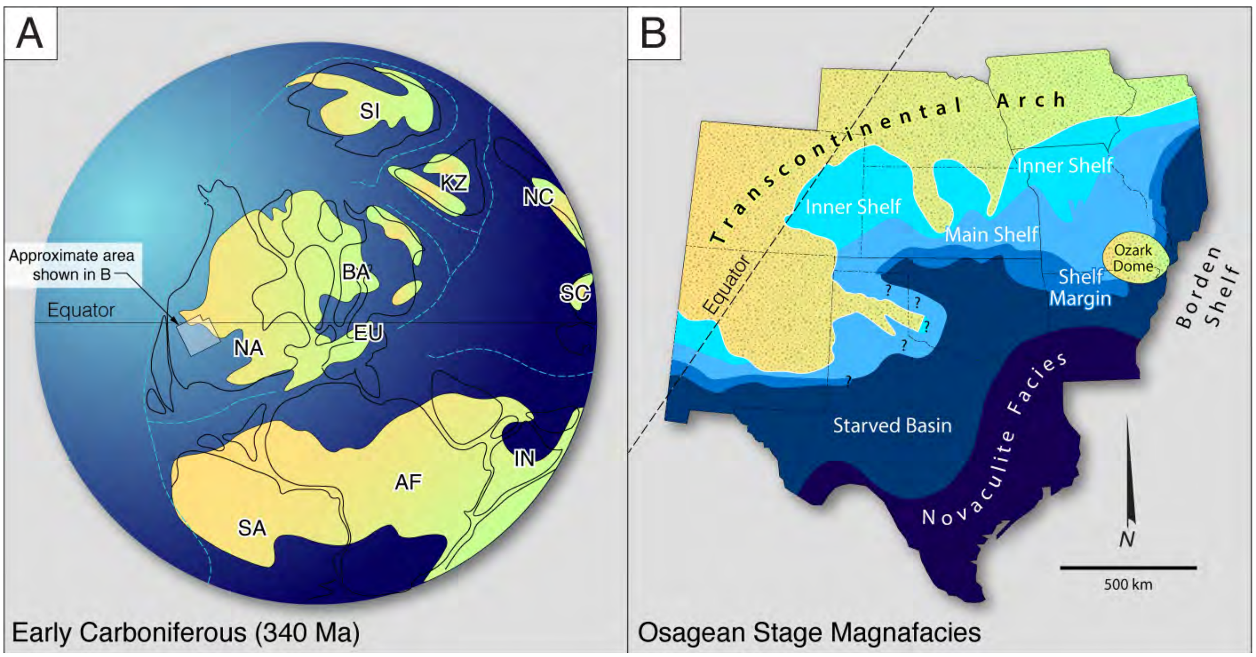


Figure II-11*. Paleogeography of Laurentia during the early Carboniferous and Mississippian magnafacies of the southern margin of Laurentia during the Osagean Epoch. Note that areas of southwestern Missouri are part of the shelf margin facies (modified from Blakey, 2011; Lane, 1978; Lane and Dekeyser, 1980).*

Mississippian strata across southwestern Missouri can vary widely in thickness. For example, quarry exposures of the Pierson Formation in Webster County show that the unit is about 60 ft (18 m) thicker west of the Fair Play Fault than it is on the east side. This thickness anomaly was also present in the Pierson Limestone at Baird Mountain. In fact, the upper Pierson Limestone actively was eroded in the Wolf Pen Gap Hollow Anticline near Pineville, and a meter-thick bed of chaotically bedded carbonates above the Wolf Pen Gap shale is present in road cuts less than 2 km to the east.

Mississippian Carbonate Slides, Slumps, and Olistoliths

In AAPG Memoir 122 (Grammer et al., eds., 2019), four different interpretations for the origin of carbonate mounds were put forward for features in the Compton and Pierson limestones: (1) reefs (Unrast and Gregg, 2019); (2) dislocated reefs (Mazzullo et al., 2019); (3) buried hills (Mazzullo et al., 2019); and (4) slide or slump masses, or so-called outrunner blocks (Childress and Grammer, 2019).

Commonly, these features are regarded as mounds (a shape identification) and compared with Dinantian strata of southern Belgium, where similar features are referred to as Waulsortian mud mounds. The Sacramento Mountains of New Mexico, Borden Shelf of Kentucky, and slope strata of western Utah have mounds of approximately the same age and with variable compositions. The idea is that most were either microbial where the microbial organisms that made them is no long obvious, or they may have formed from baffling and trapping of mud by organisms that subsequently were not preserved in a growth position. Various investigators have applied petrographic techniques and other tests to try to determine the origin or origins. Some have argued that the mounds are associated with seeps but generally most have interpreted the mud mounds as reefs. Unrast and Gregg (2019) compare the mound at Jane with a mound in Ireland and offer a reef interpretation. Mazzullo et al. (2019) argued that a few were displaced reefs, and at one locality, a mound is identified as a buried hill. Of course, in the Ozarks, not all are composed of mud.

One is left asking, "Why here?", especially since proposed lower Carboniferous mounds vary so widely in their depositional setting from shallow to relatively deep marine. They tend to occur along the state line between Missouri and Arkansas, but a few are in Oklahoma.

We view the reef interpretation for mud mounds in the Ozarks with skepticism. There is no evidence for framework, binding, or baffling in the core facies of mounds that would indicate "growth structure". Interpretation of such a feature as a displaced reef is an even more stilted interpretation. The idea of a buried hill is equally perplexing, but the idea of a lithified or semi-lithified block of carbonate rock that has been displaced structurally near a fault zone seems feasible. Damon Bassett (*in* Evans and Bassett, 2013) applied a geochemical test to see if mud supposedly trapped in mounds would show the same isotopic profile as regularly bedded strata in adjacent exposures. They did not. Rather, the mounds were relatively uniform in their isotopic signatures. Bassett argued that this could be considered evidence of mixing that is consistent with a slump interpretation.

Following the interpretations of Evans et al., (2011), Childress and Grammer (2019) considered the Jane mound as an outrunner block, essentially a large slide block with associated features, products of slumping in the lowermost carbonate unit of the Mississippian succession. Childress and Grammer (2019) considered that these features were sliding down the distally steepened ramp. The latter interpretation is somewhat unusual since the mounds are found a slope that dips to the north. In this paper we argue that the slide blocks and slumps were directed downslope into small fault-bounded intrashelf basins. *The slide masses, slumps, rafted strata, and synsedimentary folds invariably are found on the downthrown blocks adjacent to faults or faults zones.*

Evans and Bassett (2013) provided a cross section of the Jane slump complex (Fig. II-12). The only slope of note is away from the trace of the Brush Creek Fault. At Jane, the Brush Creek Fault is only a few hundred meters south. The largest cohesive slide mass and smaller satellite slump masses accumulated on a paleoslope that seeming is still present today above the Chattanooga Shale. Additional masses are found down Tanner Hollow toward the northwest. Brush Creek Fault runs ENE-WSW and continues as the Southwest City Fault. The combined fault zone is minimally 30 km in length with as much as 100 ft (30 m) of vertical displacement. Two mounds at Dogwood Canyon (referred to as Indian Creek by Troell (1962)) on Highway 86, near Blue Eye, Missouri are on the downthrown block adjacent to the Lampe Fault (Fig. II-13). The Lampe Fault has more of 100 (30 m) of offset.

An olistolith interpretation is plausible for the Pierson Limestone blocks at Pedro, along Highway 412 in northwest Arkansas. Seemingly this is the same feature identified as a buried hill in Mazzullo et al. (2019). This block is featured in the "Geo-Pic of the Week" photo in an Arkansas Geological Survey web site (Fig. II-14). The observation most telling at this locality is the bedding in the block is vertical. A second block is found about 30 m to the east. It shows normal orientation of bedding. The Pedro olistoliths are next to the Bella Vista Fault. To the east is the parallel-trending Sycamore Syncline. This pattern is repeated in Barry County, Missouri where the Washburn Syncline runs parallel to the Greasy Creek Fault. The Sycamore Syncline continues northeastward toward Bentonville, where anomalous thickness of the Bentonville Facies likely is a result of tectonic accommodation on the downthrown side of the fault (see Fig I-2,3). The Bella Vista Fault is likely the southern extension of the Bentonville-Pea Ridge Fault, which runs into the Greasy Creek Fault in Missouri. These long faults tend to have some horizontal displacement as well as vertical. The adjacent broad, gentle folds are interpreted as fault-propagation folds, where the sedimentary cover is affected by movements on the basement fault blocks.

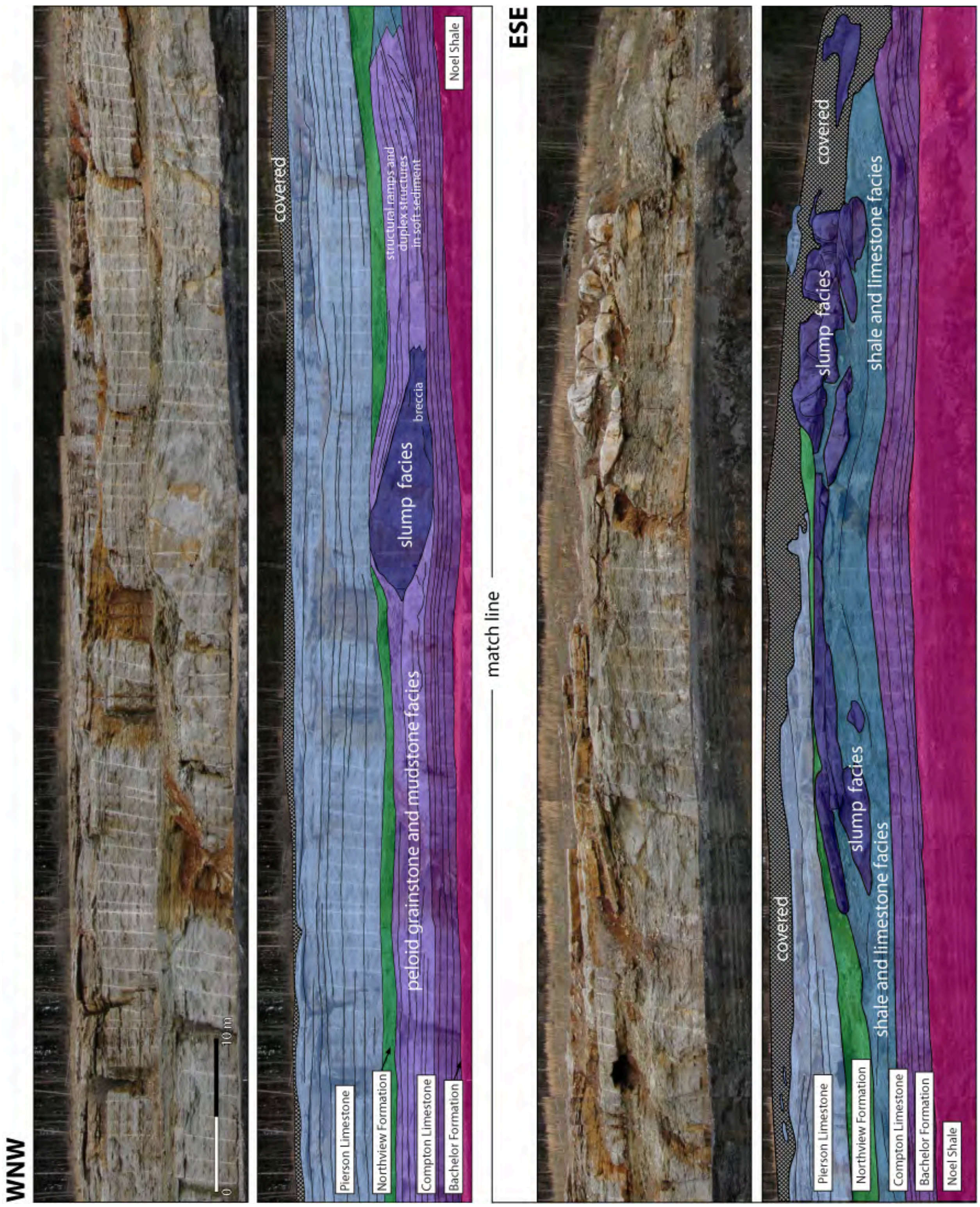


***Figure II-12**. Paleogeography of Laurentia during the early Carboniferous and Mississippian magnafacies of the southern margin of Laurentia during the Osagean Epoch. Note that areas of southwestern Missouri are part of the shelf.*

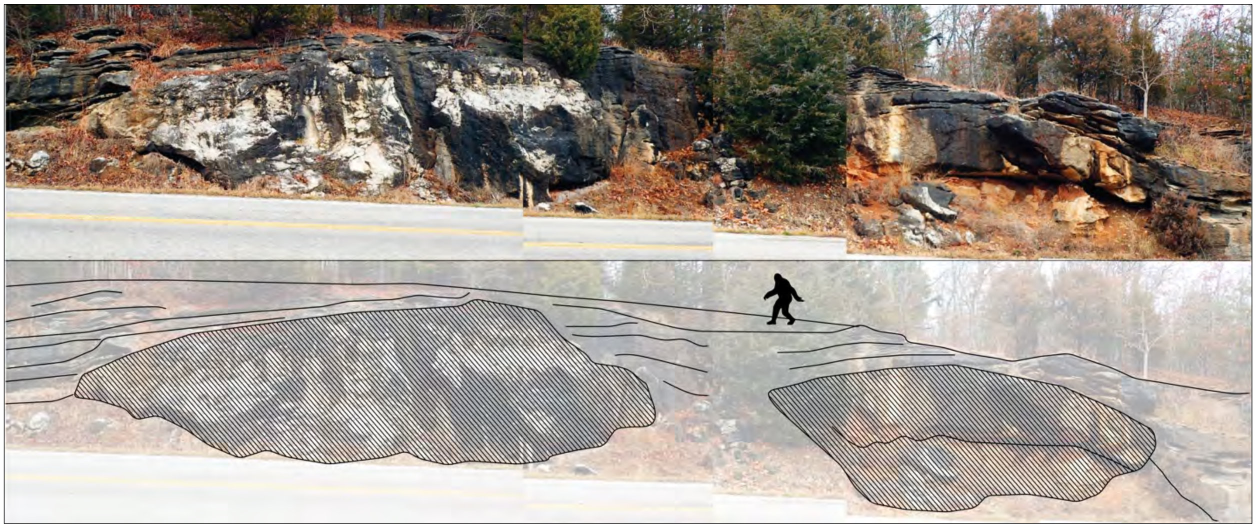


Figure II-13. *Composite photo shows cross-secitonal view of mounds at Dogwood Canyon. The interpretive diagram below indicates slide masses in cross-hatch pattern. The Northview Formation is present in a wedge to the left. Overlying strata of the Pierson Limestone are draped over the mounds. These, together with some additional localities are being studied by an MSU graduate student, Jared McAvoy. Silhouette provides an approximate scale.*

Figure II-14 (previous page)*. Images of olistoliths in a road cut along Highway 412 in northwestern Arkansas. Top left photo shows large olistolith of Pierson Limestone draped by Reeds Spring Formation. Jim Miller for scale. Top right photo shows the olistolith in detail. This obviously isn't a mud mound but was at least semi-lithified when emplaced. The bottom photo shows a nearby olistolith.*

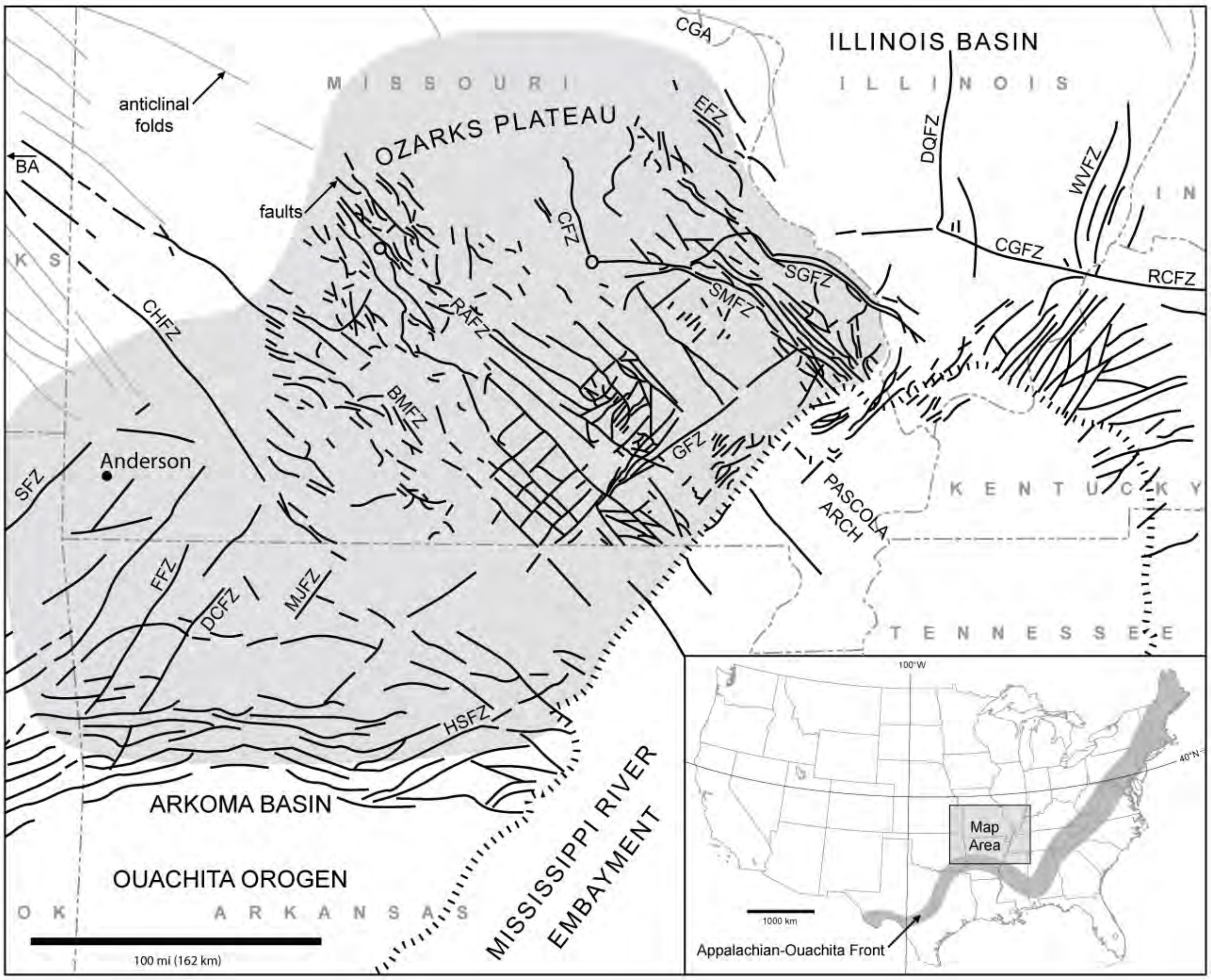


Figure II-15*. Fault map of the Ozarks: BA, Bourbon Arch; BMFZ, Bolivar-Mansfield Fault Zone; CFZ, Cuba Fault Zone; CHFZ, Chesapeake Fault Zone; CGA, Cape au Gris anticline; CGFZ, Cottage Grove Fault Zone; DCFZ, Drake's Creek Fault Zone; DQFZ, DuQuoin Fault Zone; EFZ, Eureka Fault Zone; FFZ, Fayetteville Fault Zone; GFZ, Greenville Fault Zone; HSFZ, Heber Springs Fault Zone; MJFZ, Mt. Judea Fault Zone; RAFZ, Red Arrow Fault Zone; RCFZ, Rough Creek Fault Zone; SFZ, Seneca Fault Zone, SGFZ, Ste. Genevieve Fault Zone; SMFZ, Simm's Mountain Fault Zone, and WVFZ, Wabash Valley Fault Zone (modified from Cox, 2009).*

A Structural Model for Ozarks Tectonism

Cox (2009) presented an elegant model for structural development of the Ozarks. The fault map above shows the dominant crisscross pattern of structures that he argued were related to oblique collision with the Ouachita allochthon (Fig. II-17; Cox, 2009). Although, our interpretation for the timing of epeirogenic, flexural uplift differs somewhat; we suggest that onset of convergence was mid-Devonian, continuing through Mississippian time, and ultimately culminated in the Pennsylvanian. Nevertheless, the pattern of faulting and interpreted paleo-stress field in this model is robust. It still leaves a few questions unanswered. If uplift is related to the convergence and collision, which are generally compressional features, why are there so many grabens in the Ozarks?

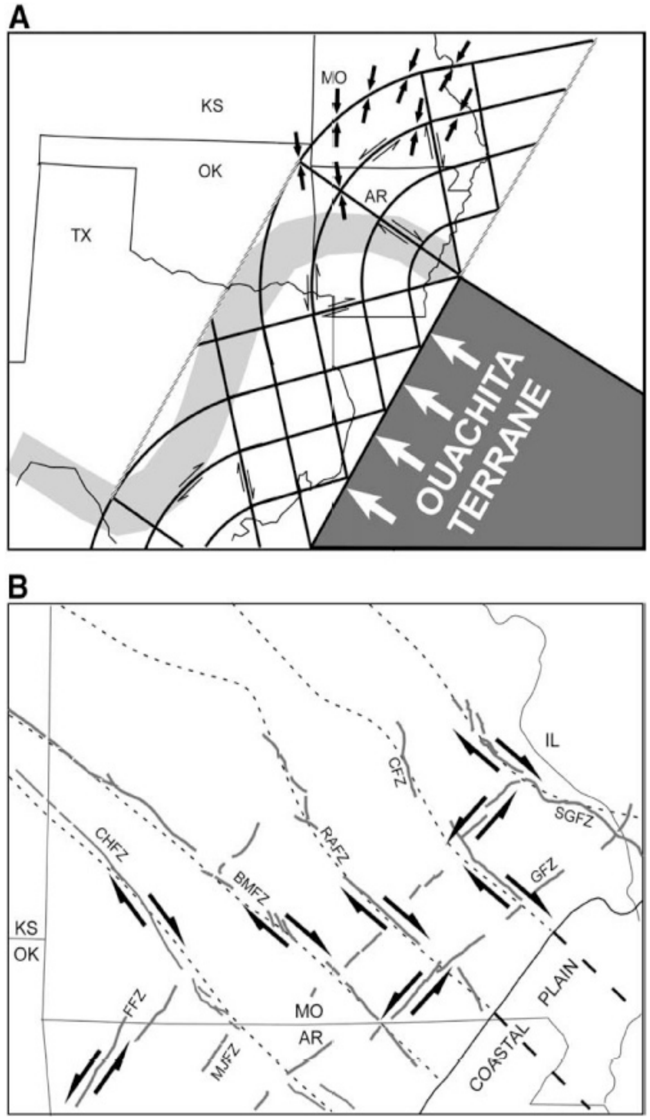


Figure II-16*. A, hypothetical trajectories of planes of maximum shear stress for a slip line field during initial docking of the Ouachita terrane with North America assuming northwest–southeast convergence. Half arrows = shear sense along slip lines; full arrows = local* H_{max} *directions; light gray pattern = present Ouachita thrust belt. B, simplified map of the study area showing basement tectonic zones (dashed lines) and prominent surface fault systems (solid lines) from Fig. 1. Half arrows show shear sense predicted by the slip line field in (A) (from Cox, 2009).*

Cox addressed the idea of such features as a series of Pennsylvanian events related to development of a tectonic indenter (Fig. II-18). Evidence of syntectonic sedimentation during the Mississippian suggests earlier movements along faults, and because the faults likely did not change general orientation or position, fault bends may have influenced the development of anomalous structural features at a much earlier phase, leading to restraining and releasing bends. Transpressional and transtensional structures were common. The Mt. Shira uplift is a fold that is blanketed by the Chattanooga Shale as well as plastically deformed carbonates of the lower Mississippian. The truncated anticline at Wolf Pen Gap Hollow seeming was related to left-lateral movement on the Brush Creek Fault (see Fig. RL-6,7).

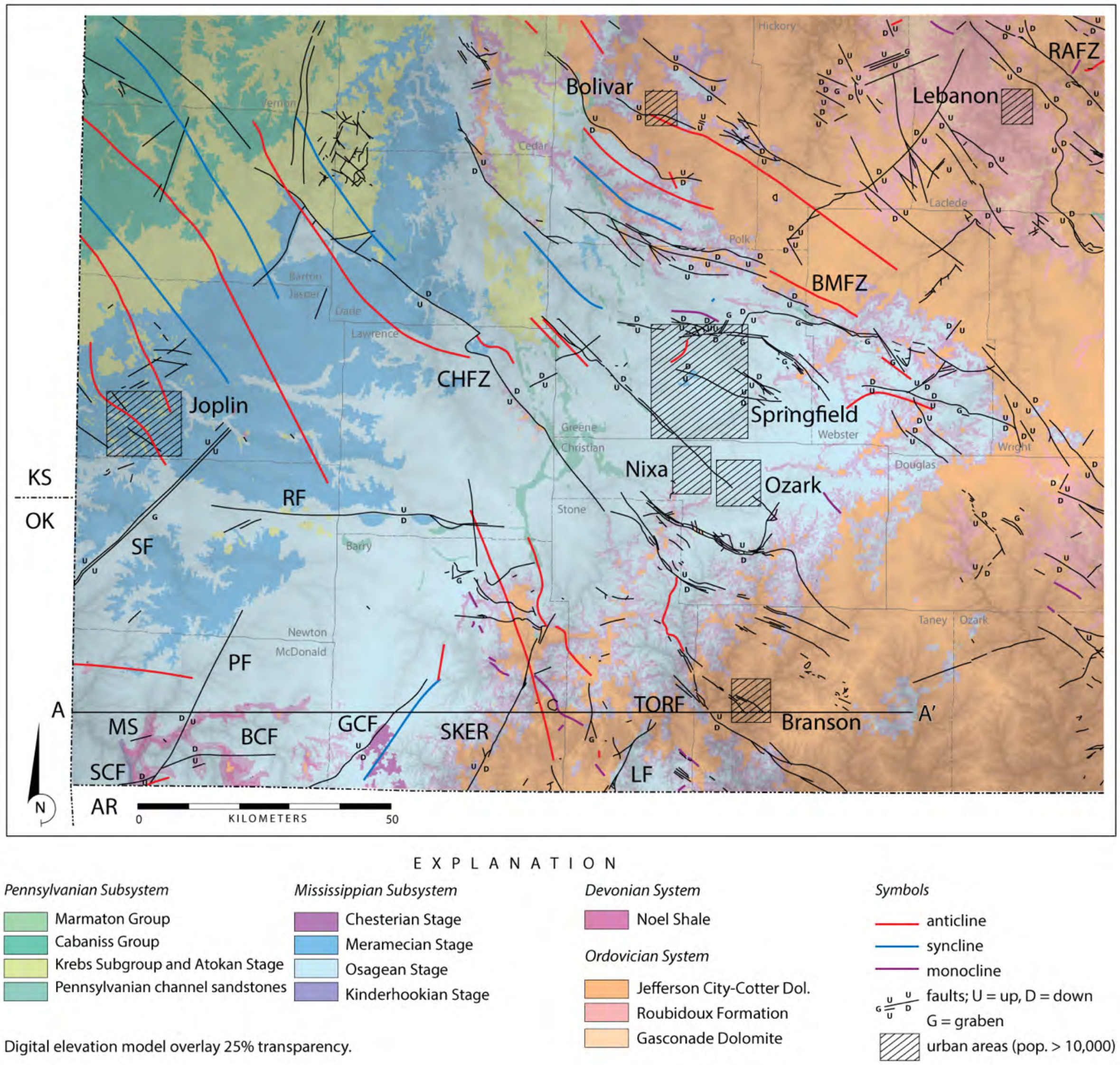


Figure II-17. *Geologic map of southwestern Missouri showing major urban centers and principal fault and structural zones: BCF, Brush Creek Fault; BMFZ, Bolivar-Mansfield Fault Zone; CHFZ, Chesapeake Fault Zone; GCF, Greasy Creek Fault; LF, Lampe Fault; MS, Mount Shira uplift; PF, Pineville Fault; RAFZ, Red Arrow Fault Zone; RF, Ritchey Fault; SF, Seneca Fault; SKER, Shell Knob-Eagle Rock structure; SWCF, Southwest City Fault; and TORF, Ten O'Clock Run Fault. The 2022 AMG field trips will focus on the petroleum system and structural geology of McDonald and southwestern Barry counties (lower left area of map. Cross section A–A', indicated by green line, is shown in Figure 3 (base map modified from Missouri Geological Survey .kml files available online at Geosciences Technical Resource Assessment Tool (GeoSTRAT)).*

The geologic and structural maps of southwestern Missouri are shown in Figs. II-17–19). Figure II-19 illustrates the idea that major bounding faults bound five areas that we interpret as transfer zones, where an array of hard and soft linkages demonstrate strain partitioning with several small grabens, anticlines, and synclines. Figure A-1 in the Appendix highlights a couple of these transfer zone base on surface geologic mapping with the integration of subsurface mapping. It is not part of this field area, but it was an easy to include as a bonus figure for folks who work in Greene County.

For this field trip, we will focus on the Brush Creek and Cassville transfer zones. Some of these were active during deposition, so that a series of intrashelf basins developed as large-scale grabens or half-grabens adjacent to major faults. The Compton and Pierson limestones especially were affected by these local depocenters, but during this time interval structural control on deposition was influential as far north as the Fair Play Fault in Polk County.

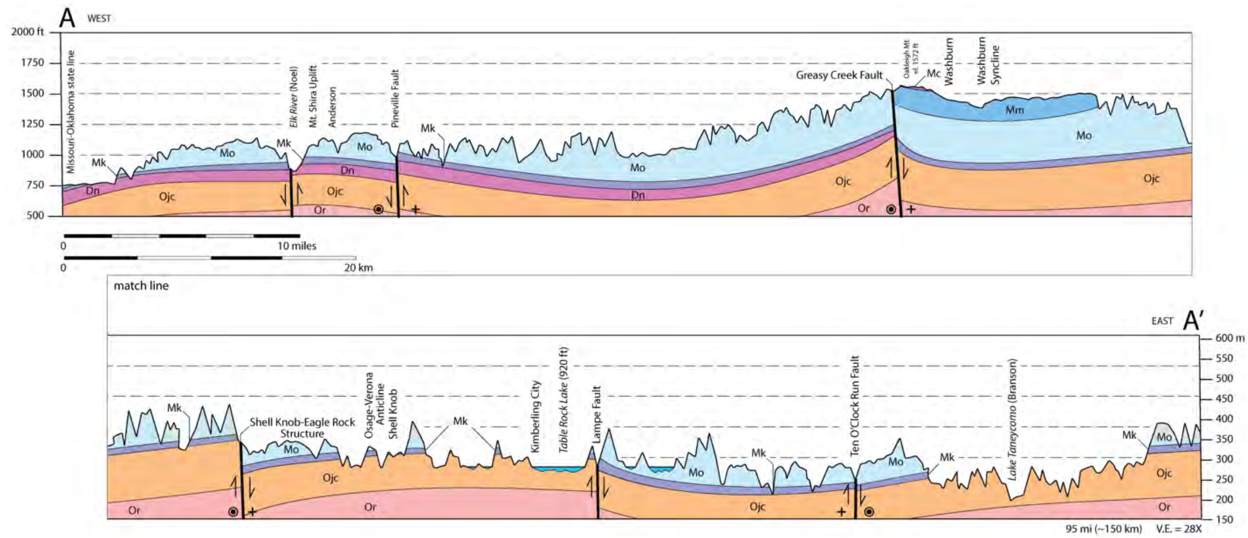


Figure II-18. *Structural cross section A–A' of southern Missouri showing principal fault and structural zones (see Fig. II-3 for location). Note that Oakleigh Mountain in southern Barry County is one of the highest topographic and stratigraphic features in southwestern Missouri.*

Ordovician and Devonian inliers are geologic map elements, essentially windows, where older strata are exposed (Fig. II-20). In southwest Missouri, their recognition is important for identifying structural features. For example, the Owens Bluff inlier straddles the Horse Creek Anticline. White Rock Prairie inlier is on the upthrown side of Brush Creek Fault. Pineville and Cyclone inliers are on the upthrown side of the Pineville Fault. Greasy Creek and Mountain inliers are on the upthrown side of Greasy Creek Fault. Based on the distribution of structural features in Fig. II-20, it is possible to construct a block diagram that illustrates the nature of the fault blocks that appear to have had both left-lateral as well as vertical movements (Fig. II-21). The five fault-bounded blocks identified in the block diagram are structural elements that include the Mt. Shira, Big Sugar Creek, Bella Vista, Seligman, and War Eagle blocks. These were the underpinning elements that affected development of intrashelf basins. A few of the syntectonic features are listed on the diagram, but there are likely many more that we will detect with continued geologic mapping of this area.

Stratigraphy is a Multi-dimensional Discipline

Some of the rocks we will see on this field trip have been visited and worked on by multiple generations of geologists, including students, professors, civil servants, petroleum geologists and geochemists. The mound-like feature at Jane is a classic example of stratigraphic feature that has had volumes of literature produced over an astonishingly small feature. It is less than 4.0 m in height and 12 m in exposed width. Mounds and mound-like features tend to have a sort of gravitational pull on geologists. I refer to this as point stratigraphy: it is somewhat one-dimensional, yet we understand that the stratigraphic record is by nature one of three dimensions with the added dimensions of time and tectonic movements.

Other mounds such as in the overhanging river bluffs above Noel, Missouri, the string of mound tops along Tanner Branch, northwest of Jane, the pair of mounds at Dogwood Canyon, near Blue Eye, Missouri, and the pair of mounds along Highway 412 east of Siloam Springs in Arkansas have received much attention. That literally is the point; it is easy to miss the forest for the trees when looking at mounds or enormous road cuts. Geologists tend to fixate on points or sections but miss the bigger picture. I refer to this as point stratigraphy: it is somewhat one-dimensional, yet we understand that the stratigraphic record is by nature one of three dimensions with the added dimensions of time and tectonic movements. It is geologic mapping that constrains our model.

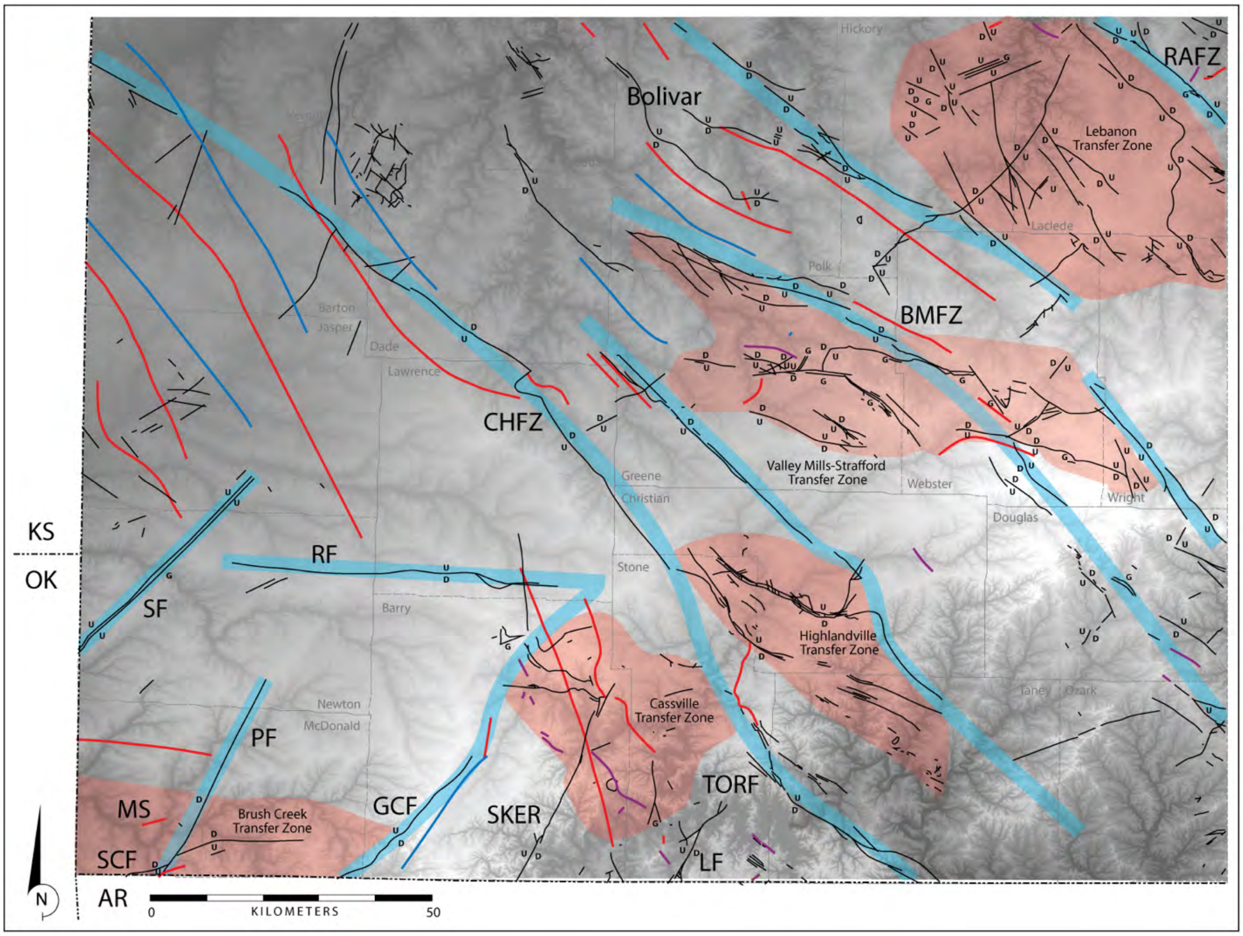
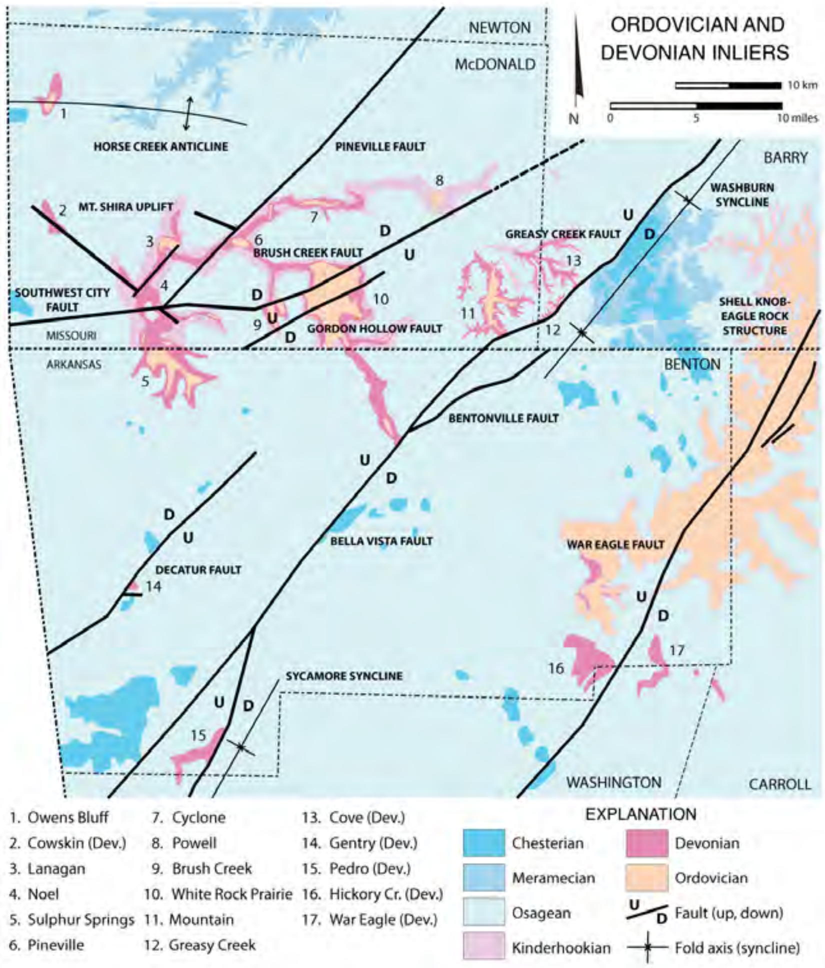


Figure II-19. *Map of principal structures and structural domains in southwestern Missouri. See Fig. II-3 for explanation of structural symbols. Major strike-slip faults shown in transparent bold light blue lines. Structural transfer zones are shown in transparent light red.*

Figure II-20 (next page). *Geologic map of southwestern Missouri and northwestern Arkansas showing lower Ordovician (Ibexian Series) and Devonian inliers and continuity of principal structures. Inliers are identified by numbers. Faults like the Bella Vista-Greasy Creek fault, Mt. Shira uplift (anticline), and Pineville and Brush Creek faults bound intrashelf basins during Mississippian time.*


ORDOVICIAN AND DEVONIAN INLIERS
N
10 km
0
5
10 miles
NEWTON
McDONALD
BARRY
BENTON
WASHINGTON
CARROLL
MISSOURI
ARKANSAS
HORSE CREEK ANTICLINE
PINEVILLE FAULT
MT. SHIRA UPLIFT
BRUSH CREEK FAULT
SOUTHWEST CITY FAULT
GORDON HOLLOW FAULT
GREASY CREEK FAULT
WASHBURN SYNCLINE
SHELL KNOB-EAGLE ROCK STRUCTURE
BENTONVILLE FAULT
BELLA VISTA FAULT
DECATUR FAULT
WAR EAGLE FAULT
SYCAMORE SYNCLINE
1. Owens Bluff
2. Cowskin (Dev.)
3. Lanagan
4. Noel
5. Sulphur Springs
6. Pineville
7. Cyclone
8. Powell
9. Brush Creek
10. White Rock Prairie
11. Mountain
12. Greasy Creek
13. Cove (Dev.)
14. Gentry (Dev.)
15. Pedro (Dev.)
16. Hickory Cr. (Dev.)
17. War Eagle (Dev.)
EXPLANATION
Chesterian
Meramecian
Osagean
Kinderhookian
Devonian
Ordovician
Fault (up, down)
Fold axis (syncline)

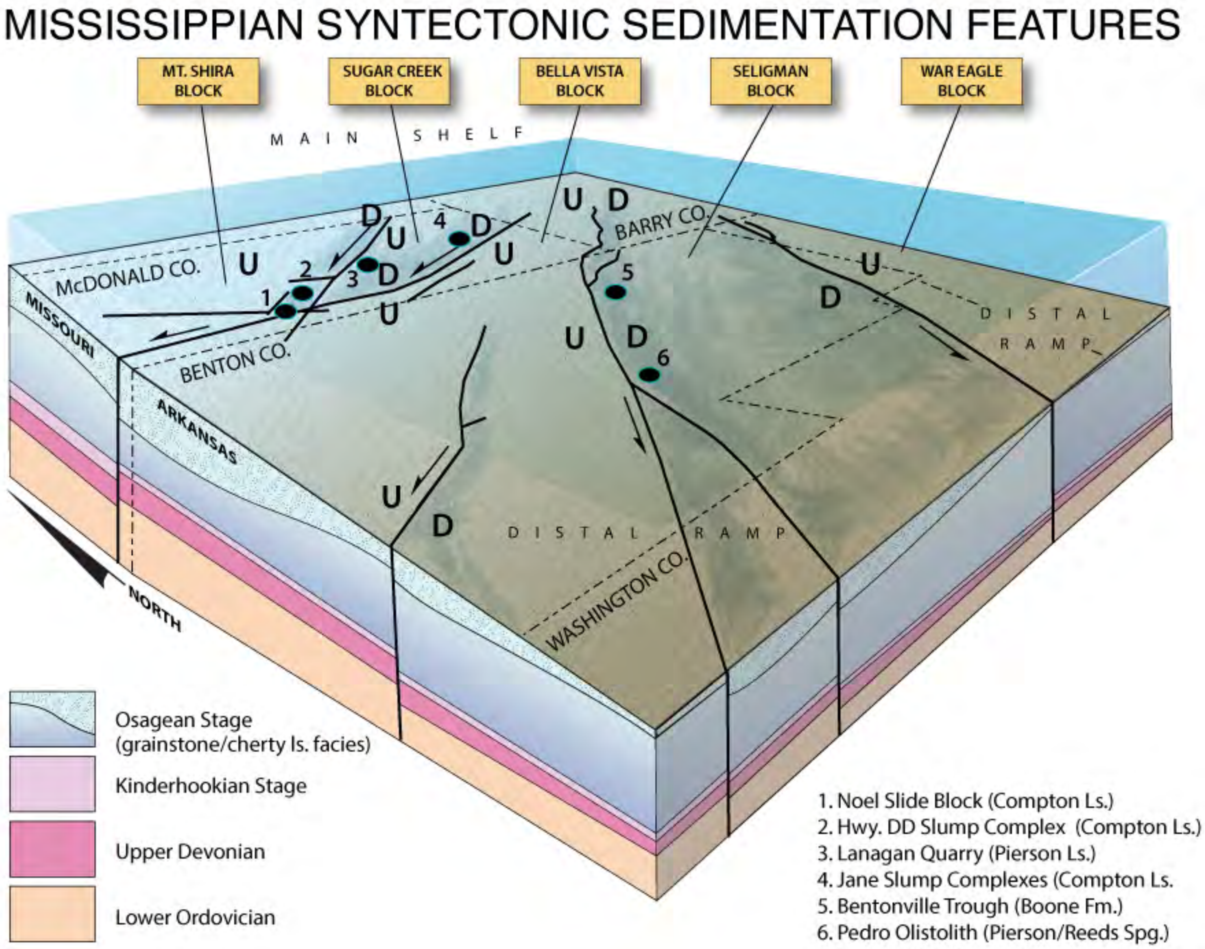


Figure II-21. *Geologic block diagram of southwestern Missouri and northwestern Arkansas during the late Osage Stage. Vertical movements on principal fault blocks bounded intrashelf basins, which actively were affected sedimentation and distal steepening of the prograding shelf margin during Mississippian time. Several of these faults also have folds and anomalous features that indicate strike-slip movements as well.*

ROAD LOG

The two field excursions for this conference will visit some important sites that show the structure and stratigraphy of southwestern Missouri. The Jane 7.5-minute quadrangle was mapped by undergraduate geology students at Missouri State University in 2012 and 2013 as part of the U.S. Geological Survey EDMAP program. The EDMAP Program allows students to map the bedrock geology and other aspects of project areas *and* be paid for their efforts. As the principal investigator, Evans supervised the project and assisted students understand the process of mapping, requirements for a quality product, and nuances of mapping geology in Missouri. The completed map (Fig. RL-1; Elson et al., 2014) and geologic report (Cauthon et al. 2014) show the exceptional efforts of these field mappers. The two lead authors were the principal mappers but two additional field mappers helped bring this project to fruition, Kevin Newbold and Laura Thayer. Several other students were involved in some of the stratigraphic work, and their names appear on the map, report, and acknowledgements. Mark Larson especially was helpful. He performed a gravity survey and made the gravity map of the quadrangle and surrounding area under the supervision of Dr. Kevin Mickus, Missouri State University. Currently, a Missouri State University undergraduate is mapping the adjoining Noel 7.5-minute quadrangle. As you reasonably understand that project has experienced some delays and setbacks due to the COVID-19 pandemic. On the field excursions, we will be focused on sites in the Jane and Noel quadrangles, but we also will visit fascinating localities in the surrounding areas of McDonald and southern Barry counties.

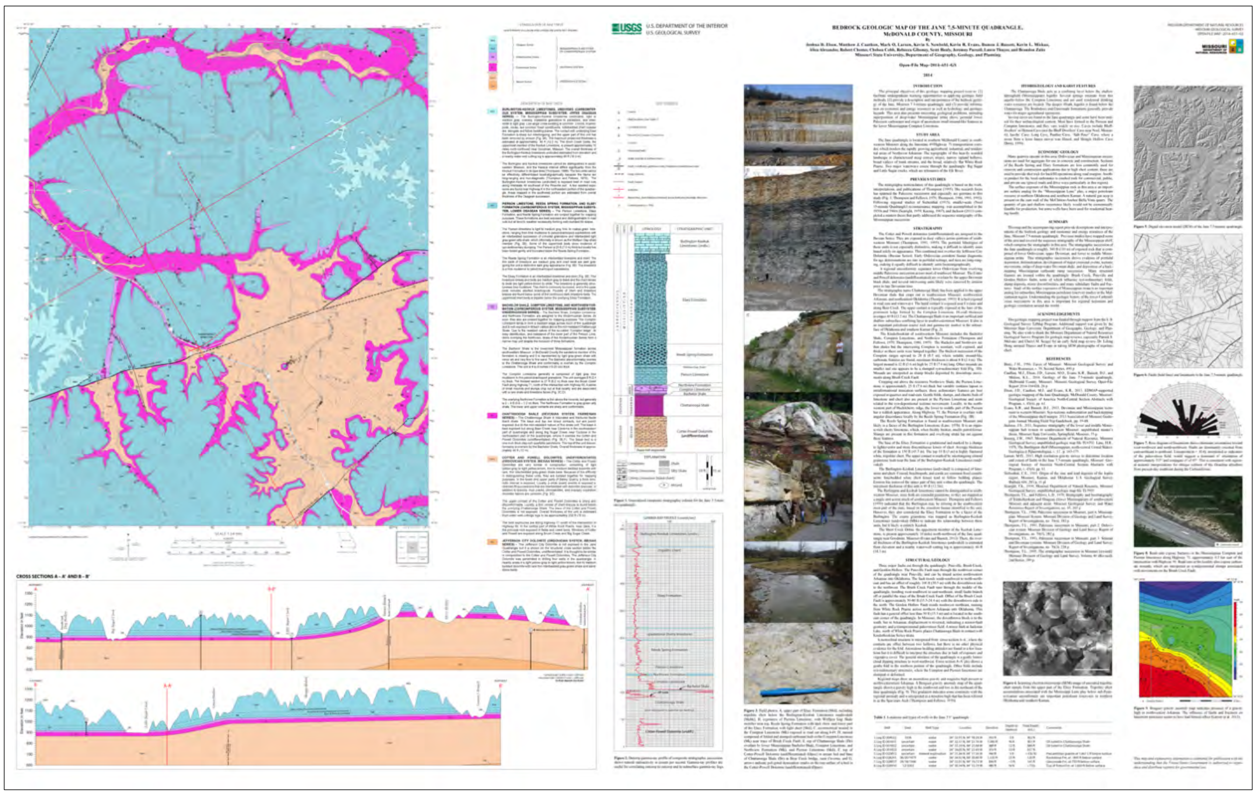


Figure RL-1. *Bedrock geologic map of the Jane 7.5-minute quadrangle by Elson et al. (2014).*

Figure RL-2 shows the routes we will be following for the two excursions of the combined field trips for Friday and Saturday. We will visit stops one through five on Friday, and six through eleven on Saturday. Table I provides a list of chronostratigraphic and lithostratigraphic units visited or at least mentioned on this field trip.

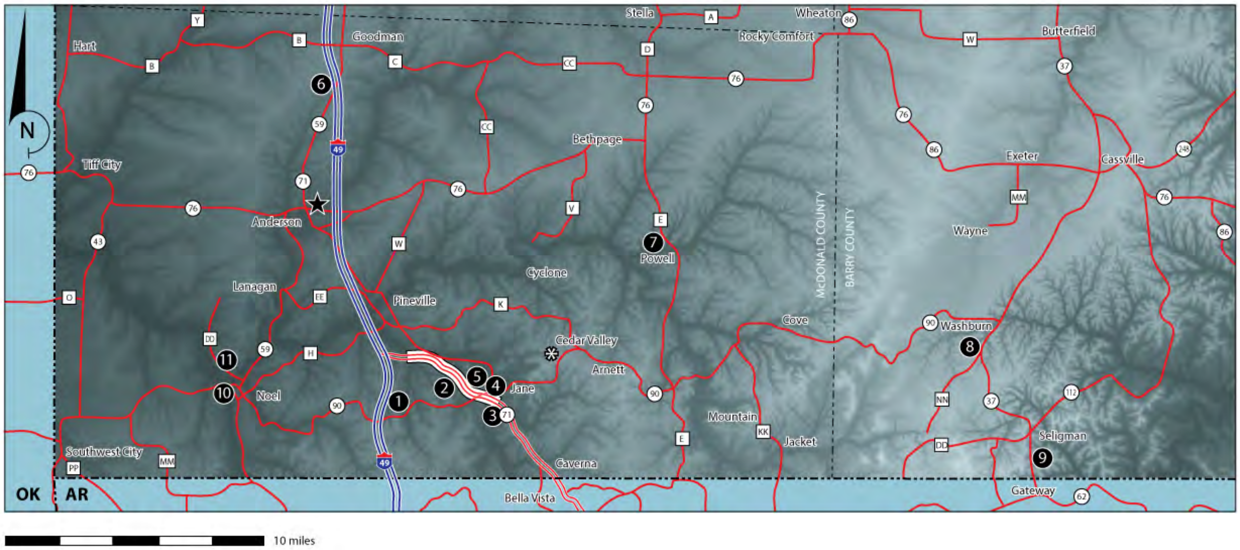


Figure RL-2. *Field trip and road map showing stops for days one and two in black-filled circles. Day one stops include numbers one through five, and day two stops are numbered six through eleven. The highlighted area along Highway 71 is the line of section for the of composite stratigraphic section in Fig. II-6. Digital elevation model (DEM) base map produced from data available at Missouri Spatial Data Information Service (MSDIS).*

Table 1. Carboniferous chronostratigraphic and lithostratigraphic units of McDonald County, southern Barry County, and Stone County, Missouri.

Subsystem	Stage	Lithostratigraphic Unit
Pennsylvanian	Morrowan	Hale Formation Limestone of Coal Mine Hill
Mississippian	Chesterian	Fayetteville Shale Wedington Sandstone Member Batesville Formation Hindsville Formation
	Meramecian	Warsaw Formation
	Osagean	Burlington-Keokuk Limestone (undivided) Short Creek Oolite Member Elsey Formation Reeds Spring Formation Pierson Limestone

	Kinderhookian	Choteau Group
		    Northview Formation
		    Compton Limestone
		Bachelor Shale

DAY 1

Friday, October 14, 2022

Start: Anderson, Missouri Econo Lodge, near the intersection of Highway 76 and I-49. Set mileage to 0.0.

Drive south on I-49 to Exit 2. Take exit. Turn left onto Highway 90 east, cross overpass, and immediately exit on I-49 north. Continue north on I-49 for less than a mile to first set of major road cuts.

(10.2 miles)

STOP 1. Graben in Elsey Formation (36.541612 °N 94.385749 °W)

Why are there so many grabens in Missouri? Missouri should have experienced shortening with the accompanying compressional folding and reverse faulting with convergence and collision of the Ouachita allochthon; grabens are extensional features (Fig. RL-3). One explanation, extrapolated from the regional structural interpretations of Cox (2009), is that transtensional and transpressional features developed between the dominant strike-slip faults. We propose here a series of transfer zones across Missouri, where hard and soft linkages between fault blocks. The timing of faulting at this locality clearly post-dates deposition of the Elsey Formation. The three small grabens seem to at an oblique angle to the Brush Creek Fault. The trace of the Brush Creek Fault crosses I-49 just south of the intersection with Highway 90 and trends WSW. At this stop, note the kerogen-rich lime mudstone bed near the base of this road cut. The Elsey Formation was deposited in relatively deep water. Mazzullo et al. (2019) have interpreted that it was subaerially exposed prior to deposition of the overlying Bentonville Facies, a shelf-margin crinoid grainstone. If one examines the relationship between the Reeds Spring and Elsey formations below the Burlington-Keokuk Limestone on the main shelf closer to Springfield, where the cherty carbonates were deposited in relatively shallow water, there is no evidence of exposure. The recrystallization of chert into tripolite was likely a phenomenon that post-dated deposition.

In addition to viewing the graben, this also is a good place for seeing differences between chert and tripolite. Tripolite is porous, recrystallized silicate rock (Fig. RL-4); most folks agree it is a product of weathering and exposure to ground water. Tripolite and interbedded lime mudstone and chert are the main reservoir rocks found in the Mississippi Lime play in Oklahoma and Kansas. One easy technique to identify tripolite is that it is hydrophilic, it can stick to one's tongue when licked. As we re-board the bus and travel to our next stop, we will pass by several road cut exposures of rock that have been assigned to the Pineville Tripolite Facies.

Continue north on I-49. Take exit 5 (Pineville Exit) toward Highway H. Turn left and immediately left again to rejoin I-49 South. Veer left onto Highway 71 South.

(16.8 miles)

STOP 2. Wolf Pen Gap Hollow Anticline (36.564562 °N, 94.352773 °W)

Figure RL-5 is a photo of Jeremiah Jackson overlooking one of the main road cuts that he measured and described for his master's thesis (Jackson, 2011). This expansive road cut is one of the most accessible in the state, and it is key for understanding the history of sea-level changes and for understanding the influence of structure on the stratigraphic succession. Jackson (2011) recognized that the unconformity at the base of the Mississippian progressively cuts out Cotter Dolomite northward. He interpreted that the Bachelor Formation, Compton Limestone, and Northview formation constitutes a discrete depositional sequence. The Pierson Limestone represented a second deepening event, and the Reeds Spring-Elsey marked an abrupt deepening that gradually gave way to deposition of the Elsey Formation. This succession ultimately was overlain by highstand higher-energy carbonates of the Burlington-Keokuk Limestone (undivided). Figure RL-6 is a composite stratigraphic section for the entire stratigraphic succession along Highway 71. The base is near the intersection of Highway 71 and Highway 90, and the top is a few miles to the north and west. Figure RL-3 shows the general area of the line of section.

The road cut on the south side of Highway 71 locality exposes an angular unconformity at the top of the Pierson Limestone and overlying strata of the basal Reeds Spring Formation (Fig. RL-7). Mazzullo et al. (2019) considered this to be a subaerial exposure surface, but we regard it as a marine truncation surface associated with syntectonic movements. This feature was likely the source for the chaotically bedded strata of the upper Pierson Limestone in Tanner Branch (Stop 5). Evans and Bassett (2013) presented a model that suggests that strike-slip movement along the Brush Creek Fault transfer zone, the anticline developed as a transpressional feature that ultimately became over-steepened (Fig. RL-8). In fact, slumps are present in the Compton through the Reeds Spring Formation, and this would have been the source area for the slumped chaotic beds. Figure RL-9 shows roll-up slumps in the Reeds Spring Formation that are exposed in the walls of the Bella Vista quarry at Caverna, Missouri.

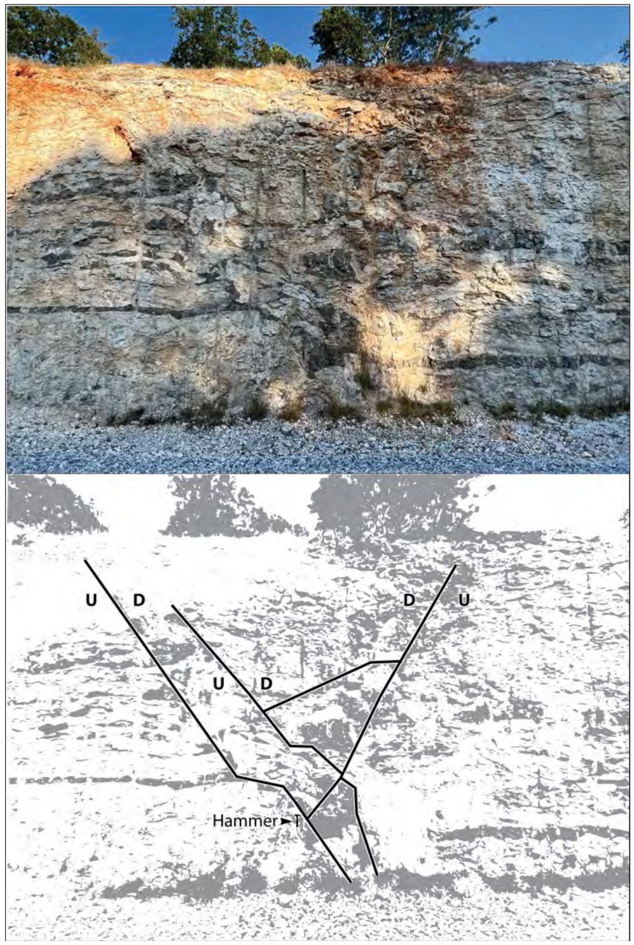


Figure RL-3. *Road cut on northbound I-49 exposes three grabens in the Elsey Formation. The image (top) shows the least weathered of the features. The bottom drawing shows the interpretive movements of fault blocks in the graben.*

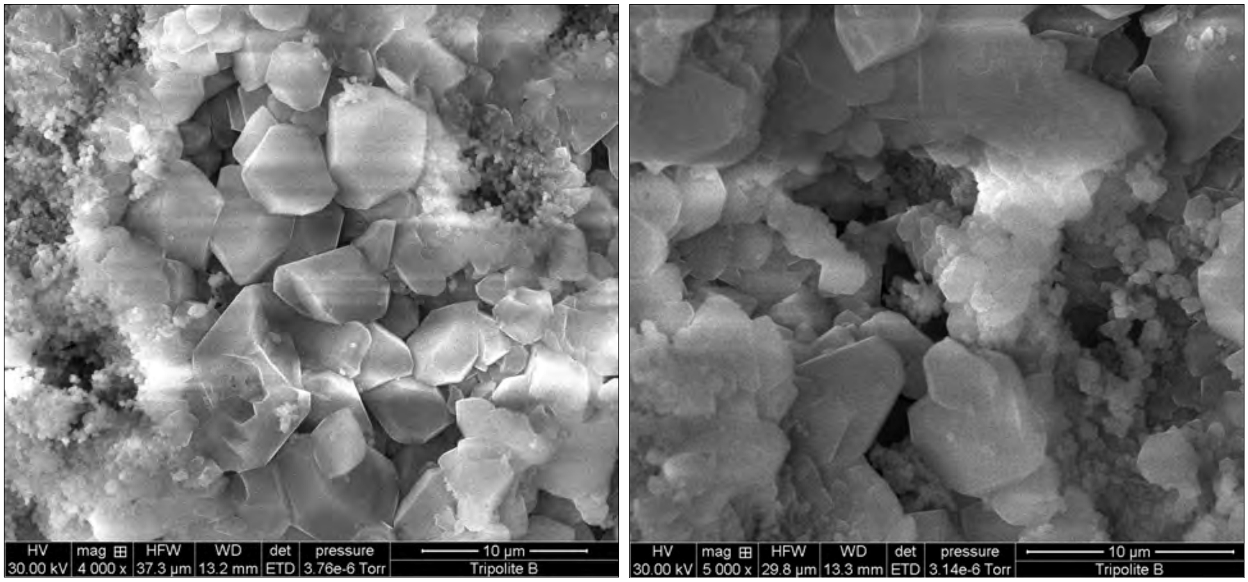


Figure RL-4 (previous page). *SEM images of tripolitic chert from the Elsey Formation collected from Highway 71. Laura Thayer, working with Evans and faculty of Missouri State University's Physics, Astronomy, and Material Science Department, produced these images (from Evans and Bassett, 2013, Fig. II-19, p. 50).*

Geologic mapping revealed an unusual silicified colonial tubeworm fauna in the Osagean Reeds Spring Formation (Fig. RL-10). The Reeds Spring is a petroliferous interbedded carbonate and chert unit approximately 15 m thick, deposited as a series of lime mudstone turbidites interbedded with siliceous mudstone; this unit is partly correlative with the upper Arkansas Novaculite in the Ouachita foredeep. Although other investigators have referred to faunal features as burrows, they clearly are clusters of discrete tubes with rare indication of cross-cutting relationships typical in burrowing. Polished samples illustrate the three-dimensional aspects of the colonies. Tubes are round to oval in cross section and rarely exceed 2.0 mm in diameter and reach up to 40 mm in length. Both light-color granular wall material and darker sediment-fill material are silicified. We provisionally identify these as tubeworms of uncertain affinity. Ultraviolet-light fluorescence indicates presence of movable hydrocarbons in some tube-fill sediment. Although the timing of the charge remains unknown, components for a methane seep community are present. Methane seep communities are rare, so this occurrence is important and potentially helpful for elucidating our understanding of extremophile niches in Paleozoic deep-marine environments.

Jack Ray, *emeritus*, Missouri State University Center for Archaeological Research has mapped chert across the Ozarks for decades (Ray, 2007). He recognizes this type of material as biogenic chert and indicates it is found in McDonald, Barry and Stone counties in the lower, dark cherts that tend to have movable hydrocarbons (Jack Ray, pers. comm., Sept. 21, 2022). Certainly, the tubes were constructional and not feeding traces such as *Planolites* or *Chondrites* as suggested Mazzullo et al. (2019).

Figure RL-5. *Jeremiah Jackson standing on top of the Burlington-Keokuk Limestone (undivided) near the top of the White Rock Prairie-Wolf Pen Gap Hollow composite stratigraphic succession (see Fig. RL-6). The Reeds Spring Formation is seen in the distant road cut. The Elsey Formation is in the two middle ground road cuts (from Evans and Bassett, 2013).*

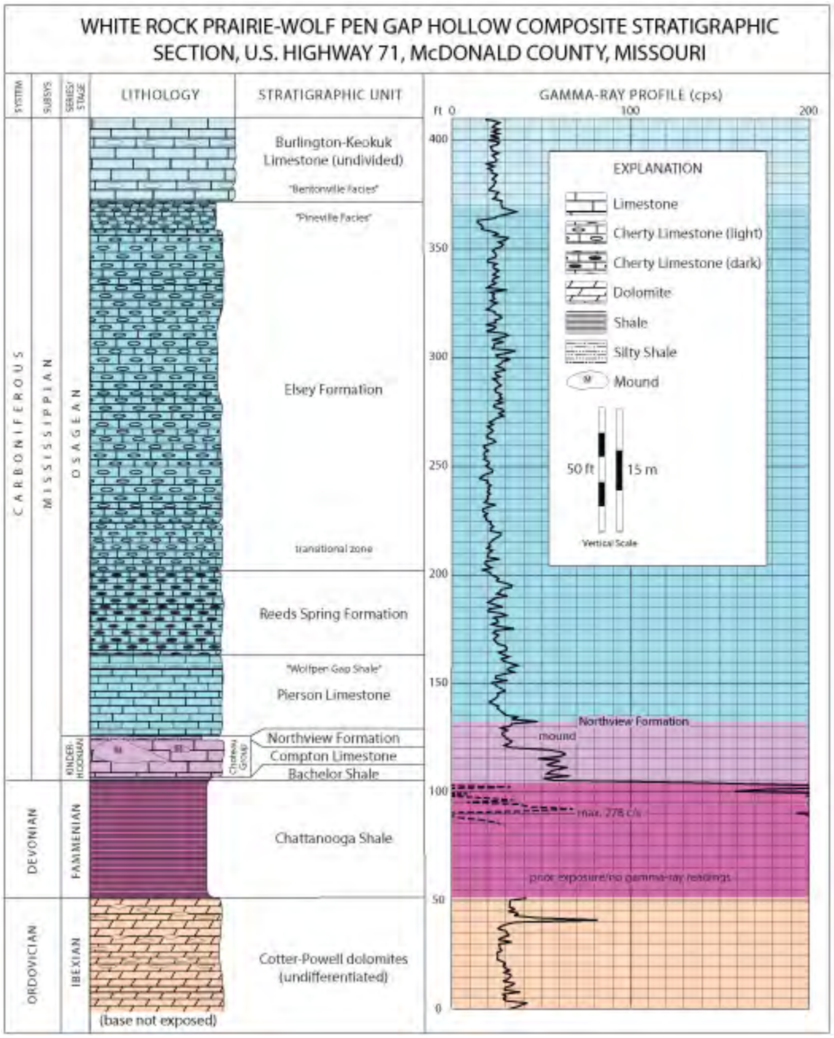


Figure RL-6. *Composite stratigraphic section and gamma-ray profile of rocks exposed between Caverna and Pineville, Missouri along Highway 71 (modified from Cauthon et al., 2014; Elson et al., 2014).*

Figure RL-7 (previous page). *Upper beds of the Pierson Limestone in the Wolf Pen Gap Hollow Anticline were truncated below the Reeds Spring Formation. at this locality. The anticline is perpendicular to the Brush Creek Fault some 3 km to the south. Michael Robbins for scale (from Evans and Bassett, 2013).*

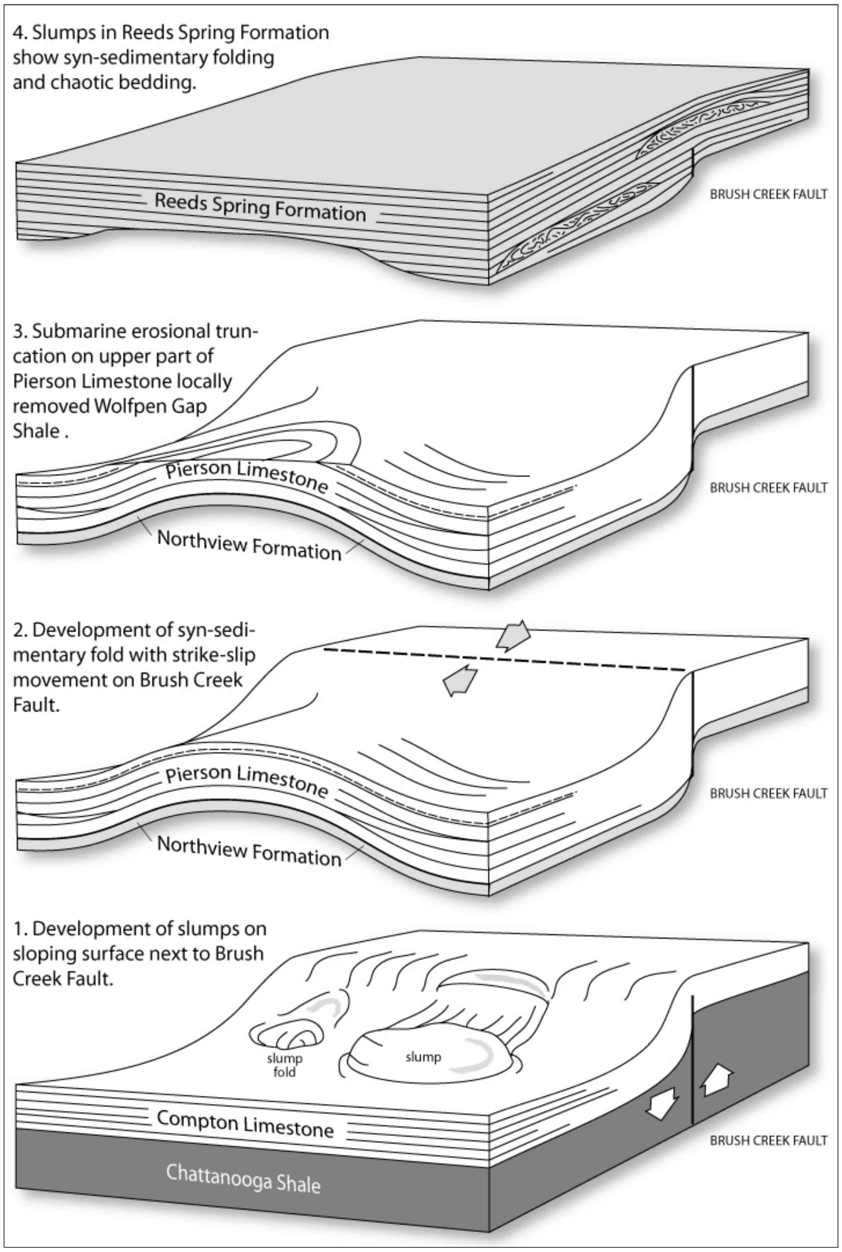


Figure RL-8. *This diagram shows a model for slump development stratigraphically from bottom to top for Kinderhookian through lower Osagean time (from Evans and Bassett, 2013). Please note, the slope is toward the Sugar Creek intrashelf basin not the shelf margin.*

Figure RL-9. *Quarry wall exposures at the Bella Vista facility in Caverna, Missouri, where penecontemporaneous folding in slumps of the Reeds Spring Formation includes chert, suggesting an early diagenetic origin for the dark chert in the unit (from Evans and Bassett, 2013). While exploring the quarry, students noted aromatics in a natural gas seep on the south wall of the quarry. In the early 1940s, a few old companies explored McDonald County for hydrocarbons.*

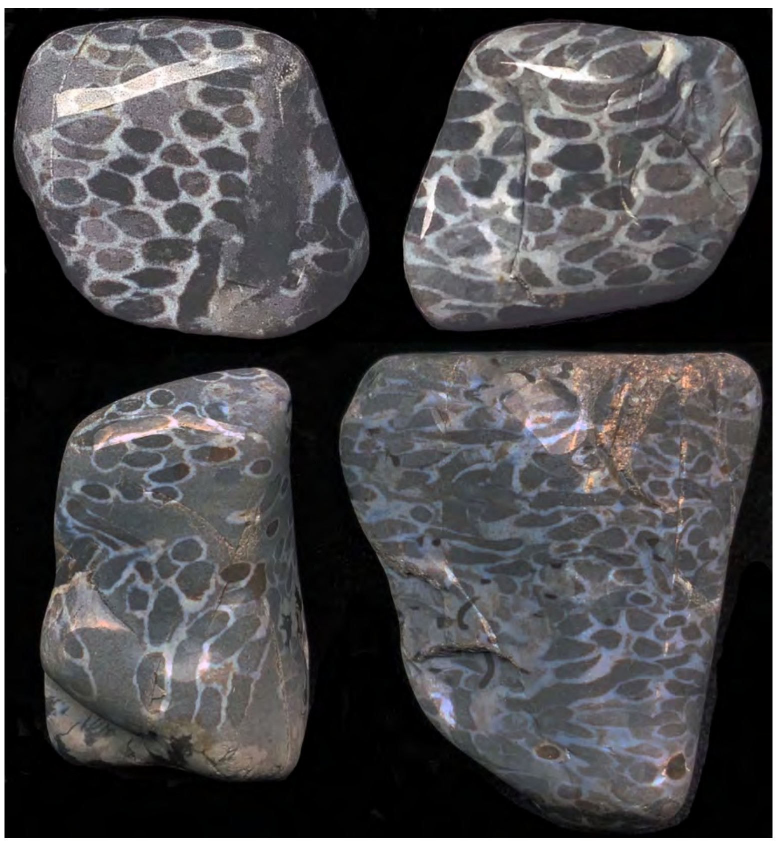


Figure RL-10. *Tumbler-polished samples of gray chert with colonial worm tubes. Note that tubes do not cross one another but tend to cluster together. Top row shows front and back of the same rock sample.*

Continue south on Highway 71. Just past the intersection of Highway 71 and Highway 90.

(19.5 miles)

STOP 3. **White Rock Prairie Inlier (36.542378 °N, 94.316443°W)**

Inlier is a geologic term for older rocks surrounded by younger strata. In McDonald County there are several of these features in southwestern Missouri and each is found on or around faults or localized uplifts.

The Cotter and Powell Dolomite (undivided)(Ibexian Series) crops out in White Rock Prairie. In contrast to the relatively deep-water carbonates in some of the Mississippian succession, this unit was an extremely shallow-water, peritidal carbonate unit. Mud cracks are visible in some beds (Fig. RL-11). Thin shale beds, planar stromatolites, and fenestral pores are common. Most of the dolomite is finely crystalline but some is sucrosic.

This stop is one of opportunity and serves as a reinforcement of the idea that the Mississippian succesion is a backstepping shelf margin. In other words, the shelf margin during lower Ordovician time was much farther south and probably today is under the fold-thrust belt that constitutes the Ouachita allochthon.

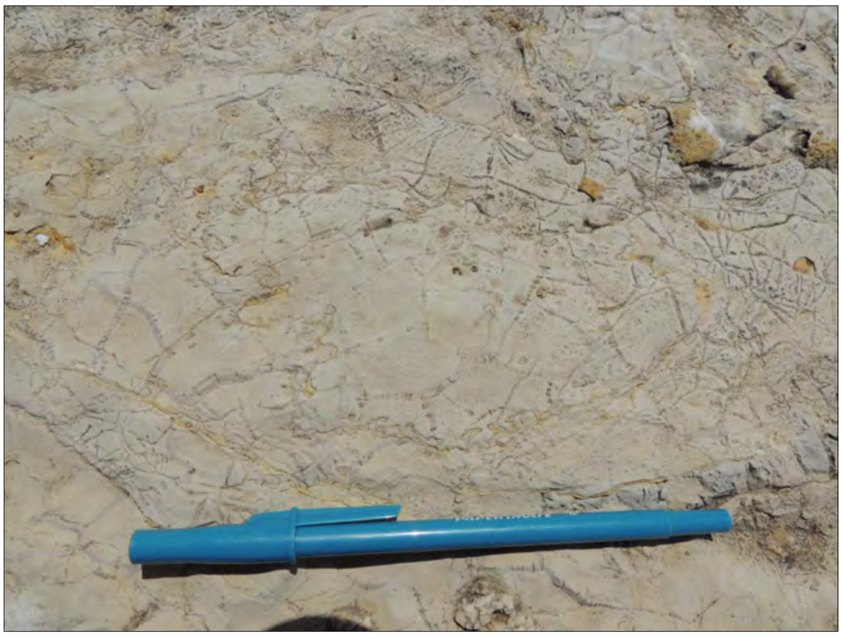


Figure RL-11. *Photo of bedding plane surface with mud cracks in Cotter-Powell Dolomite (undivided)(from Evans and Bassett, 2013).*

Continue south on Highway 71. Turn east (left) on Meadow Lark Lane. Turn north (left) on Rains Road (CR 7137). Turn west (left) on Highway 90 in the town of Jane. Continue to intersection of Highway 90 and Highway 71. Turn north (right) on Highway 71. Park across dead-end road at end of road cut.

(22.8 miles)

STOP 4. Slide and Slump Complex in Compton Limestone, Jane, Missouri (36.546522 °N, 94.327306°W)

The Jane mounds have probably received more geologic attention and are among the most controversial features in Missouri geology (Fig. RL-12–15). Mounds have been interpreted as reefs, displaced reefs, buried hills, and slumps. We consider that these mounds were related to fault movements on the Brush Creek Fault and were emplaced on the downthrown block in one or more events. The Brush Creek Fault bounds a small intrashelf, half-graben basin that collected these and other masses. Occurrences of slump or slide masses on the downthrown blocks is invariable! The Dogwood Canyon slump masses in Stone County are up to 0.7 miles (1.1 km) from the trace of the Lampe Fault and present on the eastern downthrown side. The Lampe fault has more than 100 ft (30 m) of vertical offset.

Figure RL-12. *The Jane mounds are interpreted as a slide mass (left) with detachment surface (right). The Chattanooga Shale is exposed at the base of the road cut. Approximately three inches (7.5 cm) of Bachelor Shale is found below the vertical cut face of the Compton Limestone. Several more slump masses are found to the right, where the entire section of Compton is about 42 ft (12.8 m) thick. A very thin interval of Northview Formation blankets the entire slide and slump complex, and the Pierson is exposed at the top of this segment of the road cut. Damon Bassett for scale (from Evans and Bassett, 2013).*

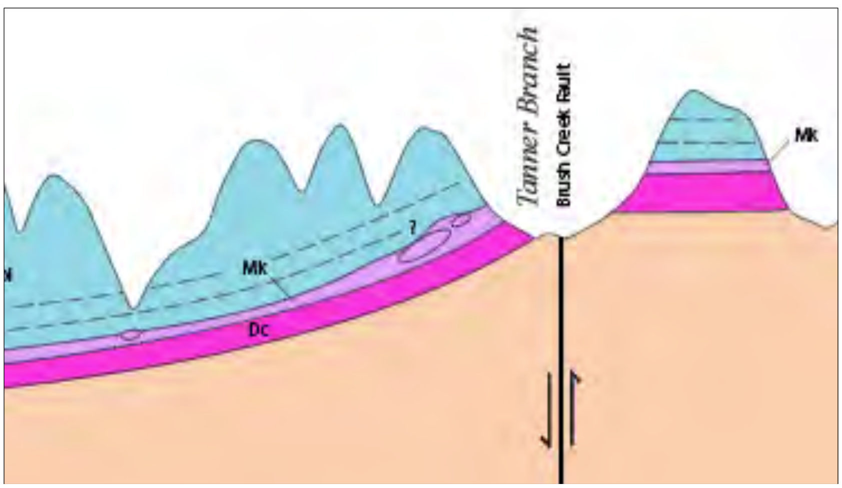


Figure RL-13. *Detail of cross section from geologic map of the Jane 7.5-minute quadrangle (Elson et al., 2014). North is to the left, and the edge of the distally steepened ramp is to the right in northern Arkansas. The Brush Creek Fault forms a half-graben-like intra-shelf basin that roughly extended from Noel to Powell, Missouri. We refer to this as the Sugar Creek fault block. Offset on the Brush Creek is approximately 50-100 ft (15-30 m) according to McCracken (1971). Morphology of the fault scarp may either have over-steepened the Compton succession or fault movements could have been the triggering mechanism for displacing the masses of cohesive mud and sheet-like beds of unlithified strata from the upthrown block or from near the trace of the fault (modified from Elson et al., 2014).*

Continue on Highway 71 north for about one quarter of a mile.

(23.1 miles)

Figure RL-14 (next page). *Photo (top), interpretive diagram (bottom) of the roll-up mound at the top of the Compton Limestone. Jackson (2011) described this and the other mounds in this complex in detail. The roll-up direction is consistent with downslope transport to the north. The trace of the Brush Creek Fault runs roughly east-west about 200 m to the south, where the Compton Limestone is missing or not exposed due to soil and vegetative cover. It is possible that the shale and lime mudstone facies of the upper Compton Limestone, which crops out below this mound, may be inter-tonguing with the Northview Formation (modified from Evans and Bassett, 2013).*

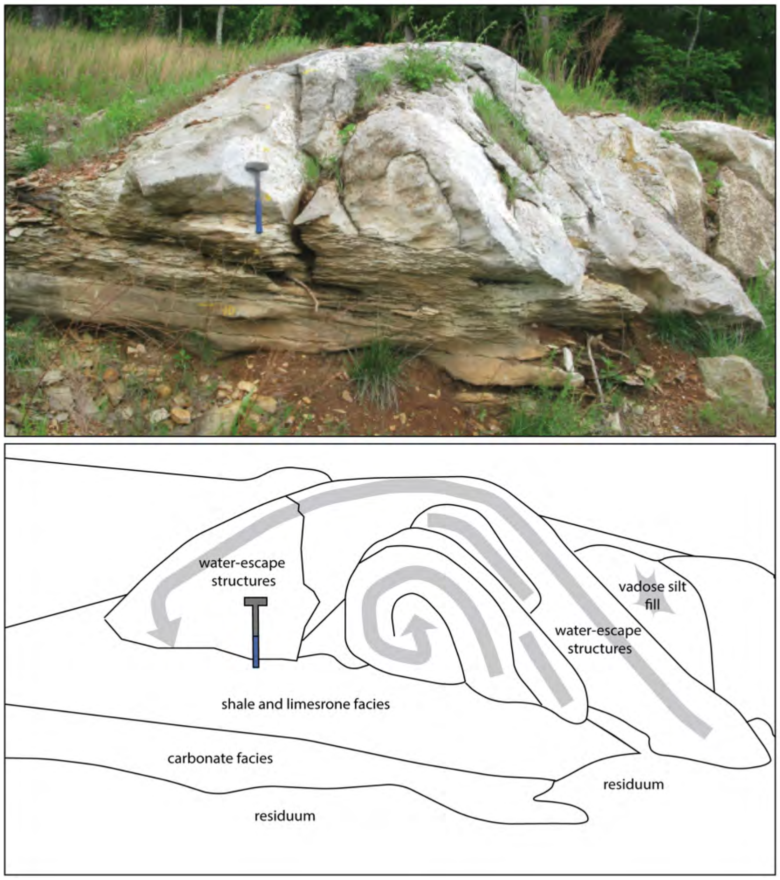


Figure RL-15. *Photo shows digitate vugs filled with coarsely crystalline calcite in the roll-up slump. These likely were syn-sedimentary water-escape structures (from Evans and Bassett, 2013).*

STOP 5. "Wolf Pen Gap Shale" and Chaotic Beds, Upper Pierson Limestone (36.549842 °N, -94.330883 °W)

The "Wolf Pen Gap Shale" is an informal stratigraphic unit that resembles the Northview Formation in composition, grain size, and color (Fig. RL-16), except the "Wolf Pen Gap Shale" also contains thin interbedded limestones. It is a very localized unit recognized by Thompson (1986). Less than three feet (~1.0 m) above the shale are one to two beds of chaotically bedded carbonate and chert clasts. We suggested at Stop 3 that these are mass wasting products associated with uplift on the Wolf Pen Gap Anticline (see Elson et al., 2014). It is possible that the shale missing from Stop 3 may have provided the slip surface for cohesive clasts of unlithified limestone to initiate their transport downslope.

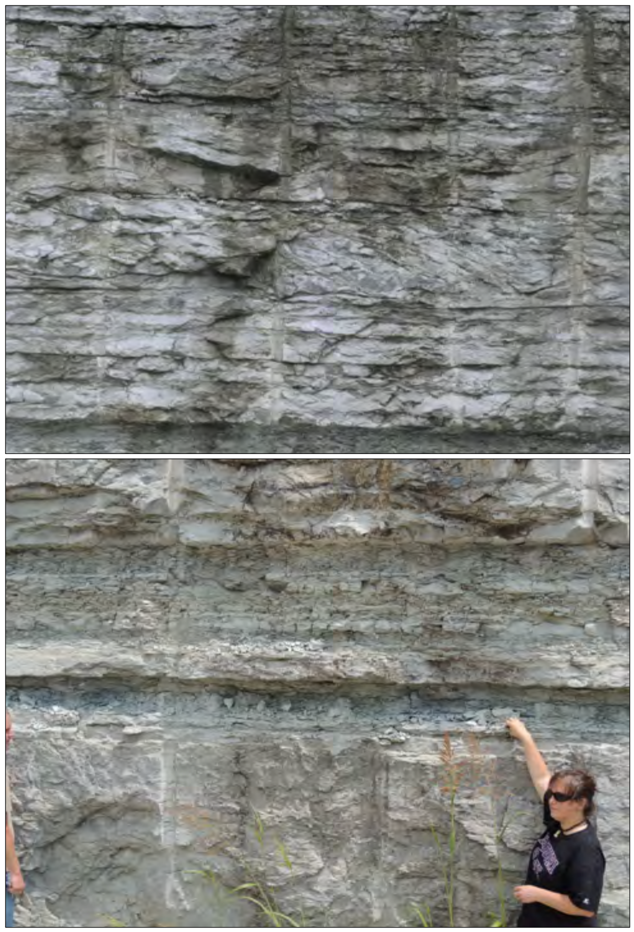


Figure RL-16. *Photo of upper beds of the Pierson Limestone along Highway 71. Upper photo, road cut exposes the Wolf Pen Gap shale. Laura Thayer for scale. Lower photo, chaotic beds in the middle of the photo are composed of slump blocks and folded clasts of Pierson Limestone above the Wolf Pen Gap shale that is exposed at the bottom of the photo. We argue that the upper Pierson Limestone commonly was affected by tectonic movements (folding and faulting) as well as truncational events, where buried faults may have uplifted the sedimentary cover to produce mass wasting events and deposits in localized areas. Lower photo, road cut exposes the Wolf Pen Gap shale. Laura Thayer for scale.*

End of first field excursion. Return to Econo Lodge. Follow Highway 71 and then I-49 north.

(33.0 miles)

The drive to Cedar Valley, venue for the AMG Business Meeting and Banquet, is approximately 15.5 miles. From Econo Lodge, drive south on I-49, veer left on Highway 71 toward Caverna, Missouri. Turn left on Highway 90. Follow Highway 90 for about 10 miles and the event center will be on the north side of the road.

DAY 2

Saturday, October 15, 2022

Start: Anderson, Missouri Econo Lodge. Set mileage to 0.0.

Drive north on I-49 to Exit 17. Turn left on Highway B and immediately turn left again onto I-49 and proceed south for about one mile. Park on right side adjacent to exit 16 to Highway 59.

(7.9 miles)

STOP 6. Goodman Fault (36.724817 °N, 94.420639 °W)

The Goodman Fault is a reverse fault that cuts Osagean Stage strata and likely is a product of the collisional phase associated with docking of the Ouachita allochthon (Fig. RL-17, 18). As we drove north along I-49, there were many folds in the Pineville Facies of the Elsey Formation. In the Jefferson City Dolomite near Jefferson City many folds there are attributed to karstification. Are folds in the Elsey Formation due to karstification also? It would seem likely that karstification of the Elsey likely post-dated faulting at Goodman. Tripolite is not a competent rock that would efficiently allow for the transmission of a paleo-stress field up-section to more competent rocks. If ground water is required to produce tripolite, it likely saturated the Elsey Formation at much later in time.

The top bed of this road cut is the Short Creek Oolite. We will see another Oolite at Stop 9, so it should be interesting to compare the two units.

Figure RL-17. *Panoramic photo of road cut on southbound I-49 near Goodman, Missouri. Rock hammer, a few feet to right of Jared McAvoy, is on the footwall of a reverse fault, which runs uphill to the right. Fault movements here post-date deposition of the Osagean series carbonates and chert. The uppermost stratigraphic unit at this locality is the Short Creek Oolite.*

We will drive a little over an hour to get to our next stop. Proceed down exit ramp to Highway 59/Business 71. Turn left and proceed east on Highway 59. Turn east (right) on Highway C. At McNatt, Missouri, Highway C intersects with Highway CC. follow Highway CC east (left).

As we proceed along the route on Highway CC, the hill east of McNatt has the distinctive name Coal Mine Hill. We cross the trace of the Pineville Fault on the downslope side of the hill. Gentile and Thompson (2004) described a graben in the Burlington-Keokuk Limestone that contained silty carbonates assigned to the Pennsylvanian Morrowan stage and younger Pennsylvanian strata.

Highway CC joins Highway 76 at Longview, Missouri. Continue east on Highway 76 until it reaches a T-intersection with Highway E. Turn south (right) on Highway E. We descend into valley tributaries of Big Sugar Creek north of Powell, Missouri.

(61.0 miles)

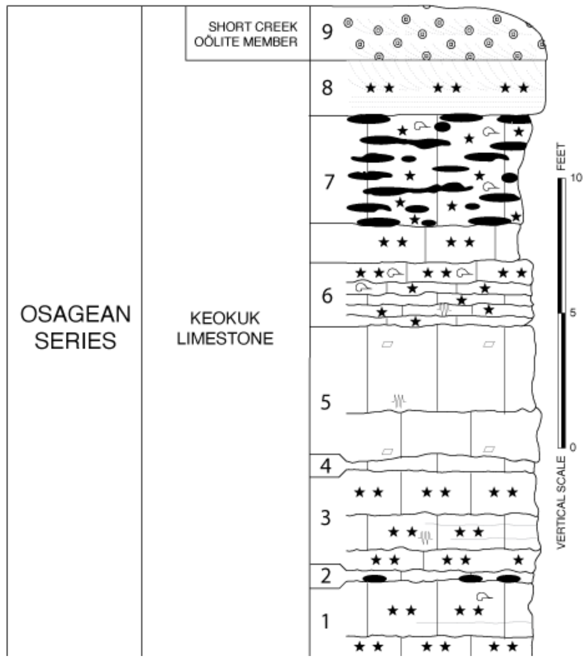


Figure RL-18. *Stratigraphic column of road cut in upper part of Burlington-Keokuk limestones (undivided) at STOP 6, southwest of Goodman, Missouri on Interstate 49. A reverse fault with slicken lines is exposed in the middle part of the road cut. Slicken lines on the footwall indicate a sense of transport to the northwest (from Evans and Bassett, 2013).*

STOP 7 (cultural). Powell Inlier (36.622071 °N, 94.180388 °W)

Powell is a place to stretch our legs, enjoy fresh air, and talk about the geology and culture of the hills and hollows. Snacks and refreshments will be made available here.

The Powell inlier is a product of deep erosion rather than uplift. Cotter Dolomite, exposed in the valley, is overlain by upper Devonian Chattanooga Shale, and Mississippian strata cap the numerous bluffs in the area. Bee Bluff (Fig. RL-19; 36.629399 °N, 94.188192 °W), is a striking example, which we passed below less than a mile north from "downtown" Powell. A relatively high escarpment is located to the east, adjacent to the Greasy Creek Fault (see Fig. II-16).

Powell was ideally located as a town site in a broad valley at the junction of Mike's Creek and Big Sugar Creek with several other hollows in the surrounding area. It is the home of Albert E. Brumley and Sons, Inc., a music publishing company now owned by Hartford Music Company. Brumley wrote the famous Christian hymn, "I'll Fly Away". The company has been awarded multiple Grammy Awards. Robert Brumley, the son of Albert, hosted annual music festivals on his property. Minnie Pearl and Grandpa Jones were performers at the event. Robert passed away in late 2020. Southwest of the store, a truss-supported bridge over Big Sugar Creek, on Cowan Ridge Road, was built in 1915. It is on the National Register of Historic Places (Fig. RL-19).

Continue south on Highway E. At intersection of Highway E and Highway 90, turn east (left) onto Highway 90. After about 20, Highway 90 intersects with Highway 39. Turn south (right) on Highway 39. One mile south, turn west (right) onto CR 1050. Park near entrance.

(88.3 miles)

STOP 8. Warsaw Formation, Washburn, Missouri (36.565956 °N, 93.970357 °W)

The Warsaw Formation looks almost identical to the Burlington-Keokuk Limestone (undivided), except it tends to contain different fossil assemblages and, here, more chert (Fig. RL-20). These rocks are on the downthrown block of Greasy Creek Fault and are stratigraphically higher than most of the succession in McDonald County (see Fig. II-18). The Washburn syncline is a gentle and broad trough-like flexural feature that runs SSW-NNE, parallel to Greasy Creek Fault. The Washburn syncline may be a fault-propogation fold related to vertical displacement of basement rocks. The geology of the Cassville 15-minute quadrangle was mapped by Ed Clarke (1941). He recognized the Short Creek Oolite in Seligman Hollow and a few other localities east and west of Highway 39, but he did not map that interval as a discrete unit, probably because of a lack of exposure. Instead, he lumped the Keokuk Limestone with the Warsaw Formation. Geologic mapping is an art constrained by science and commonsense.

Figure RL-19. *Photo of culturally important cultural features at Powell, Missouri. Top, Bee Bluff, Missouri on Highway E, approximately 0.5 miles north of Stop 7. Late Devonian Chattanooga Shale is exposed at road level. Lower recessive carbonate unit is Compton Limestone. The Northview Formation forms the notch in the middle part of the bluff. Note NE-SW and NW-SE conjugate joint sets in upper beds of bluff in the overlying Pierson Limestone. This area is designated as a sensitive area by the Missouri Department of Transportation. No digging is allowed. Bottom, Powell Bridge over Big Sugar Creek was built in 1915.*

Figure RL-20*. Left, photo of road cuts in Warsaw Formation on Highway 39 at intersection with Farm Road 1050. Right, detail from southwestern corner of geologic map of the Cassville 15 minute-quadrangle showing distributions of the Keokuk Limestone and Warsaw Formation (undivided) in blue. Chesterian and younger strata are in dark red, brown and pink (from Clarke, 1941). Stop 8 is just above the top of this map. Stop 9*

Continue south on Highway 37. Pass through the town of Seligman. Turn east (left) into the Cenex parking lot and Ruby's Liquor Store to turn around. Turn north (right) onto Highway 37 north. Park on shoulder.

(93.9 miles)

STOP 9. Hindsville Formation and Batesville Sandstone, Seligman, Missouri (36.510055 °N, 93.932728 °W)

The upper bed of the Hindsville Formation is a cross-bedded ooid grainstone. An interesting aspect of this road cut is the occurrence of *Agassizocrinus conicus* Owen and Shumard 1852 in the upper surface of that unit (Strimpel, 1977). The holdfast of *A. conicus* is hemispherical and something of a mushroom anchor. It shows the adaptation of this species to the constantly shifting carbonate sands of these shoal.

Figure RL-21*. Road cut in Hindsville and Batesville formations, just south of Seligman, Missouri. The top bed of the Hindsville is a cross-bedded ooid grainstone that has yielded the unusual holdfasts of Agassizocrinus sp. The Batesville includes a shale and sandy carbonate. The Wedington Member of the Fayetteville Shale is exposed at the top of this road cut.*

Follow Highway 37 north to Washburn. Turn west (left on Highway 90. Proceed down Highway 90 to Cedar Valley. Turn into Cedar Valley. Driving a bus into this facility will be at the driver's discretion. We may have to walk in about a quarter of a mile.

(118.4 miles)

LUNCH STOP. Cedar Valley (36.566568 °N, 94.268245 °W)

STOP 10. Slide block and pinch outs, Noel, Missouri (36.550300 °N, 94.497611 °W)

This stop is included because it is one of the most remarkable outcrops in McDonald County, yet it is nearly inaccessible. As a consequence, we will only see it from the roadside (and maybe not that depending upon the time). The Chattanooga Shale is exposed at the base. The overlying Compton Limestone exhibits extremely variable bedding. Mazzullo et al. (2019) interpreted the block shown on the left side of Fig. RL-22 as a displaced reef. We interpret it as a slide block. Note the lapout of beds onto the top and bottom side of that bed. There is a complex relationship in all the units of the lower Mississippian. In the Noel EDMAP project, we will be mapping this area with a drone to be able to properly interpret structures.

Figure RL-22. *Stratal pinch-outs or truncations are found along this overhanging bluff. The photo at right shows a slide block (above the vine).*

STOP 11. Slump Complex in Compton Limestone, Highway DD, Noel, Missouri (36.560170 °N, 94.498410 °W)

We drove by markedly atypical lower Mississippian strata along Highway 59. The outcrops on Highway DD appear relatively normal until we approach the large cut across from Elk River. Stop 11, is a mélange of carbonates. Look for the folds and the slide mass at the upper left side of this cut. Deformation extends northward up the road for nearly 100 m. The interpretation for this accumulation is a slump complex. Note that the Northview Formation and Pierson Limestone are draped over the southern edge of this accumulation. This is one of the key areas we hope to sort out as we continue mapping the geology of the Noel 7.5-minute quadrangle.

Figure RL-22*. Slump complex in Compton Limestone overlain by a thinned Northview Formation and draping Pierson Limestone. Logan Rogers for scale (photo by Jared McAvoy).*

Follow Highway DD north to Highway EE. Turn east (right). At intersection with Highway 59, turn north (left). Highway 59 joins Highway 76 in the outskirts of Anderson, Continue east on Highway 76. Turn right (south on Business 71/76. Return to Econo Lodge.

End of Road Log.

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DISCLAIMER

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APPENDIX

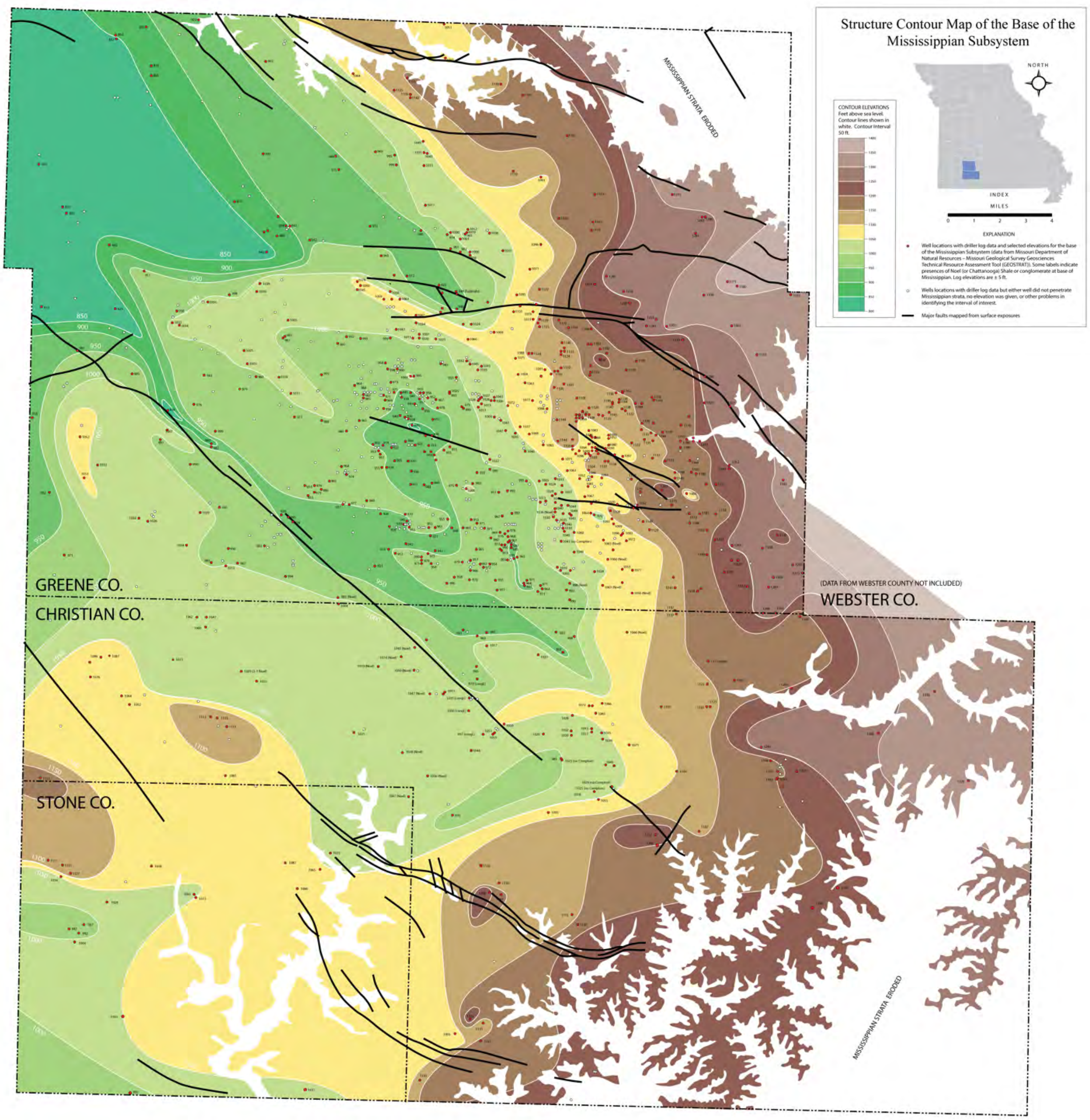

Figure A-1. *Structure contour map for base of the Mississippian subsystem for Greene, Christian, and northern Stone counties, Missouri (data from Geosciences Technical Resource Assessment Tool (GeoSTRAT)). Note, faults are based on geologic mapping of surface exposures rather than subsurface data. Areas where the interpreted structure contours show steep slopes commonly indicates locations of faults or associated structures. The cluster of major and minor faults and structures near the Highlandville (southern) and Valley Mills fault zones (northern) are proposed to constitute the Highlandville and Valley-Mills-Strafford transfer zones.*