GUIDEBOOK FOR
SELECTED GEOLOGIC STOPS IN THE ARBUCKLE MOUNTAINS

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Cover photo: Viola Limestone (Ordovician) overturned above the Bromide Formation (Ordovician) on the north flank of the Arbuckle anticline; this is the deepest cut in the Arbuckle Mountains, with a vertical span of 156 ft (47.5 m); view looking east on Interstate 35.

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INTRODUCTION

General Geology of Oklahoma

Structure

Oklahoma is a region of complex geology where a mobile belt of Paleozoic geosynclines and uplifts on the south abuts against the margin of the North American craton to the north. Major geologic provinces of Oklahoma are shown in Figure 1. The southern Midcontinent contains one of the greatest thicknesses of sedimentary rocks preserved in North America. These sediments are preserved in a series of major depositional and structural basins separated by orogenic uplifts that occurred mainly during Pennsylvanian time. As much as 39,000 ft (12,000 m) of strata is preserved in the deep Anadarko basin, about 29,520 ft (9,000 m) in the Ardmore basin, and about 26,000 ft (8,000 m) in the southern part of the Arkoma basin and Marietta basin (Fig. 1). These thick sedimentary sequences accumulated along the southern margin of the North American craton during Paleozoic episodes of subsidence of the Anadarko, Ardmore, and Marietta basins, and of the foredeep areas north and west of the Ouachita trough. The predominant WNW-trending trough comprising the Anadarko, Ardmore, and Marietta basins, and the associated uplifts, has been referred to as the southern Oklahoma geosyncline (Ham and others, 1964; Ham and Wilson, 1967) or the southern Oklahoma aulacogen (Schatski, 1946; Gilbert, 1983; Brewer and others, 1983). Hoffman and others (1974) thought this and other aulacogens were the failed arm of a triple junction on a mantle plume.

Southern Oklahoma contains the most-accessible, best-exposed, and best-understood aulacogen in the United States. The southern Oklahoma aulacogen can be traced about 250 mi (400 km) across Oklahoma and the Texas Panhandle. The framework rocks for the aulacogen are massive granitic rocks yielding ages between 1,300 and 1,400 m.y. These are cut by dikes of varying compositions striking about N. 60° W. The basement rocks have exerted an exceptionally strong influence on the sedimentary history of the region. The Paleozoic history can be divided into four general major phases of development (Denison, 1982).

Phase I (Early and Middle Cambrian)

- Extensional igneous phase characterized by bimodal igneous suite, probably associated with thick sedimentary deposits during the earlier basaltic activity.
- Major faulting occurred parallel to the previously defined N. 60° W. direction.

Phase II (Late Cambrian-Middle Mississippian)

- Passive shelf sedimentation characterized by very thick shallow-water carbonate units and associated sandstones and shales.
- These units are double in thickness (11,000 ft; 3,350 m) in areas underlain by Cambrian igneous rocks, but only about 6,500 ft (1,980 m) thick where underlain by massive Precambrian granites.

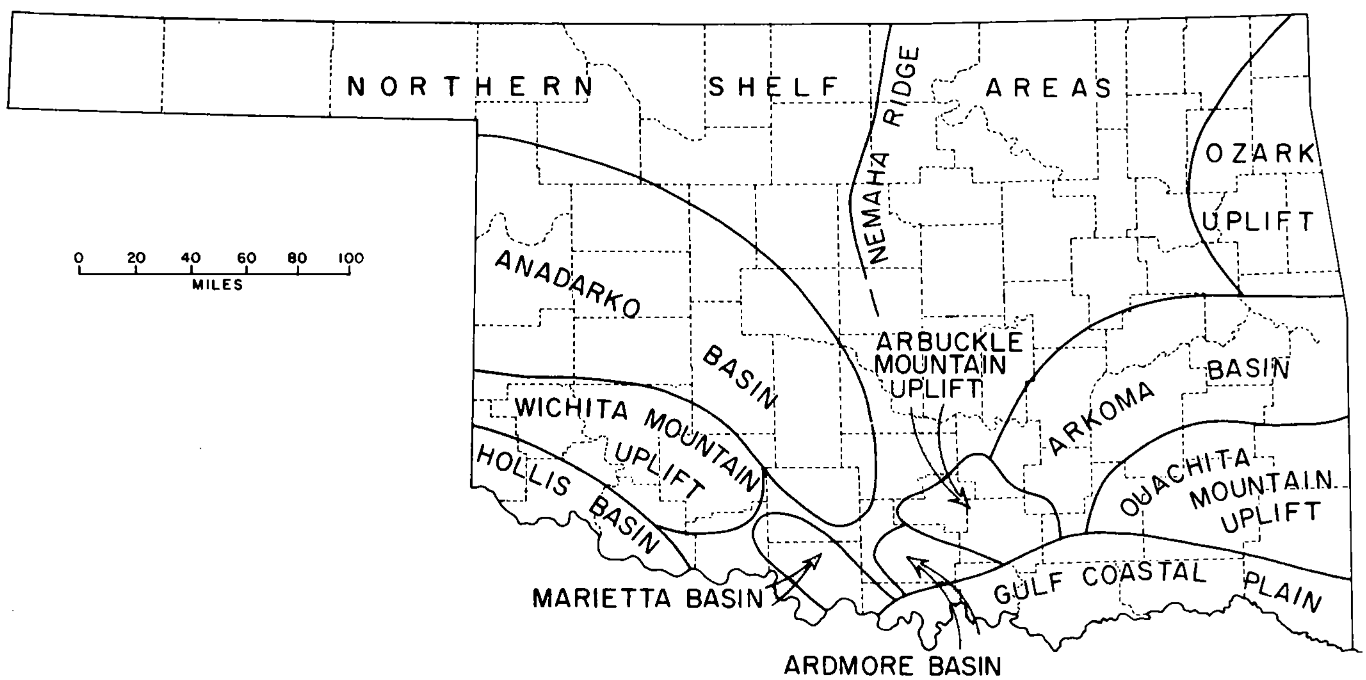

Figure 1. Major geologic provinces of Oklahoma.

Phase III (Early to Late Pennsylvanian)

- Deformational phase with compressional forces producing spectacular uplifts that were rising and shedding clastics into the adjacent basins.

Tomlinson and McBee (1959) suggested that the principal deformation began along the axis of the Wichita-Criner arch in Early Pennsylvanian (Morrowan) time. Ham (1969) considered the peak of the Arbuckle orogeny to have occurred in the Virgilian, based upon widespread conglomerates of this age. However, in the Arbuckle Mountains these conglomerates are cut by relatively minor faults and are gently folded, but overlie older rocks with tremendous angular unconformity. Consequently, Denison (1982), using this criterion considered the peak of major deformation to be earlier, essentially completed by Virgilian time.

Phase IV (Latest Pennsylvanian to Permian)

- Post-orogenic phase characterized by thick clastic red beds and locally associated evaporite formation.
- Filling in of major basins and the burial of older structures beneath mildly deformed to undeformed, largely clastic rocks of Late Pennsylvanian and Permian age.
- Thicknesses of 7,000 ft (2,130 m) are reported for this clastic sequence near the axis of the Anadarko basin (Johnson and Denison, 1973).

Stratigraphy

Most of the outcropping rocks in Oklahoma are of sedimentary origin and of Paleozoic age. The thickness of Paleozoic sediments ranges from 2,000 to 10,000 ft (600 to 3,000 m) in cratonic shelf areas on the north to 30,000 to 40,000 ft (9,000 to 12,000 m) in deep basins on the south (Fig. 2). According to Ham (1973), 17,000 ft (5,183 m) of Late Cambrian through Mississippian sediment accumulated in the southern Oklahoma aulacogen. The combination of continued subsidence and periodic orogenic activity led to further accumulations of 13,000 ft (3,963 m) of mostly terrigenous clastic sediment during the Pennsylvanian. This combined thickness of 30,000 ft (9,000 m) of sediment was folded and faulted during the deformation stage to become the present-day Arbuckle Mountains (Fig. 2).

Sedimentary rocks overlie a basement of Precambrian to Middle Cambrian igenous rocks, Precambrian metamorphic rocks, and mildly metamorphosed Precambrian sediments. Carbonates dominant the Upper Cambrian to Lower Mississippian strata and attest to the early and middle Paleozoic crustal stability in most of Oklahoma prior to the major episodes of mountain-building characterizing the Pennsylvanian. Thick clastic sequences of shale and sandstone predominate in the Upper Mississippian and Pennsylvanian successions. Permian sediments are characterized by red-bed sequences consisting of mudstones, shales, and sandstones, limestones, and locally interbedded evaporite deposits. Triassic and Jurassic strata, limited primarily to the Panhandle of western Oklahoma, consist principally of red-bed sequences (mudstones, shales, sandstones) of continental origin. Cre-

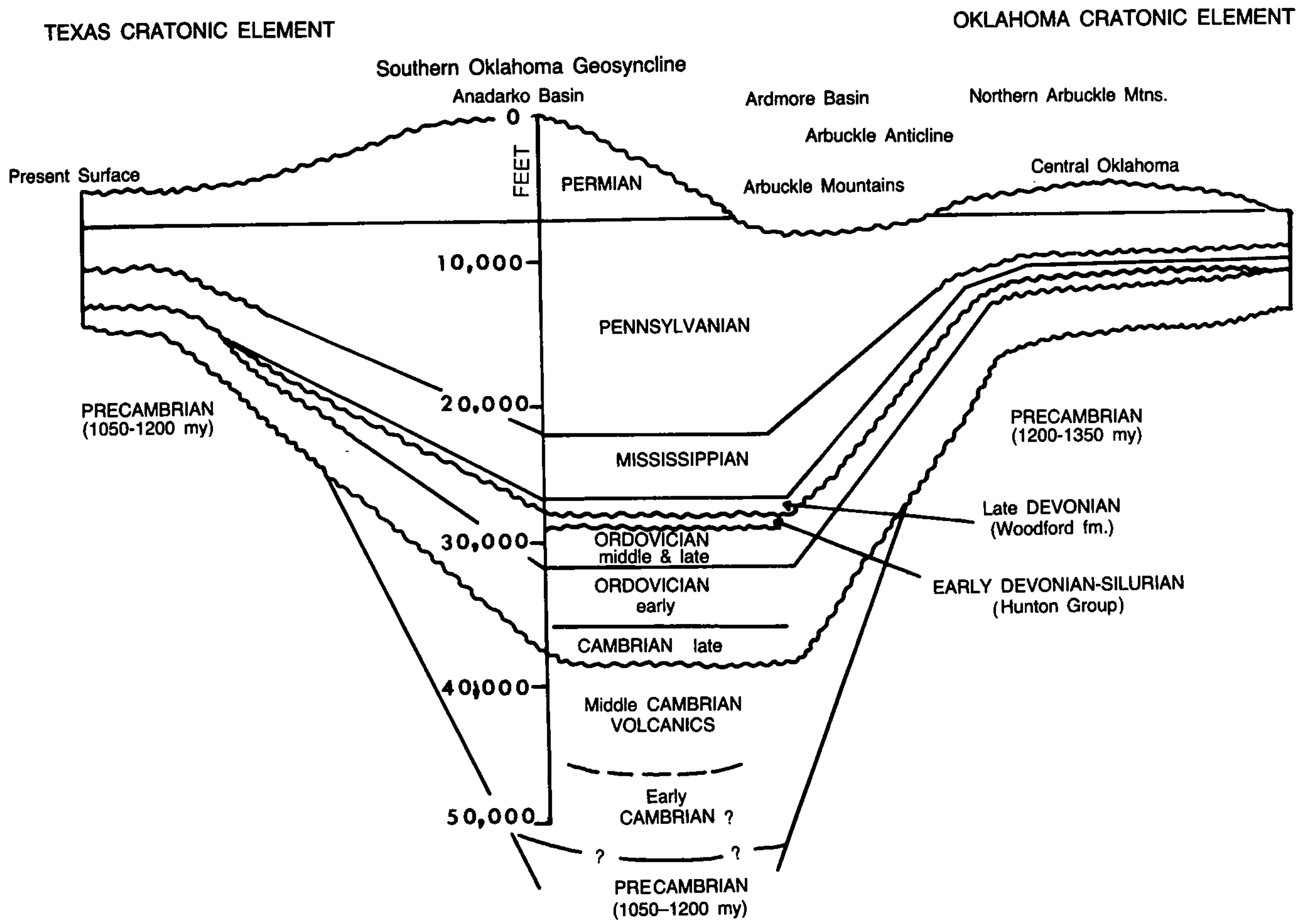

Figure 2. Diagrammatic cross section demonstrating the thickening of sediment in the southern Oklahoma aulacogen (Ham, 1973).

taceous strata outcrop in the southeast along the edge of the Gulf Coastal Plain (Fig. 1) and are generally composed of unconsolidated sands, gravels, and clays, with subordinate amounts of limestone. Cretaceous beds dip gently southward toward the Gulf of Mexico. Tertiary deposits in western Oklahoma consist of unconsolidated sands, clays, and gravels deposited by ancient streams draining the Rocky Mountains.

General Geology of the Arbuckle Mountains

The Arbuckle Mountains are located just north of the Texas-Oklahoma border in south-central Oklahoma (Fig. 1). The geologic province consists of roughly 1,000 mi^2 (2,778 km^2) of outcrop consisting of a huge inlier of Precambrian rocks and about 15,000 ft (4,500 m) of folded and faulted Paleozoic sedimentary rocks ranging in age from Cambrian through Late Pennsylvanian (Virgilian). The oldest rocks are igneous rocks exposed in the core of the Tishomingo arch, which are dated to be about 1.35 b.y. old (Fig. 3). Cambrian rhyolite forms the core of the Arbuckle anticline and is dated at about 500 m.y. old. These Cambrian rocks are not found above the granite on the Tishomingo arch (Fig. 3).

The province is covered on the east, north, and west by gently westward-dipping Permian-Pennsylvanian strata and on the south by gently southward-dipping Early Cretaceous sediments of the Gulf Coastal Plain. Reference to the Arbuckle outcrops as the Arbuckle Mountains is somewhat misleading in that about 80% of the area consists of gently rolling plains. Only in the western area is reference to the Arbuckle outcrops as "mountains" perhaps warranted; there the Arbuckle anticline (the major area of interest on this field trip) attains an altitute of 1,377 ft (420 m, the highest point in the Arbuckle Mountains), and a total relief of 607 ft (185 m).

Cambrian through Mississippian strata, about 10,000 ft (3,050 m) thick, mostly carbonates, constitute the best outcrops and greatest area of exposure of this marine sequence in all the Midcontinent region, and perhaps the world. The sedimentary rock column within the southern Oklahoma aulacogen is about 7 times thicker than coeval rocks on the adjacent craton (Fig 4.).

The mechanisms for the structural deformation of the Arbuckle region are as yet unproven, but many theories have been published. Most of these theories center around the orientation and movement direction of the major faults in the area. Published deformation models include (1) local gravity-slide fault system, (2) block-uplift system along high-angle normal faults, (3) left-lateral strike-slip fault system, (4) right-lateral strike-slip fault system, and (5) low-angle reverse fault system. The most common proposed structural interpretation is a left-lateral strike-slip system. The following lines of evidence are offered in support: (1) the orientation of fractures and small faults to the major faults, (2) angular relationships observed between the major folds and faults, (3) the collection of horizontal slickensides along fault and fracture planes, and (4) subsurface data. However, the amount of offset along the faults is not always clearly defined.

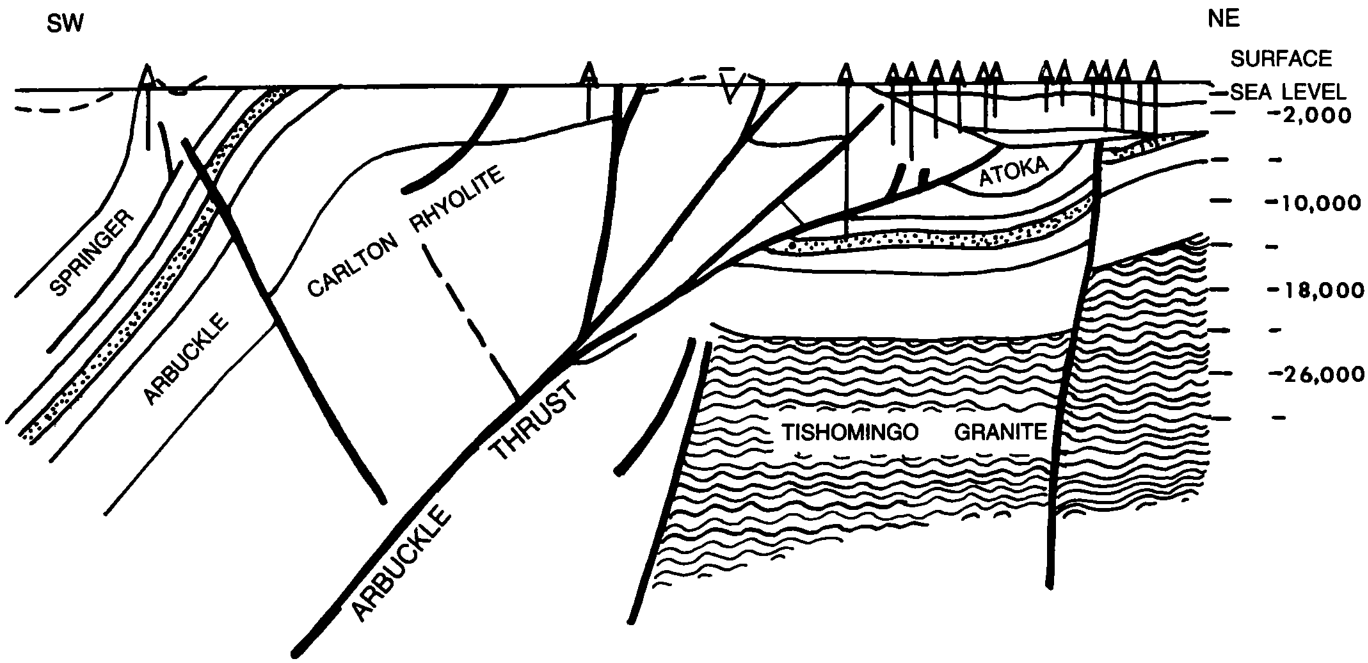

Figure 3. Southwest-northeast structural cross section from the Ardmore basin to the Pauls Valley uplift (Brown, 1984).

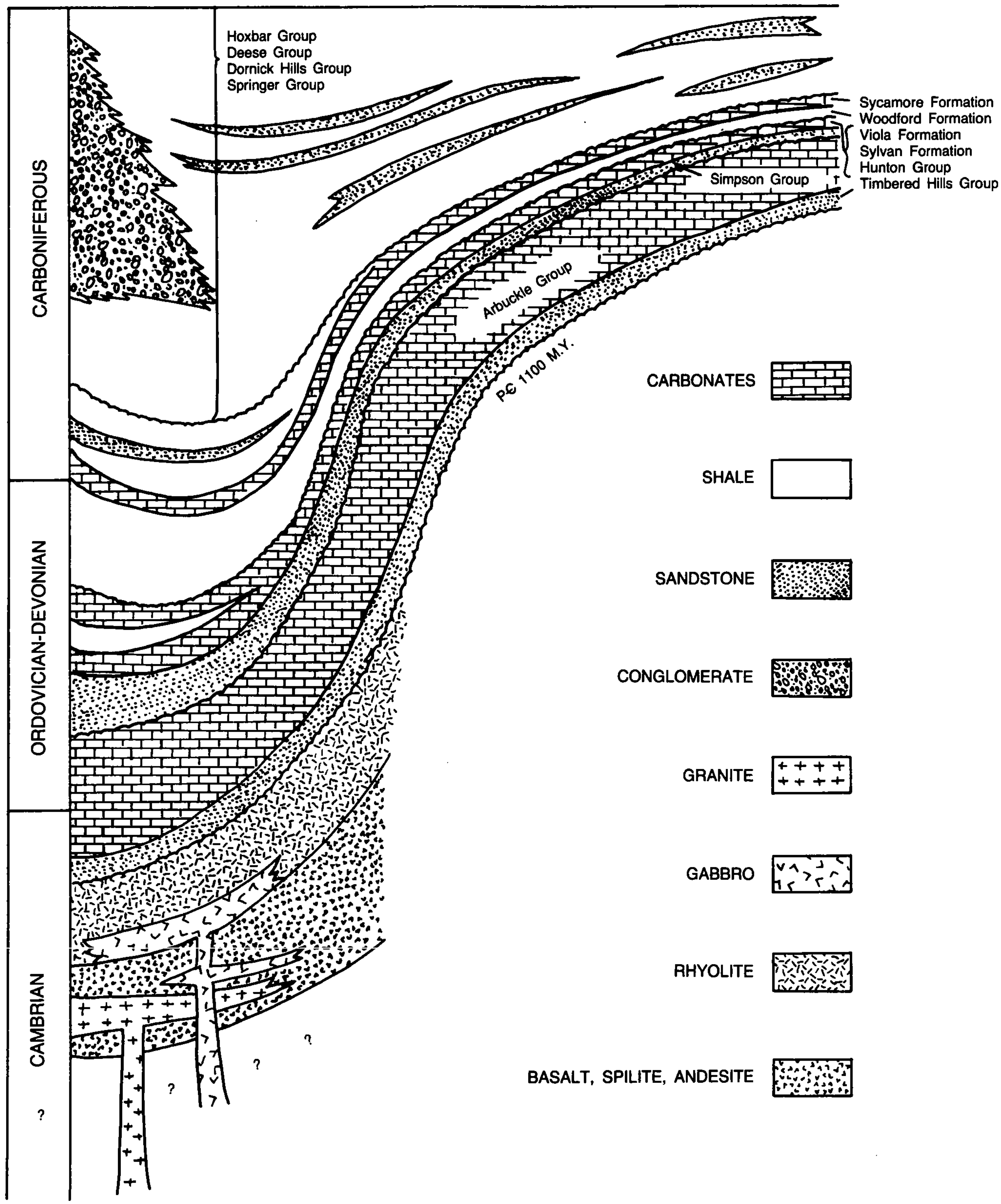

Figure 4. Idealized stratigraphic section demonstrating thickness variations and facies from the craton (right) into the aulacogen (left). (Modified from Wickham and Denison, 1978)

DESCRIPTION OF FIELD-TRIP STOPS

Interstate Highway 35 was completed in 1970 after the removal of about 4 million yards of rock at a cost of only $4 million. Interstate 35 cuts north-south through 7 mi (11 km) of steeply dipping rocks of the Arbuckle anticline, exposing about 10,000 ft (3,050 m) of Cambrian through Mississippian rocks, mostly carbonates, with successively older rocks toward the middle and top of the anticline (Fig. 5). The rocks are exposed in a homoclinal sequence dipping off the south flank of the Arbuckle anticline; these same strata are also well exposed in a series of fault blocks on the north flank of the anticline.

The locations for the field-trip stops are shown in Figures 6 and 7. Typical folding is illustrated in Figure 8, and the stratigraphic sequence for the Arbuckle Mountains is shown in Figure 9. The stops are selected to demonstrate some unique stratigraphic and structural features in the Arbuckle Mountains of southern Oklahoma.

EXTREME CAUTION MUST BE EXERCISED AT STOPS 1, 1A, AND 2, WHICH ARE ALONG INTERSTATE 35.

Stop 1

Kindblade Formation (Middle Arbuckle Group, Lower Ordovician)

Peritidal carbonates and "tombstone topography" on the south flank of the Arbuckle anticline.

Location:

Along the west side and median of the southbound lane of Interstate 35, just south of the turnout, Murray-Carter Counties, Springer Quadrangle, CNE1/4 sec. 24, T. 2 S., R. 1 E. (Fig. 6).

Significance:

- Sedimentary structures characteristic of shallow-water peritidal Ordovician carbonates.
- Morphologic diversity of organic buildups.
- Biotic simplicity of Ordovician organic buildups.
- Characteristic "tombstone topography."

Description:

The Kindblade Formation is well exposed in the Arbuckle Mountains and consists primarily of thin- to thick-bedded carbonates that characteristically crop out with dips as steep as 60°, thus imparting to the sequence its unique "tombstone topography" (Fig. 10).

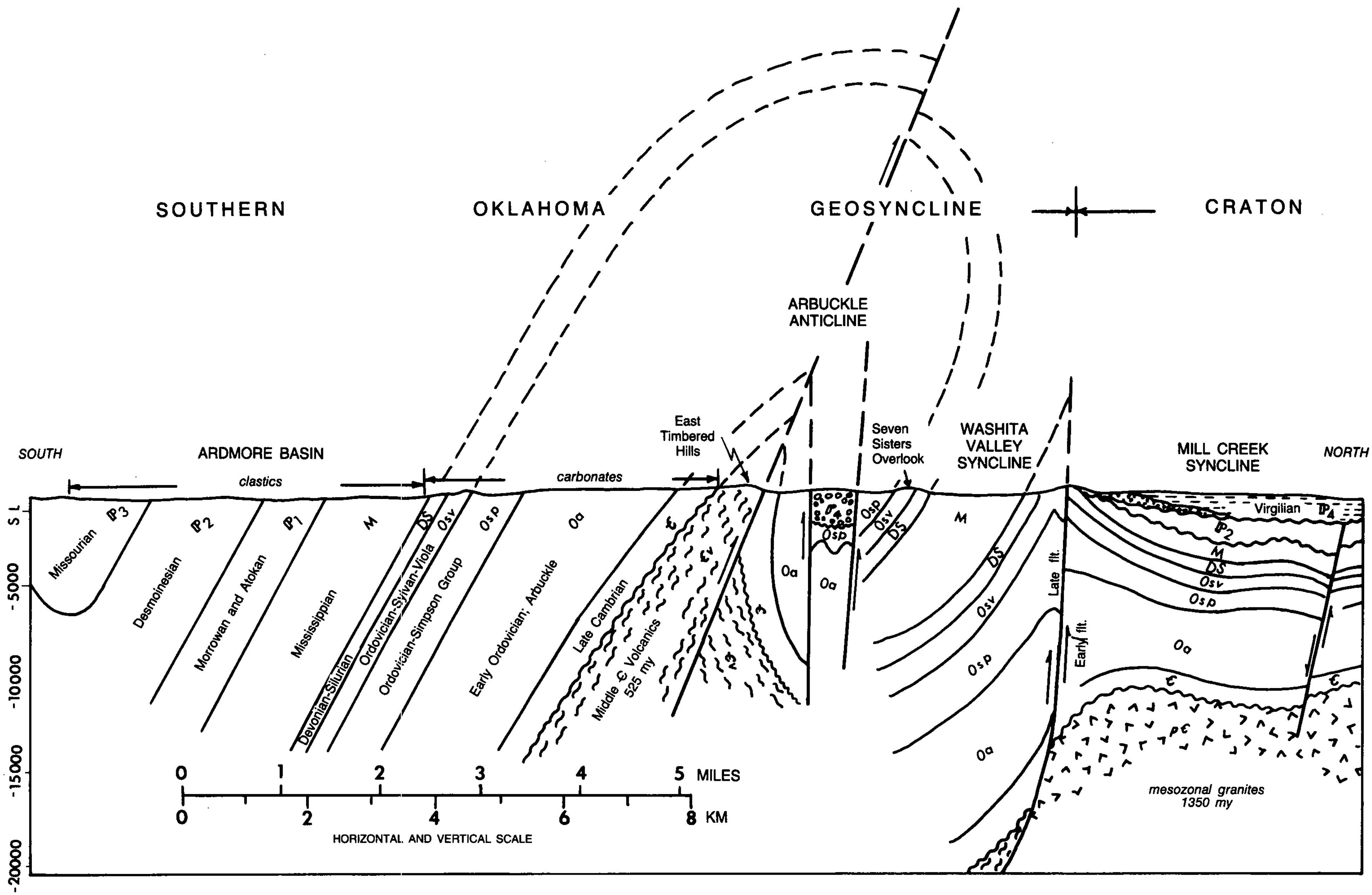

Figure 5. Structural cross section of Arbuckle Mountains in the vicinity of Interstate 35. See Figure 7 for location of cross section. (Modified from Ham, 1969)

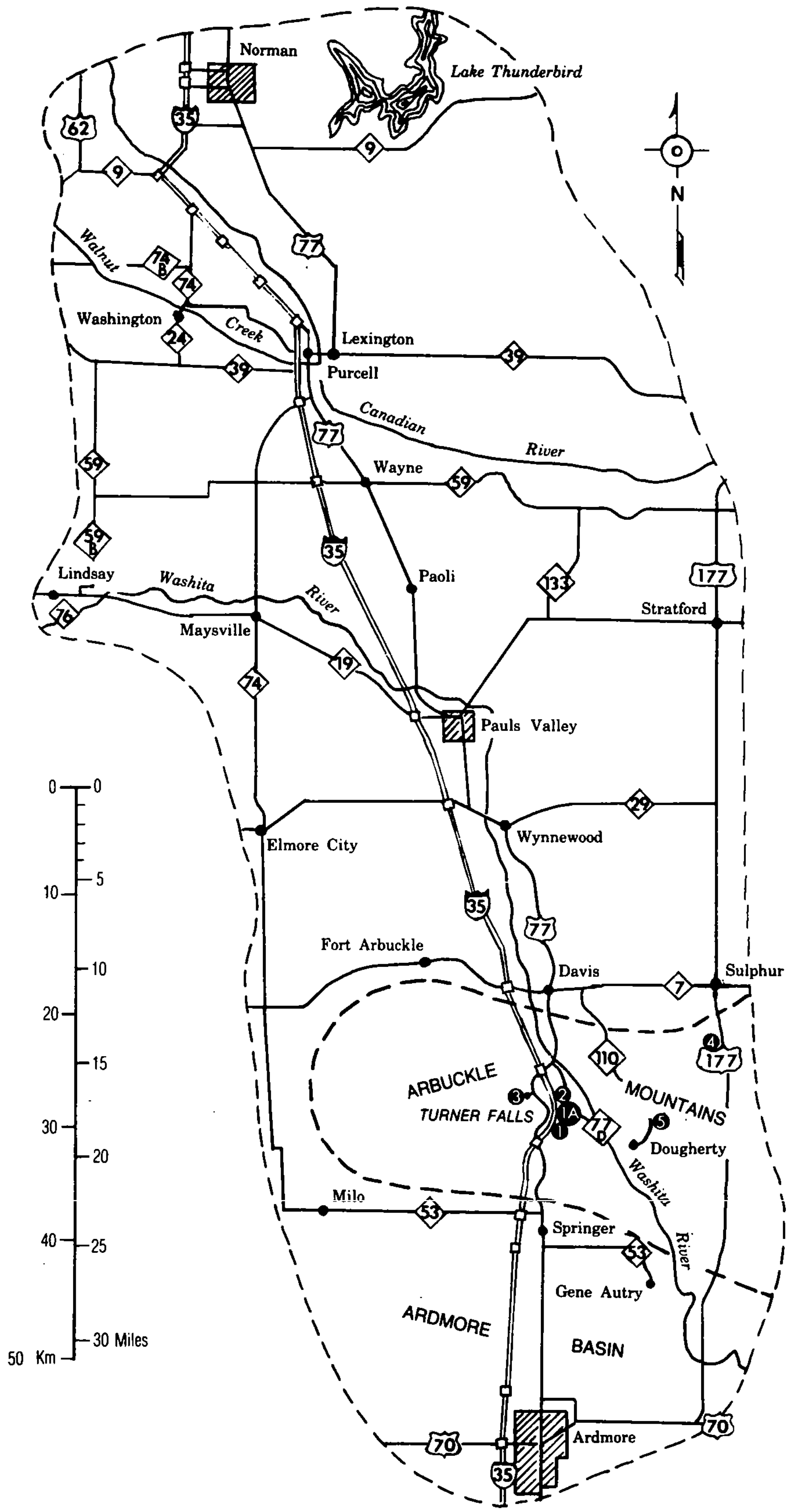

Figure 6. Generalized road map along the field-trip route, showing stops.

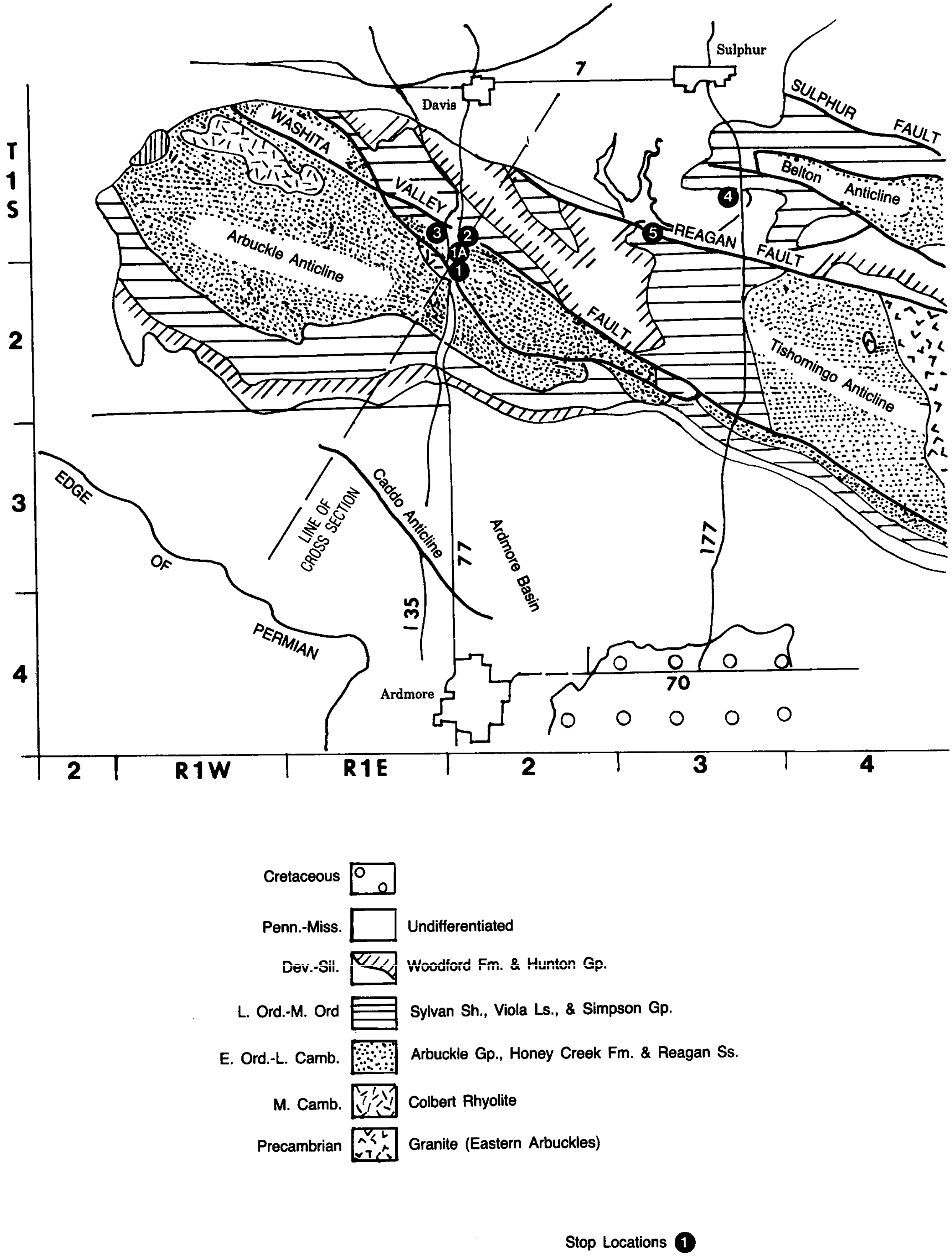

Figure 7. Generalized geologic map of Arbuckle Mountains, showing location of field-trip stops. See Figure 5 for structural cross section. (Modified from Ham, 1969)

Figure 8. Arbuckle-style folding in the Fort Sill Limestone, base of the Arbuckle Group, Upper Cambrian, near milepost 48, I-35, southbound lane.

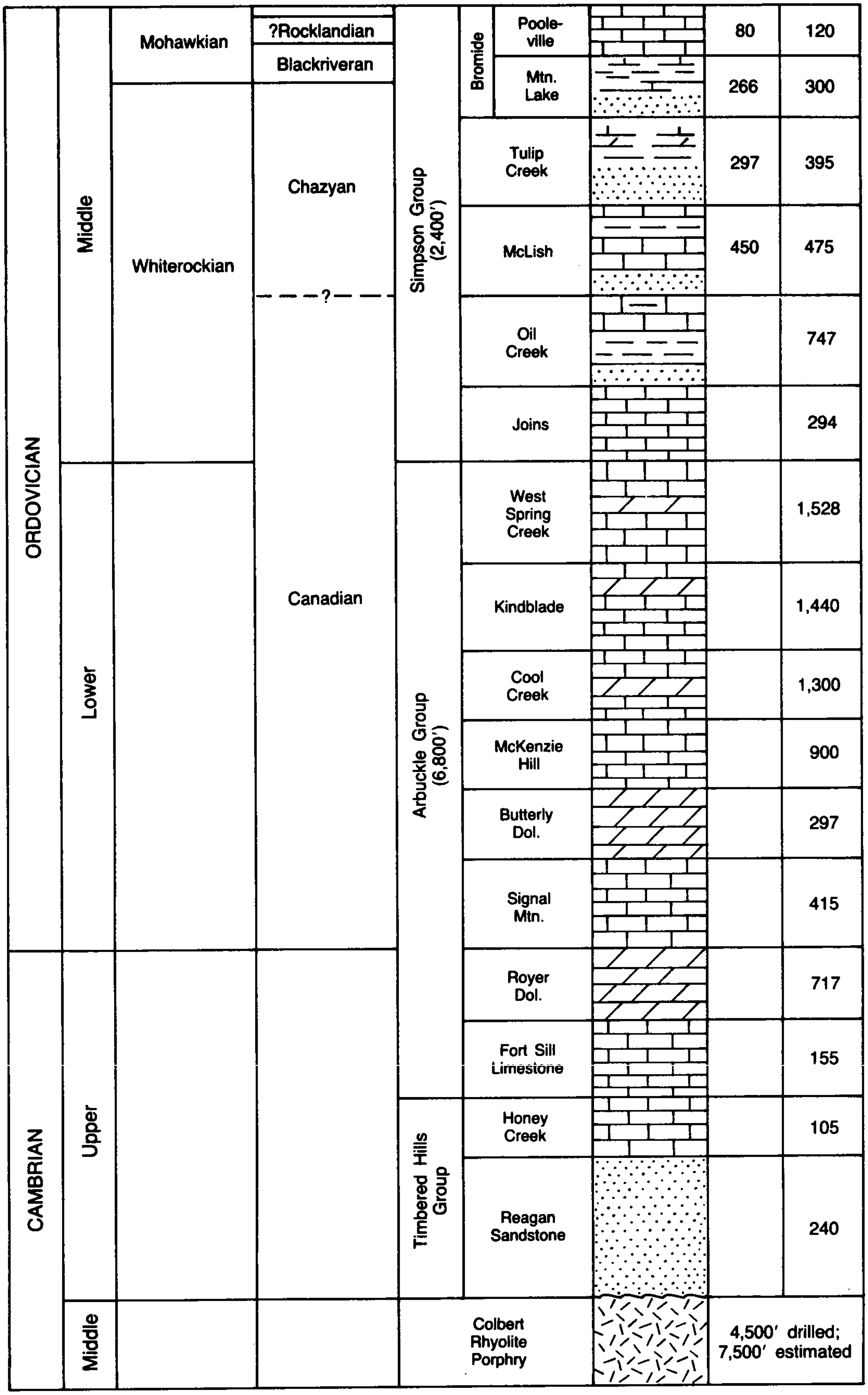

Figure 9. Stratigraphic succession of units exposed on Interstate 35.

Chronostratigraphic Units: System	Series		Stages	Lithostratigraphic Units		Lithology	Thickness (ft.): North Limb	Thickness (ft.): South Limb
PENN.				Collings Ranch Conglomerate			3,000' estimated	
MISSISSIPPIAN				Goddard Shale			2,500' + Not exposed	
MISSISSIPPIAN				Delaware Creek Shale				425
MISSISSIPPIAN		? Osagian-Meramecian ?		Sycamore Limestone			221	370
MISSISSIPPIAN		Kinderhookian		Woodford Shale			274	290
DEVONIAN		Chautauquan		Woodford Shale				
DEVONIAN		Helderbergian		Hunton Group (132-229)	Bois d'Arc Limestone		0-19	8
DEVONIAN		Helderbergian		Hunton Group (132-229)	Haragan Marlstone		16-48	26
SILURIAN	Upper	Pridolian-Ludlovian		Hunton Group (132-229)	Henryhouse Marlstone		17-78	190
SILURIAN	Upper	Wenlockian		Hunton Group (132-229)	Clarita Limestone		13	12
SILURIAN	Lower	Llandoverian		Hunton Group (132-229)	Cochrane Limestone		6+	13
ORDOVICIAN	Upper	Cincinnatian	Hirnantian	Hunton Group (132-229)	Keel Limestone		3-7	0-1
ORDOVICIAN	Upper	Cincinnatian	Richmondian		Syivan Shale		275	305
ORDOVICIAN	Upper	Cincinnatian	Maysvillian	Viola (650-720)	Welling Limestone		710	684
ORDOVICIAN	Upper	Cincinnatian	Edenian	Viola (650-720)	Welling Limestone / Viola Springs			
ORDOVICIAN	Upper	Cincinnatian	Shermanian	Viola (650-720)	Viola Springs			
ORDOVICIAN			Kirkfieldian	Viola (650-720)	Viola Springs			

Figure 9. *Continued.*

Figure 10. Characteristic "tombstone topography" of Kindblade Formation developed in beds of limestone dipping 50-60° along the south flank of the Arbuckle anticline; looking west, I-35, southbound lane. Stop 1.

The "tombstones" result from differential weathering of the limestones and dolomitic limestones which form the slab-like outcrops.

The most complete section of the Kindblade Formation occurs in the Arbuckle anticline and is approximately 1,400 ft (426 m) thick. At this stop only the lowermost 130-140 ft (39-42 m) is exposed (Fig. 11). The Kindblade excellently displays depositional features typical of Cambrian-Ordovician shallow-water intertidal-subtidal carbonate sedimentation in many regions of North America. Depositional textures and sedimentary structures of the Kindblade peritidal carbonates are extremely well preserved because this unit has not experienced the extreme dolomitization that often characterizes other Cambrian-Ordovician carbonate sequences.

The succession (1) consists predominantly of peritidal carbonates, (2) exhibits some evidence of shoaling-upward cyclicity, (3) demonstrates some evidence of deposition in environments experiencing occasional periods of elevated salinities and subaerial exposure, and (4) records some episodic sedimentation events.

The principal lithofacies include (1) stromatolitic boundstones; (2) intraformational conglomerates; (3) skeletal wackestones, packstones, and grainstones; (4) lime mudstones; and (5) intraclast packstones. Secondary lithofacies include quartz arenites and very thin calcareous shales/mudstones. Linear ropey chert nodules, in part spicular, occur in some facies. Some chert-replaced lithistid sponges also occur in some units.

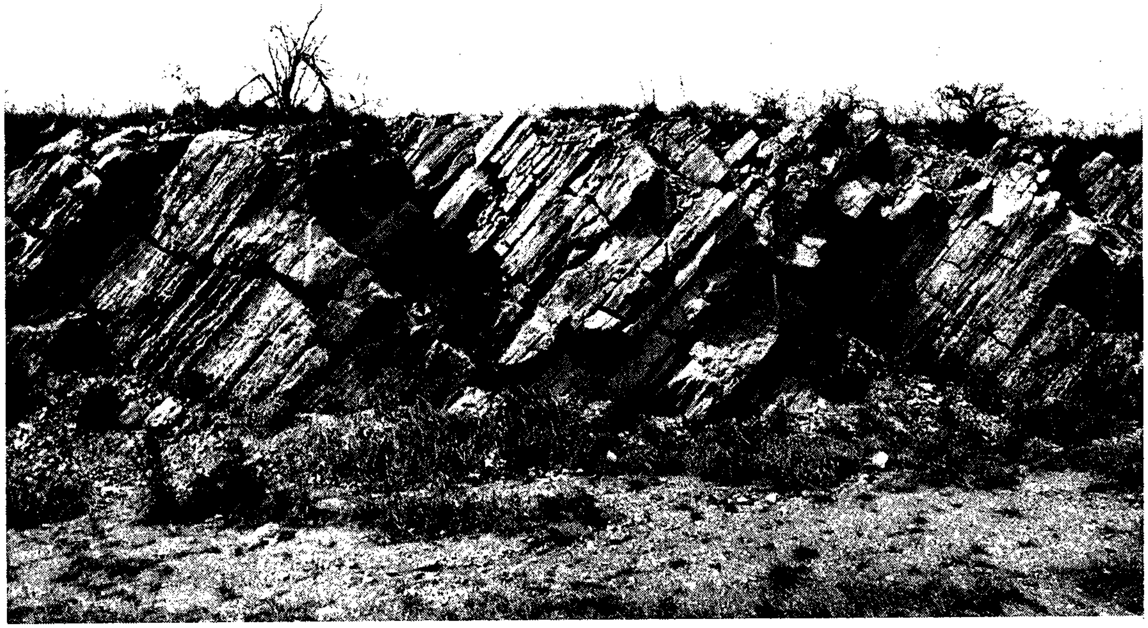

Figure 11. Outcrop character of Kindblade Formation, Arbuckle Group, Lower Ordovician; exposed on south flank of Arbuckle anticline. Stop 1.

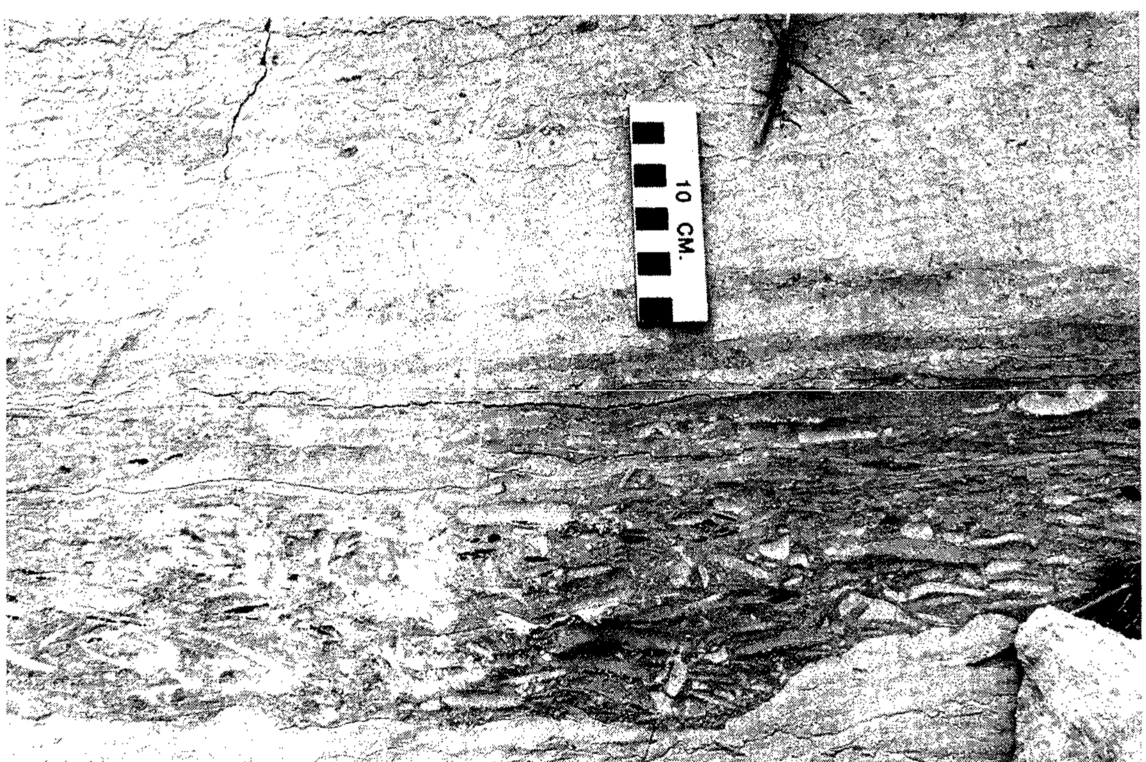

Figure 12. Lower part of bed is an intraformational conglomerate (IFC) composed primarily of ripped-up algal and lime mud clasts (storm event); note scoured base of bed. Upper part consists of laminations of encrusting stromatolitic algae that formed on top of the storm deposit. Stop 1.

Intraclast packstones and intraformational conglomerates are common at the base of these cyclic sequences (Fig. 12). The clasts consist predominantly of ripped-up algal fragments, but limestone fragments are also a common component. The clasts are usually rod-shaped, and packing arrangements are (1) preferentially aligned (flat-pebble conglomerate), (2) vertically stacked, and (3) randomly arranged. This facies probably represents storm deposits. The bases of these beds are usually irregular due to scour, and the tops sharp. The conglomerates are often overlain by wrinkled laminae of stromatolitic algae that grew on top of the storm layer (Fig. 13). Some tops show evidence of bioturbation and desiccation.

Skeletal fragments reported from the Kindblade Formation include lithistid sponges, algae, nautiloid cephalopods, other mollusks, trilobites, brachiopods, conodonts, pelmatozoan fragments, and silicified chiton plates. The skeletal grains are highly abraded and broken, occurring in the interareas between stromatolites. Most of the fossil fragments were derived from subjacent, less-stressful biotopes. Gastropods have been observed in association with some of the stromatolites and most likely constitute the most common in situ faunal element that lived on the stromatolites. Most likely the gastropods grazed on the prolific organic buildups in a manner similar to that of the gregarious accumulations of the modern gastropod *Batillaria*, found on Recent stromatolites on the western side of Andros Island in the Bahamas.

Organic buildups in the Kindblade consist predominantly of stromatolitic algae and lithistid sponges. The upper surfaces of many of the mounds appear to be truncated in part, and bioturbated. The preserved fauna and flora of the stromatolites and algal mats are sparse. Although the stromatolitic laminations attest to the former presence of other algal forms, tubules of the encrusting blue-green alga *Girvanella* are the most commonly recognized alga. Some algal colonies appear to be laterally linked (LLH), but the majority are individual domes (Figs. 14,15).

Sedimentary features to be observed at this stop in the Kindblade Formation include (1) intraformational conglomerates and packing arrangements, (2) organic buildups, (3) parallel laminations, (4) chert-replaced sponges, (5) algal mats, and (6) rare subaerial exposure surfaces.

Depositional Environment:

The apparent lack of vertical ecologic zonation of the organic buildups within the Kindblade Formation suggests that the environment--at least for this part of the section at this locality--was primarily shallow subtidal; however, evidence of associated intertidal conditions and periodic storm events is provided by intraformational conglomerates, intraclast packstones, small-scale scour features, truncated organic mounds, and small erosional channels, surrounding some of the buildups. The occasional very thin shale or mudstone and yellowish- to reddish- discoloration zone at the tops of some shallowing-upward sequences suggest possible rare periods of subaerial exposure.

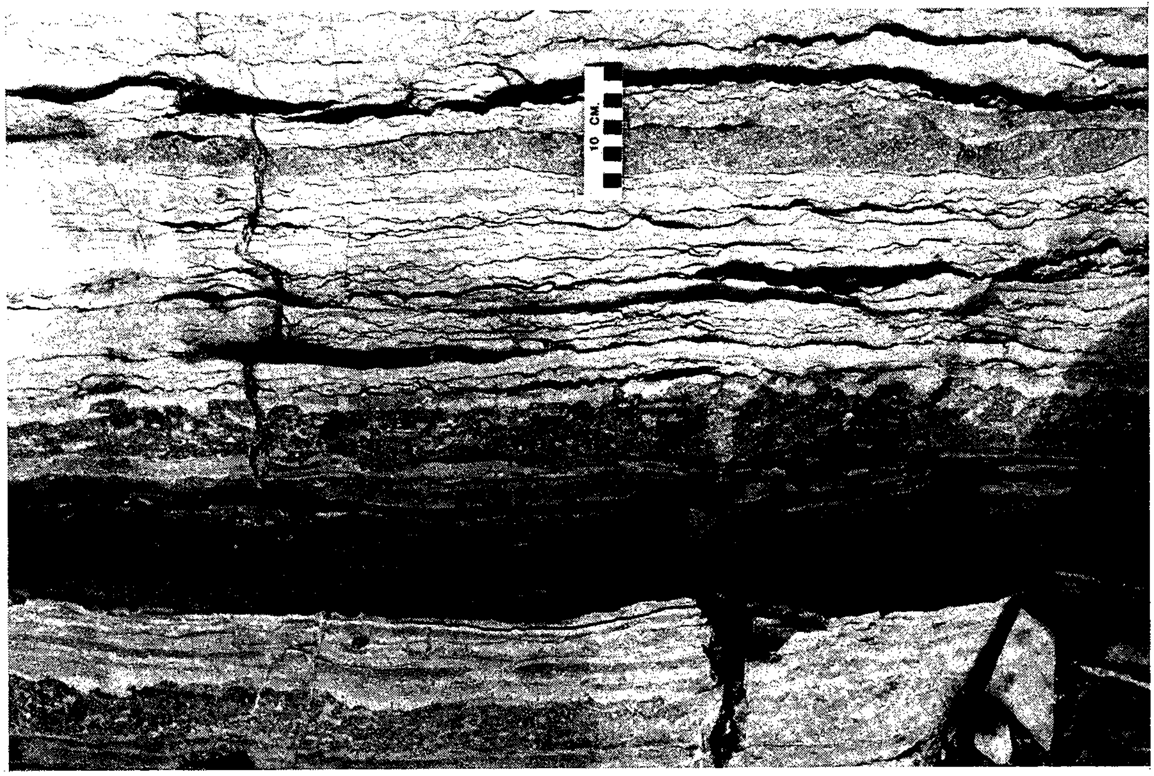

Figure 13. Typical small-scale cyclic bedding, consisting of alternating darker layers of storm deposits (algal rip-up clasts) and lighter crenulated layers of stromatolitic algae. Stop 1.

Figure 14. Stromatolitic algal colony of the stacked hemispheroid (SH) growth form. Stop 1.

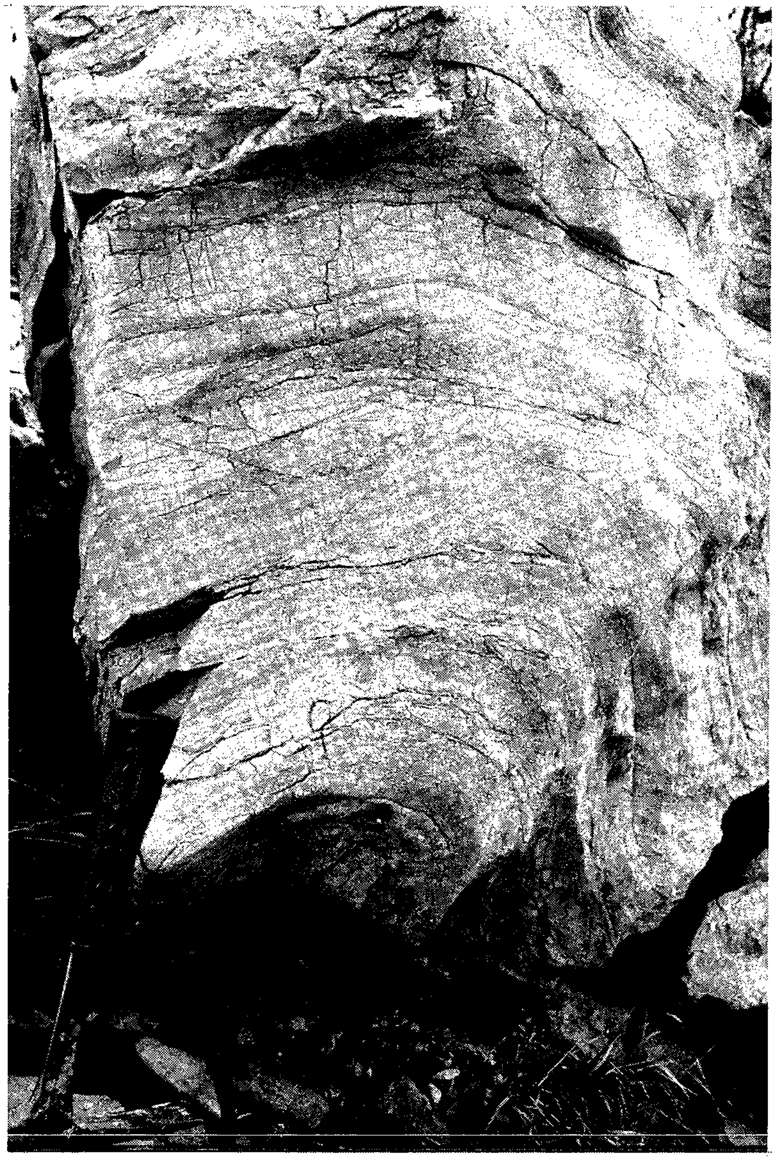

Figure 15. Large domal algal mound composed of algally laminated stromatolites; note interareas composed of thin bands of algal rip-up clasts and skeletal grains transitional into intraformational conglomerates. Stop 1.

Stop 1A

Structural Styles in the Lower Kindblade Limestone

Structural style of folds in the lower Kindblade Limestone (middle Arbuckle Group, Lower Ordovician) on the south flank of the Arbuckle anticline.

Location:

In and around scenic turnout, east side of northbound lane of Interstate 35, Murray County, Turner Falls Quadrangle, SE1/4SE1/4 sec. 13, T. 2 S., R. 1 E. (Fig. 6).

Significance:

- Illustrates on a small scale the basic structural styles found throughout the Arbuckle Mountains: relation of plunge to synclines and anticlines, bedding plane and flexural slip, "rabbit ear" structure, cross-crestal faults and folds, normal and reverse faulting.
- Observation of structural features in both map and cross-section view.
- Example of classic "tombstone topography."

Description:

In this area the classic "tombstone topography" of the Arbuckle Group is well developed. In the area between the road cut and the parking area, these "tombstones" outline a series of small folds in the lower Kindblade Limestone (Fig. 16).

This stop demonstrates exceptionally well some of the structural styles found throughout the Arbuckle Mountains. The topography in this area permits observation of features in both map and cross-section view, which enables visualization of the various structural styles in three dimensions. Walking from south to north, a small, tight anticline-syncline pair is observed, followed by a slightly broader anticline and syncline (Fig. 17). The small anticlinal "ear" is the result of detachment which can be traced into bedding-plane slip on the south flank of the underlying anticline. At the road-cut break, a single slab is folded into a broad syncline, and the plunge of the fold can easily be measured at 24°, N. 62° W. Figure 16 is a map view of this area.

In proceeding downsection along the east side of northbound I-35, anticlines tighten and synclines broaden. Conversely, anticlines broaden and synclines tighten upsection. In response to this concentric upward tightening of the synclines, volumetric adjustments are necessary to compensate for the increasing asymmetry. At this outcrop the volume has been adjusted by detachments apparently crowded out of a syncline on the south flank of the anticline. As a result, a secondary fold develops as the detachment dies out upward into a fault-fold interchange; this fold is known as a "rabbit ear" anticline (Tomlinson, 1952). At depth, the detachment dies out in bedding and is thus termed *bedding plane slip*. Visual offset and slickensides indicate these slippage planes. Close observation of the top

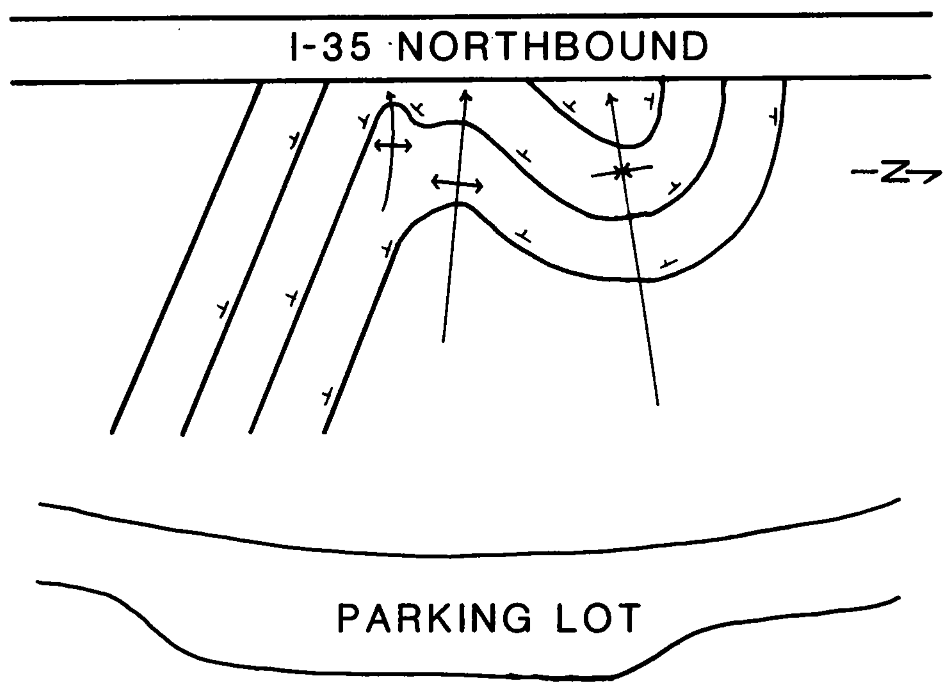

Figure 16. Map view of Stop 1A. The numerous "tombstones" define the structure of this anticline-syncline pair (Brown and Grayson, 1985).

Figure 17. Syncline-anticline-syncline folding in the lower Kindblade Formation. Structures represent small flexure on the downdropped side of a normal fault that strikes E-W, off the left margin of the photograph. Stop 1A.

Figure 18. Closeup of anticline shown in Figure 17, demonstrating interpreted structural relationships. Stop 1A. (Brown and Grayson, 1985)

of the outcrop reveals another volume adjustment which has formed as a result of the "rabbit ear" emplacement. Detachment on the flank of the anticline has produced yet another small fold known as a "*cross crestal*" anticline. Figure 18 illustrates interpreted structural relationships of this exposure according to Brown (1982), Nielsen and Brown (1984), and Brown and Grayson (1985).

Along the west side of northbound I-35 is another exposure of the plunging anticline. As a result of this NW plunge, the rocks exposed here are stratigraphically higher than those along the east side of the highway. The "rabbit ear" is no longer seen, because it is stratigraphically lower than the beds exposed here. Instead, the volume has been adjusted by a small reverse fault. Note that the syncline is now more tightly folded than on the east side of the highway, confirming the upward-tightening concept.

Continuing to the west in the down-plunge direction, a third exposure of this structure is observed on the east side of the southbound lane of I-35. As noted in the first road cut at this location, the tightening of the syncline and volume adjustments to compensate for the asymmetry are seen, but in a slightly different structural style. The volume adjustments in this syncline are particularly interesting: rather than detachments and development of "rabbit ear" anticlines, minor thrust faulting has developed.

At this stop, there is a broad anticline and tight syncline developed along the S-dipping southern flank of the Arbuckle anticline. The sense of vergence of this small anticline is to the north, up the flank of the Arbuckle anticline, in the same general orientation as the Arbuckle anticline itself. The "rabbit ear" and other detachment features also show this northerly vergence. Thus, the formation of the smaller anticline-and-syncline pair are likely volume-adjusting wrinkles formed as the Arbuckle anticline itself was developed by compression. Consequently, these small flank structures provide miniature models for the overall deformation of the Arbuckle anticline.

Stop 2

Collings Ranch Conglomerate

Character and structural relations of the Collings Ranch Conglomerate (Late Pennsylvanian, middle Virgilian).

Location:

Northbound lane, median, and southbound lane of Interstate 35, about halfway between the Davis and Turner Falls turnoffs, Murray County, Turner Falls Quadrangle, SW1/4NE1/4 sec. 31, T. 1 S., R. 2 E. (Fig 6).

Significance:

- Conglomerate records some of the latest tectonic events in the evolution of the southern Oklahoma aulacogen; principal depositional product dating the Arbuckle orogeny.
- Pronounced angular unconformity.

- Deposition in proximal part of an alluvial-fan complex.
- Polymict conglomerate composed of rock fragments from Cambrian-Ordovician Arbuckle Group.
- Alternate hypotheses explaining the occurrence and preservation of the conglomerate.

Description:

The Collings Ranch Conglomerate is well exposed along both lanes and in the median of I-35 on the north flank of the Arbuckle anticline. The conglomerate has been folded into a steep-faulted (northern limb), asymmetric, NW-trending syncline and preserved within a graben-like basin 0.5-1.0 mi (0.8-1.6 km) wide (Fig. 19). The slightly-dipping Collings Ranch Conglomerate overlies vertical to slightly overturned beds of the Ordovician Bromide and Viola Formations with great angular unconformity in the northernmost part of the outcrop (Fig. 20).

The Bromide dips to the south at about 60°. The unconformity is irregular, and near the southern edge of the western exposure it falls abruptly beneath road level. Fay (1973) interpreted this abrupt fall as a fault scarp buried by conglomerate deposition. The southern contact is fault-bounded between the Collings Ranch and the West Spring Creek Formation (Arbuckle Group), but it is not exposed at this outcrop (Fig. 21).

The formation is a massive limestone-boulder conglomerate approximately 3,000 ft (915 m) thick, deposited during the Late Pennsylvanian (middle Virgilian). The pinkish-gray conglomerate comprises stacked-pebble and cobble conglomerates forming lenticular beds that are moderately cemented. Contacts of the thick, subparallel layers either are erosional scour-and-fill structures or are defined by discontinuous surfaces of red calcareous mudstone. The average composition of the Collings Ranch is a pebble-to-boulder, clay-to-sandy, unsorted, clast-supported lithrudite. In general, the stratigraphic sequence coarsens upward from the base. Overall, the sorting is very poor due to the mixture of clay with particles that range in size from silt and sand to boulder (Fig. 22). The deposit is texturally immature, with angularity ranging from subangular to subrounded and rounded (Fig. 22). Compositionally, the deposit is immature due to the predominant percentage of carbonate rock clasts.

Close examination of the clasts in the conglomerate reveals that most of the rock fragments appear to have been derived from a sedimentary source, namely the Cambrian-Ordovician Arbuckle Group (Ham, 1973); this suggests either that the igneous core of the Arbuckles was not exposed at this time or that it did not outcrop within the drainage basin of the conglomerate. The clasts are composed predominantly of micritic limestone, with minor clasts of sandstone and red-clay matrix. Probable sources of carbonate clasts include the McKenzie Hill, Cool Creek, Kindblade, and West Spring Creek Formations, as well as the Viola and Hunton Limestones (Ham, 1954) (Fig. 9). Detailed studies of the conglomerates reveal that much pressure solution has taken place between carbonate clasts. Glahn and Laury (1985) suggested that this pressure solution was a response to tectonically induced stress with a strong horizontal component. The sandstone clasts consist of mature quartz arenites from the Simpson Group (Fig. 9).

Figure 19. Preservation of Collings Ranch Conglomerate (Late Pennsylvanian) in an asymmetric syncline within a graben-like basin. Exposure in median of I-35, looking northwest. Stop 2.

Figure 20. View of Collings Ranch Conglomerate overlying the Ordovician Viola Formation with great angular unconformity. Conglomerates show a lenticular geometry. Looking west on I-35. Stop 2.

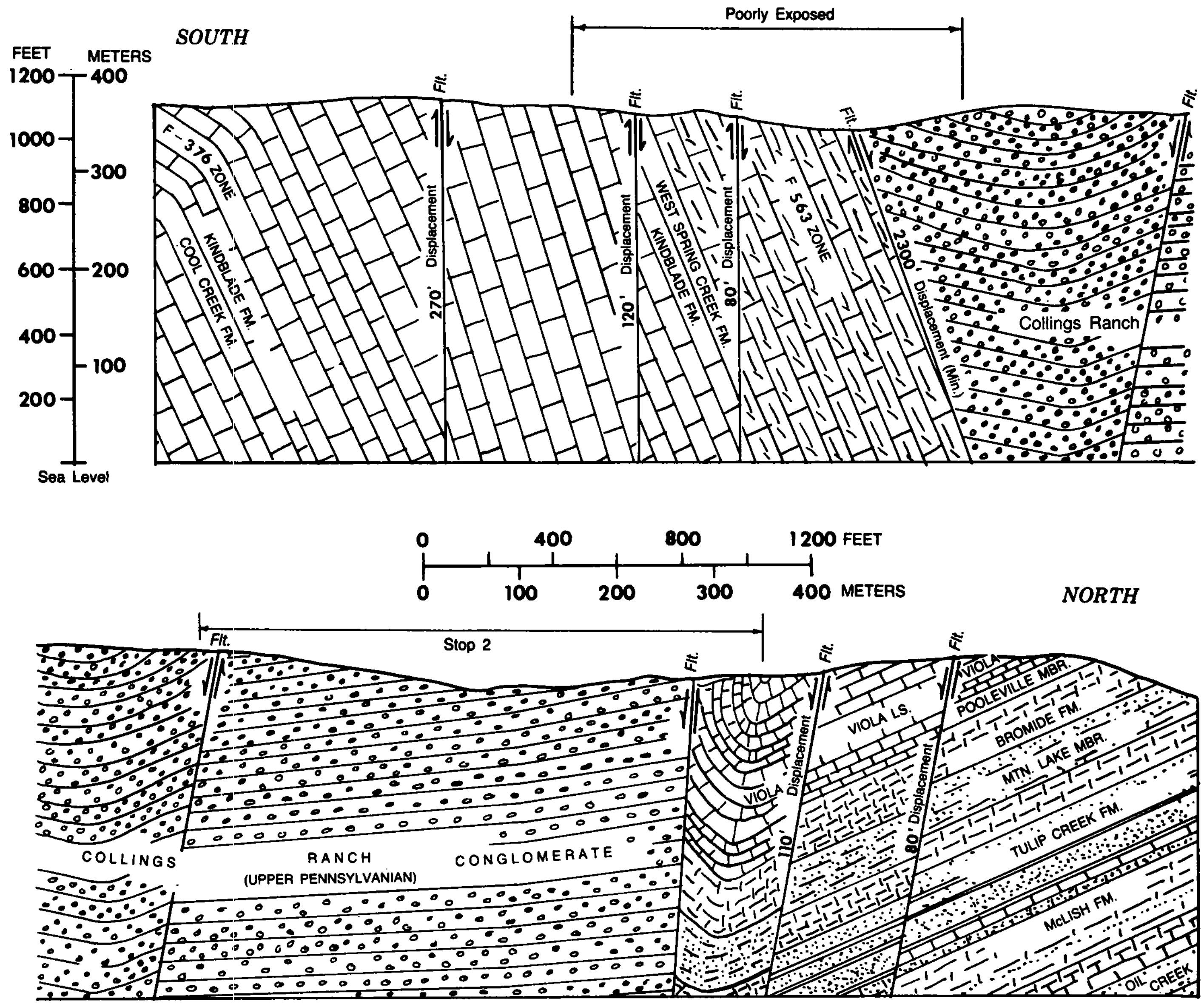

Figure 21. Schematic north-south cross section along part of I-35, showing outcropping units and interpreted structural relationships. Stop 2. (Modified from Fay, 1969)

Figure 22. Closeup of Collings Ranch Conglomerate, a pebble-to-boulder, clay-to-sandy, unsorted, clast-supported lithrudite. Most of the rock fragments were cannibalized from the Cambrian-Ordovician Arbuckle Group. Stop 2.

Depositional Environment:

Sediment characteristics indicate deposition in the proximal part of an alluvial-fan complex (Brown and Reneer, 1985). Depositional facies recognized at this stop include (1) debris flows either in channel geometries or spread laterally as sheets or lobes; (2) braided stream-channel fills; and (3) mud-flow deposits. Channelized debris flows consist of poorly sorted, graded, clast-supported deposits with larger fragments randomly arranged. This facies is more common at the southern end of the outcrop, decreasing to the north. Massive sheet or lobe deposits are more common at the northern end and consist of poorly sorted, clast-supported deposits exhibiting grading or inverse grading.

Braided-stream-channel fills, diagnostic of the proximal focus of an alluvial-fan system, are characteristically poorly to moderately sorted, contain less clay matrix, exhibit thin-to-lenticular geometries, and fine upward.

Mud-flow deposits consist of finer-grained deposits ranging from sand to clay, with clay as the dominant composition. These deposits occur in lenticular and bedded layers associated with larger rock fragments. These deposits represent either waning sediment supply due to the lowering of the source area or overbank deposits resulting from periodic floods.

The grading and inverse grading present in the Collings Ranch suggest gentle, fluctuating uplift of the Arbuckle Mountains. Each bed grading from debris flow to mud flow may in fact represent an individual tectonic pulse, that is, a single sedimentation event (Brown and Reneer, 1985). The overall coarsening-upward sequence is the result of progradation of the alluvial fan with continued uplift and erosion of the source area.

Discussion:

The Collings Ranch Conglomerate was deposited in a graben-like basin, trending WNW, which was several miles in length and as much as 0.5-1.0 mi (0.8-1.6 km) in width. As noted earlier, faulting occurs at both the north and south boundaries of the graben-like basin in which the conglomerate is preserved (Fig. 21). The south fault of the graben is one of the principal through-going faults of the Arbuckle Mountains, the Washita Valley fault (Figs. 5,7). The Washita Valley fault is a long, straight fault zone trending NW to the western edge of the Arbuckle Mountains, where it is covered by the Late Pennsylvanian (Virgilian) Vanoss Conglomerate (Fig. 5); this relationship demonstrates that the Vanoss is younger than the Collings Ranch Conglomerate. The fault is nearly vertical at the surface, but it may dip either N or S at various points along its length. There is some evidence that the fault was active at least as far back as Cambrian time.

Tanner (1967) interpreted the Washita Valley fault to be a major left-lateral fault having about 40 mi (66 km) of slip. This is a popular thesis because of the numerous subordinate en echelon faults and folds, and the apparent offset of stratigraphic units across the Washita Valley fault. The presence of the Collings Ranch Conglomerate has very interesting implications in this regard, if in fact the Washita Valley fault was a left-lateral wrench system during deposition of the conglomerate. According to Wickham (in Wickham and Denison, 1978), the aulacogen theory predicts that such a major fault zone originated as a normal fault with intermittent dip-slip displacement throughout the subsiding phase of the aulacogen. Pennsylvanian wrench faulting would then have reactivated this older fault system, giving it a predominantly horizontal displacement. As cited above, the conglomerate is preserved in a graben-like depression several miles long and at least 0.5 mi (0.8 km) wide. Tracing the fault delineates a rather sharp bend in the Washita Valley system. Applying a left-lateral system to this fault results in what is termed a *releasing bend* (Crowell, 1974), which is the direction to free or release the blocks as they glide past each other. This system results in a pull-apart (local extension) and subsiding sedimentary basin in which synorogenic deposits such as the Collings Ranch Conglomerate can accumulate and be preserved. If in fact this is the case, then the apparent maximum reported thickness of 3,000 ft (900 m) assigned to the conglomerate (Ham, 1973) may be incorrect, especially when the maximum vertical thickness that can be measured at any one locality is only about 300 ft (90 m). The deposit may in fact represent a series of small, stacked-up fans that record a continuous syntectonic signature as the basin gradually opened.

Brown (1982,1984) and Brown and Reneer (1985) have proposed an alternative explanation for the preservation of the Collings Ranch Conglomerate on the north flank of the Arbuckle anticline. According to these workers, the conglomerate was deposited in a true graben formed during crestal extension of the Arbuckle anticline. After initiation, the graben was rotated to an offcrest position as the anticline tightened. This explanation is more compatible with Ham's (1954) ideas and his assigned estimate of the thickness of the conglomerates.

Subsequently, the fault system reactivated and transpressed the basin fill, resulting in prelithification folding and faulting, and significant pressure solution between rotating limestone clasts. It is these reactivated faults that presently delineate the boundaries of the conglomerate exposures.

In summary, Wickham (1978) proposed that stresses affecting the region were resolved into a complex of left-lateral wrench movements associated both with localized compression (transpression) and with extension (transtension). The Collings Ranch Conglomerate accumulated in what appears to have been a small, closed, transtensional, pull-apart basin, bounded by major faults. Brown (1982,1984; Brown and Reneer, 1985) has challenged the wrench interpretation, suggesting an enhanced role for pure compression and low-angle reverse faulting. Subsequently the conglomerate was affected by further tectonic pulses, and as a result bears a significant deformational signature.

Stop 3

Turner Falls Overlook

Peritidal Ordovician carbonates,
Pleistocene tufa and travertine deposits.

Location:

Turner Falls overlook is located at the gift shop on U.S. Highway 77, approximately 3 mi (4.8 km) south of Davis and about 3 mi (4.8 km) north of the southern U.S. Highway 77 exit off I-35, Murray County, Turner Falls Quadrangle, SE1/4NE1/4 sec. 36, T. 1 S., R. 1 E. (Fig. 6).

Significance:

- Organic vs. inorganic origin for nonmarine carbonate deposits.
- Preserved record of climatic fluctuations during the Pleistocene.
- Active and inactive travertine and tufa deposits; prograding waterfall.
- Study of various criteria that signal the former presence of now-vanished evaporites in peritidal carbonates.
- Superb sedimentary structures of peritidal carbonates; particularly noteworthy are the varieties of stromatolites and intraformational conglomerates.

General Description:

Turner Falls is a popular tourist attraction in the Arbuckle Mountains and is the most impressive waterfall in Oklahoma. The best known view of the falls is from this overlook, on the south side of the trace of the Washita Valley fault zone, just north of the crest of the Arbuckle anticline (Fig. 5). The view from the overlook takes in not only the falls, but also the crest of the East Timbered Hills anticline, the hills immediately to the southwest of the overlook with the radio tower. The East Timbered Hills anticline is cored with Cambrian Carlton Rhyolite, typical rock of the southern Oklahoma aulacogen (Fig. 5).

A generalized geologic map of the Turner Falls overlook area is shown in Figure 23. Between the rhyolite and the overlook are complexly folded Cambrian-Ordovician rocks on the north limb of the Arbuckle anticline. A fault trace parallels the valley of Honey Creek, separating Cool Creek Limestone at the overlook from McKenzie Hill Limestone, well exposed downstream and across the valley in a bold cliff face. Above the cliff and barely behind it is a small lateral valley, occupied by a few deciduous trees, which marks the trace of the Washita Valley fault. Beyond the fault is the Collings Ranch Conglomerate (Fig. 23). A number of faults are mapped in this region. Several are part of the Washita Valley fault system, but others are part of the Chapman Ranch thrust fault, which follows the base of the East Timbered Hills, on the east and north sides.

Turner Falls Travertine Deposits

General Description:

All streams flowing across the limestone beds of the Arbuckle Mountains dissolve calcium carbonate, carrying much of it away in solution. Turner Falls is of unusual geologic interest because the tumbling waters of Honey Creek have deposited a complex edifice of calcium carbonate; as a result, the waterfall scarp is not receding upstream, as is the case with most waterfalls, but has advanced (prograded) downstream as an impressive cliff of travertine and tufa. The thickness of the travertine gradually increased with the passage of water over it, until the falls reached a maximum height of 150 ft (45 m). During Pleistocene time, increased rainfall caused Honey Creek to cut a gorge into the depositional platform it had built, reducing the waterfall to half its former height. This beautiful waterfall is presently maintaining a steady state, that is, receiving about as much calcium

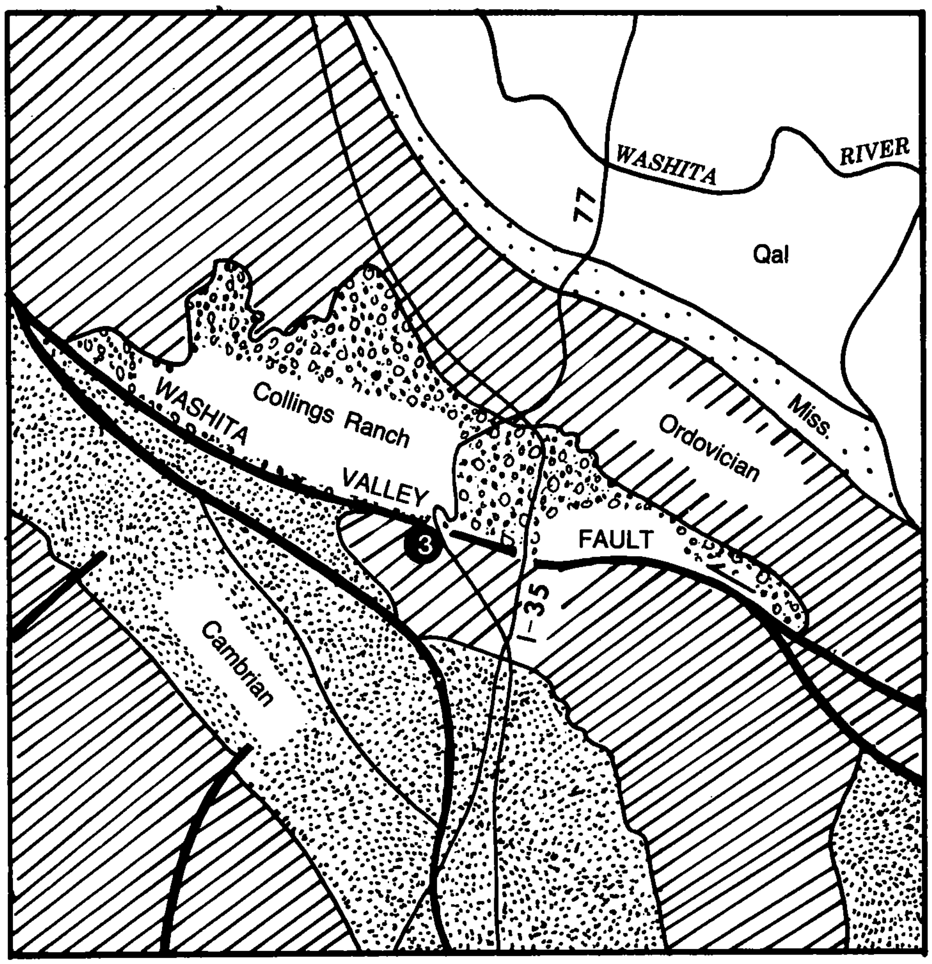

Figure 23. Generalized geologic map of Turner Falls area. Stop 3. (Modified from Brown and Grayson, 1985)

carbonate in the form of stream-floor deposits as is mechanically abraded during floods. The water of Honey Creek flows over an active, fan-shaped deposit; older, inactive deposits tower above the falls (Figs. 24-25).

Depositional Environment:

The travertine deposits form as a result of both physicochemical factors (i.e., evaporation) and biological induction (i.e., photosynthesis by algae). The travertine deposits occur both within and alongside the stream bank. Deposits alongside the stream represent an older period of deposition; after this initial deposition, the stream cut down through its deposits, leaving travertine deposits lining the streams (Fig. 24). The deposits range from thin (millimeter) coatings on the country rocks to masses nearly 98 ft (30 m) thick; the thickest deposits occur at past or present sites of waterfalls. Much of the travertine is bedded. The beds consist mainly of porous travertine which precipitated around organic material such as algae and mosses. Love and Chafetz (1988) studied waterfall travertine deposits in the Arbuckle Mountains and noted that the deposits retain virtually no evidence of their organic origin. Their study revealed that the range of crust types actually reflects a diagenetic sequence from crusts with obvious organic structures to crusts composed almost entirely of coarse, columnar, sparry crystals retaining virtually no evidence of organic origin. In light of these findings, caution certainly is warranted before automatically assuming an inorganic origin for similar-looking crusts present in other nonmarine carbonate deposits.

Pleistocene History:

Emig (1917) first recognized that the Turner Falls travertine is a complex deposit that records fluctuations in Pleistocene climate. Five distinct stages can be recognized in the evolution of the deposit:

Stage 1

- Initial dissection of area by vigorous streams with steep gradients.
- Initial excavation of Honey Creek Valley gorge downstream from the falls.

Stage 2

- Warmer, drier climates, resulting in calcite saturation and major travertine deposition.
- Deposition results in travertine cliff approximately 100 ft (30 m) high and 300 ft (90 m) wide.
- Local unconformities due to irregularities in stream bed, reflecting numerous faults and dip variations in the bedrock (i.e., intratravertine disconformable surfaces).
- Cave systems developed in older travertine deposits represent primary cavities (not resulting from solution) formed behind large tree trunks cemented into the travertine, forming obstructions in the waterfall.

Figure 24. Turner Falls, with waterfall travertine deposits along Honey Creek. The water runs over an active, fan-shaped deposit; older, inactive deposits tower above the falls. The waterfall is about 70 ft (21 m) high.

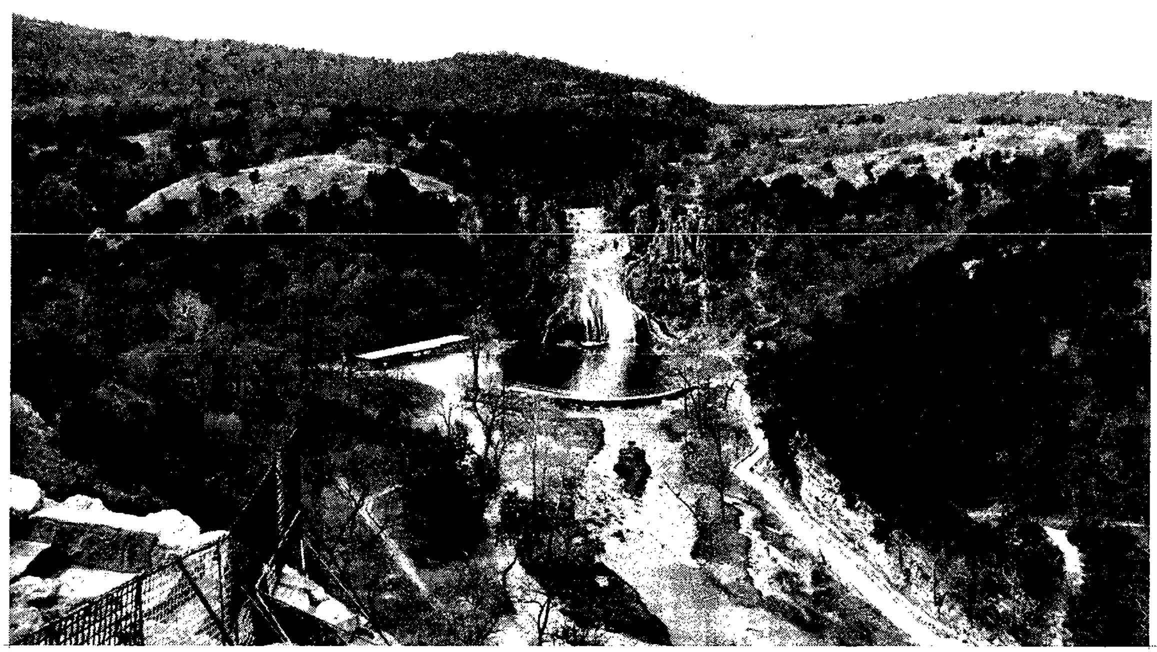

Figure 25. Turner Falls as viewed from the overlook area on Highway 77. Stop 3.

Stage 3

- Some evidence of speleothems (i.e., flowstone, crude stalactites) within the older travertine deposits.
- Probably formed during semi-arid stage, with greatly diminished and probably intermittent flow of Honey Creek.

Stage 4

- Cessation of carbonate precipitation, presumably during a wetter and cooler stage.
- Honey Creek eroded its own deposit, forming the steep-sided gorge above the modern waterfall.

Stage 5

- Honey Creek re-established its constructive mode, presumably during a warmer and drier period.
- Modern travertine-tufa deposits at the falls are the result.

The entire travertine-tufa edifice at Turner Falls is an excellent expression of how climatic variations--as opposed to tectonic or other adjustments to base level--can control fluvial erosion.

Ordovician Platform (Peritidal) Carbonates;
Cool Creek Formation, Arbuckle Group, Early Ordovician

General Description:

The Cool Creek Formation, upon which the overlook is situated, is part of the Cambrian-Ordovician Arbuckle Group, a thick accumulation (6,000 ft; 1,830 m) of platform carbonates whose lithic equivalents are present throughout most of the southern Midcontinent. The Cool Creek Formation occurs about 3,300 ft (1,006 m) stratigraphically below the top of the Arbuckle Group (Fig. 9).

The lower boundary of the formation (contact with the McKenzie Hill Formation) is marked by the incoming of abundant quartz sand into the sequence. The upper boundary with the Kindblade Formation unfortunately is defined on paleontological criteria, namely, the earliest occurrence of the enigmatic gastropod genus, *Ceratopea.*

Two excellent sections (the best exposures of this formation in Oklahoma) can be studied at this stop. The thicker, stratigraphically lower section (starts about 300 ft, 90 m above the base) is exposed along the cliff below the gift shop and formerly could be examined from the steps leading down to the falls. Unfortunately, the walkway is now barricaded because deterioration of the steps has produced an extremely dangerous path that has resulted in injuries to the adventuresome. The second section is a road cut on U.S. Highway 77 that is conveniently located directly across the highway from the gift shop (Fig. 26).

Figure 26. Outcrop character of the lower part of the Cool Creek Formation, Arbuckle Group, Lower Ordovician. Stop 3.

Lithofacies:

Major peritidal facies recognized in this 1,312-ft (400-m) unit consist of cyclic packages of (1) stromatolitic boundstones (principal facies); (2) intraformational conglomerates; (3) quartz-rich, oolitic packstones and grainstones; (4) peloidal wackestones, packstones, and grainstones; (5) thin, small-scale, trough-cross-bedded quartz arenites; (6) lime mudstones, and (7) heterolithic units. Chertification and dolomitization have affected these facies in varying degrees. However, the effects of dolomitization, which is so prevalent in many other Cambrian-Ordovician sequences, is minimal. Consequently, sedimentary structures so characteristic of peritidal carbonates are exceptionally well preserved at this stop. A generalized stratigraphic section of the exposures along U.S. Highway 77 is shown in Figure 27.

Algal boundstones with chert nodules constitute the most common facies. Many of the stromatolitic zones are exceptionally well exposed, and a variety of geometries are present. External forms recognized in the Cool Creek include (1) encrustations, (2) mats, (3) mounds, and (4) reefs. Internal organization into several morphologic growth forms of stromatolites and thrombolites (e.g., dendritic, digital, cylindrical, columnal, etc.) can be seen at this stop. The differing forms of boundstone are a response to varying water depths. Digitate stromatolites are the most common of the algal-boundstone facies and are generally found as small, circular to elongate heads, large mounds up to 5 ft (1.5 m) thick, and tabular beds (Fig. 28). Thrombolites, cryptalgalaminites, laterally linked hemispheroids (LLH), stacked hemispheroids (SH), and oncolites are present, but in subordinate quantities (Fig. 29). A dendritic form is shown in Figure 30.

Thrombolites in the Cool Creek are poorly organized internally and lack the laminated character of stromatolites. Laminations, if present, consist of vague, convex-upward laminations. Thrombolite mounds are as much as 3.3 ft (1.0 m) wide and externally exhibit a distinctive clotted texture (Fig. 28). Chert nodules commonly are associated with the thrombolites.

Cryptalgal crusts are fairly common in the Cool Creek. They begin as thin cryptalgalaminites, but generally grow into laterally linked hemispheroids (LLH) (Fig. 29).

Intraformational conglomerates (Fig. 31) and flat-pebble conglomerates are abundant throughout the Cool Creek Formation. These occur in erosive-based beds that are usually about 1 ft (30 cm) thick. Most of the clasts are lime mud, but they also include fragments of encrusting stromatolites. Algal desiccation chips are especially numerous around the stromatolitic mounds. The clasts are disc- or rod-shaped, resulting in four types of packing arrangements: (1) random, (2) flat, (3) imbricate, and (4) vertical. Most of the conglomerates are mud-supported. The clasts probably owe their origin to storms (Fig. 32); some were subsequently sorted by waves and tidal currents.

Heterolithic units in the Cool Creek are characterized by a variety of bedding types, of which flaser bedding is predominant. The units consist of alternating light and dark layers of lime mudstone and quartz-rich calcarenites. The calcarenites frequently show small-scale cross-bedding, in many cases related to ripple marks. Units of this type may be cut by both subaerial and subaqueous mud cracks.

Grainstones are a common facies in the Cool Creek Formation. The principal allochems are intraclasts and ooliths. Skeletal fragments are uncommon; they include trilobites, brachiopods, and gastropods. On the outcrops, gastropods are usually the only fossils

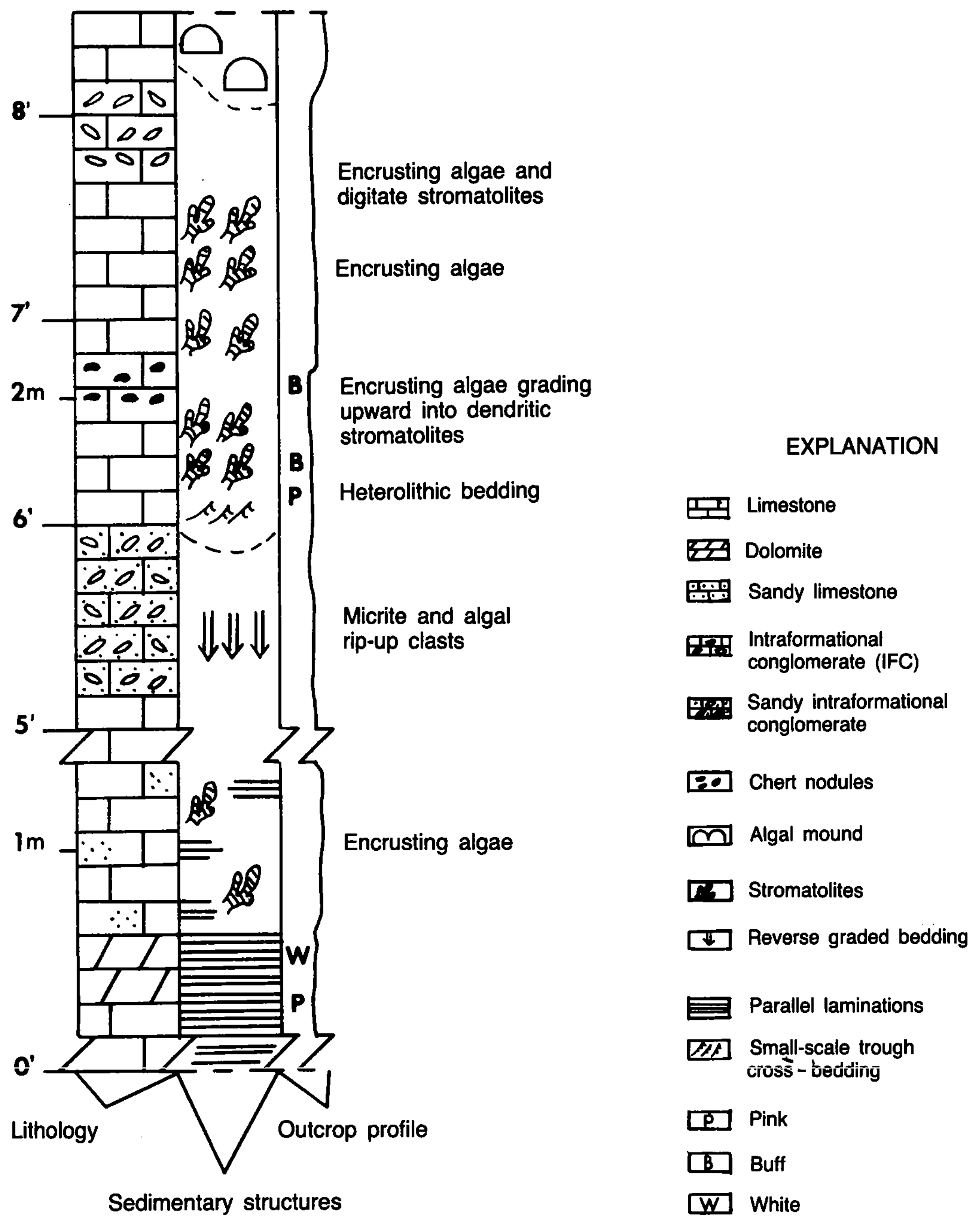

Figure 27. Stratigraphic section of the Cool Creek Formation measured along U.S. Highway 77, across from the gift shop at Turner Falls overlook. Stop 3. (Ragland and Donovan, 1985)

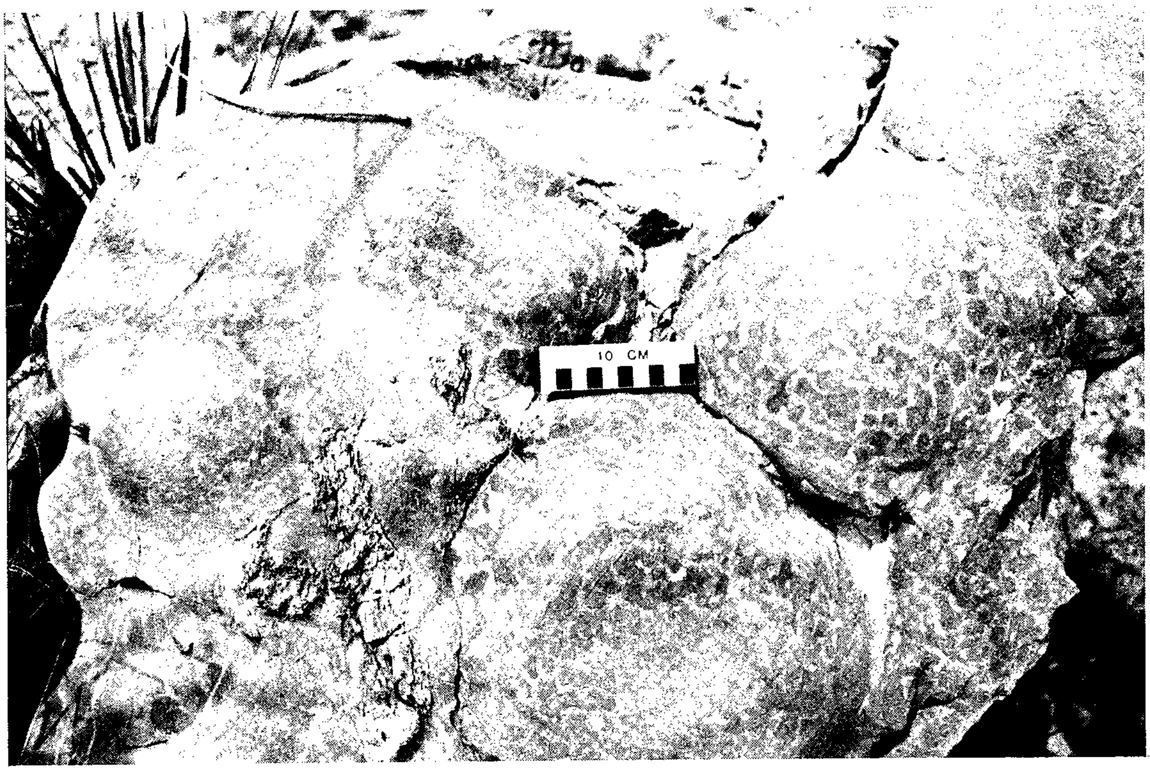

Figure 28. Top view of thrombolite mounds, showing characteristic clotted texture and associated chert. Stop 3.

Figure 29. Laterally linked hemispheroid (LLH) stromatolitic growth form that began as thin cryptalgalaminites. Stop 3.

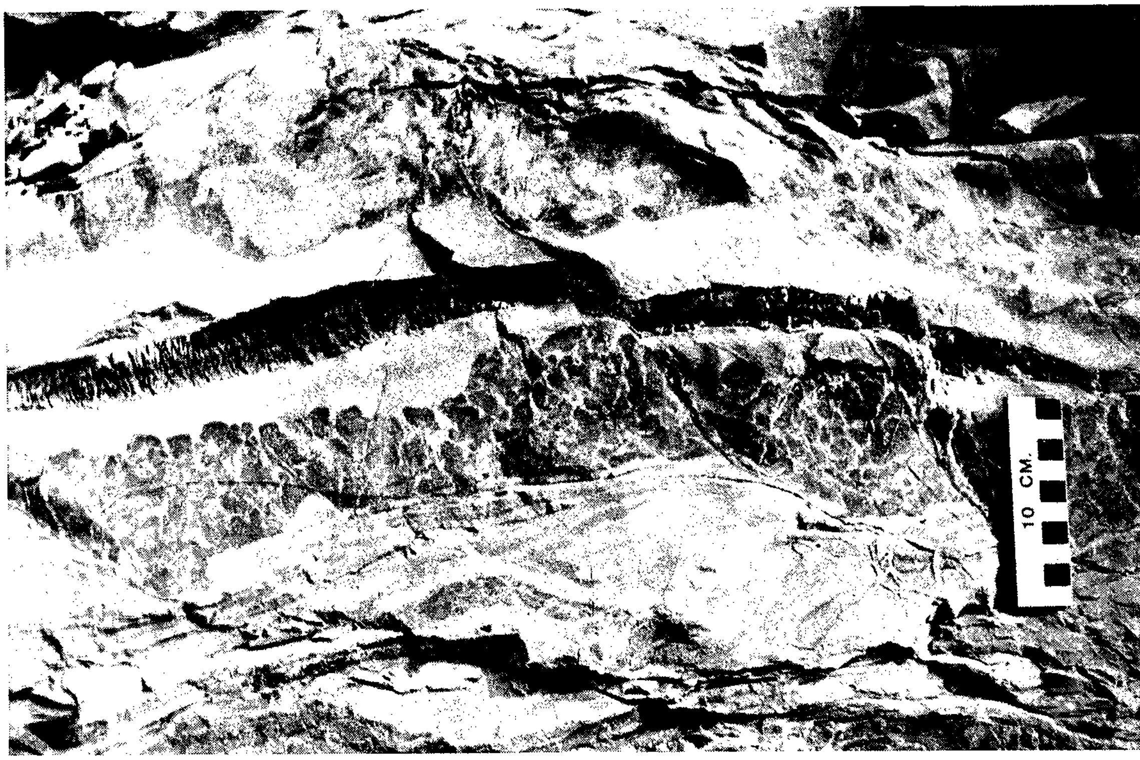

Figure 30. Dendritic algal colony, showing texture intermediate between stromatolites and thrombolites. Stop 3.

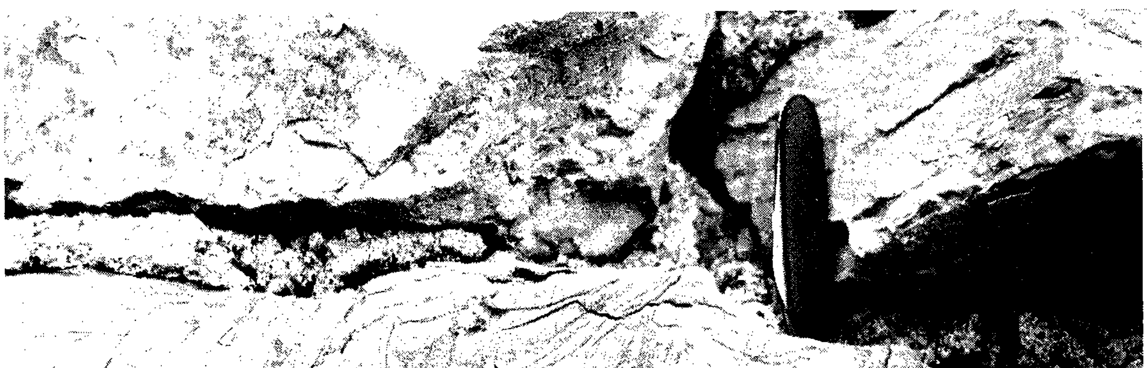

Figure 31. Block of Cool Creek Limestone used as building stone in gift-shop wall. Block has been emplaced upside down. Base of unit consists of vertically packed intraformational conglomerate (IFC), consisting of rod-shaped clasts of lime mud. Upper part of bed is composed of wavy-laminated micrite layers (algal-mat structures), alternating with quartz-rich laminae. Note erosive planar top surface of IFC bed on which laminated micrite and encrusting algae were deposited. Stop 3.

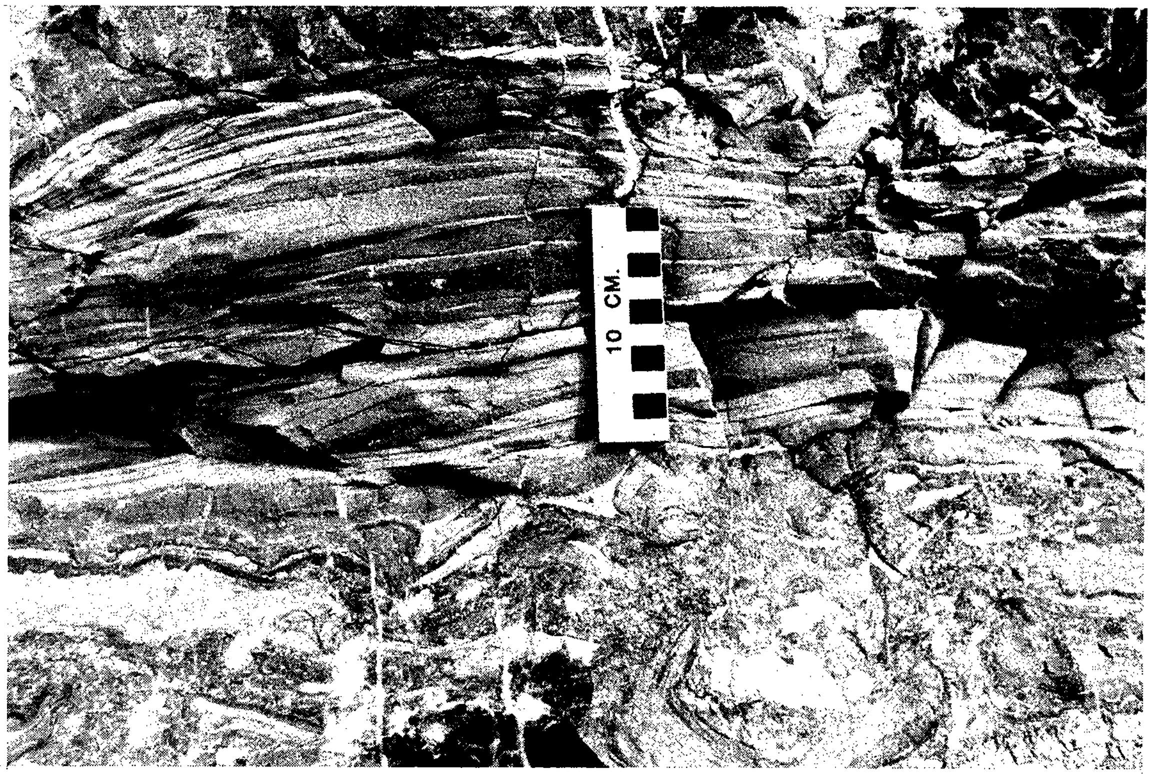

Figure 32. Base of unit marked by a storm deposit composed of intraformational clasts, minor quartz sand, and algal-boundstone fragments. The storm deposit is overlain by a heterolithic unit composed of alternating layers of lime mud and quartz-rich calcarenites. The extreme upper left corner shows part of a dendritic algal colony that grew after stabilization of the heterolithic unit. Stop 3.

observed. Some of the quartz-rich grainstones exhibit cross-bedding. Grainstones sometimes occur as infill between algal mounds and in heterolithic units interbedded with lime mudstone.

Packstones and wackestones are also a common facies in the Cool Creek. The allochems are dominated by well-sorted peloids, probably fecal pellets. Some of the beds display well-developed laminations; others are bioturbated.

Varying amounts of quartz sands are common in most of the Cool Creek lithofacies. The bedded quartz arenites are thin and commonly exhibit small-scale trough cross-bedding. The abundance of detrital quartz and the overall lack of sponge spicules in the Cool Creek imply that the detrital quarz may serve as the principal source for the abundant chert in the section.

Evidence for the former presence of bedded and nodular evaporites in the Cool Creek is extensive, despite their absence in outcrops. Evaporites in the subsurface Cool Creek have been reported. Chert is present in several beds and has replaced, in part, several of the lithofacies described above. Some of the chert nodules contain abundant molds and pseudomorphs after gypsum, anhydrite, and possibly halite. SEM studies by Ragland and Donovan (1984) have confirmed the presence of very small crystals of anhydrite and celestite in the pseudomorph-bearing cherts. Thick solution-collapse breccias also indicate the former presence of evaporites in the Cool Creek; those breccias are best seen in the thicker section exposed on the cliff below the gift shop. St. John and Eby (1978) noted that other evidence for hypersaline conditions and vanished evaporites--such as restricted faunas, high-relief stromatolites, syndepositionally broken ooids, and length-slow chalcedony--is less conclusive, but when combined with the breccias and chertified nodules, provides additional confirmation.

Depositional Environment:

The lithofacies and sedimentary structures of the Cool Creek Formation suggest that the formation was deposited in a hypersaline, peritidal, semi-arid or arid setting. Most lithofacies bear the imprint of tidal-flat (supratidal to shallow-subtidal) sedimentation, with periodic supratidal settings of sabkha-type, as evidenced by the evaporite relicts. The carbonate packages seem to exhibit some form of shoaling-upward cyclicity, but this is not proved.

The biota is dominated by blue-green-algae colonies that assist in delineating the regional paleoenvironment. The individual boundstone morphologies help to define more-subtle variations in the local paleoenvironment. Algal growth initially consisted of crusts and mats, probably confined to the supratidal zone or restricted bays subject to periodic clastic influx. Digital-stromatolite structures developed in the intertidal zone. In addition, the growth of some algal colonies resulted in laterally persistent beds of algal reefs. In the slightly deeper-water subtidal zone, cyclic growth of algal colonies resulted in a variety of stromatolitic textures, of which mounds were most common. In the subtidal zone, where the mounds were neither subaerially exposed nor subjected to significant clastic influx as regularly as growths near the shoreline, thrombolitic textures formed (Fig. 28). Growth forms intermediate between thrombolites and stromatolites developed in transitional-depth zones. Periodically, algal buildups were disrupted and perhaps destroyed by salinity extremes (vanished evaporite relicts and subaqueous shrinkage cracks), storms (intraformational conglomerates), and migration of sand shoals (quartz-rich arenites). Body fossils are rare, but burrowed lime mudstones containing abundant peloids are an abundant lithofacies. Possibly the growth of some algal colonies was inhibited by grazing invertebrates, particularly gastropods.

Stop 4

Buckhorn Asphalt Quarry

Buckhorn asphalt quarry; Deese Group, Boggy Formation, Desmoinesian.

Location:

About 4.5 mi (15 km) southeast of Sulphur, just west of Highway 177, Murray County, Sulphur South Quadrangle, SW1/4SE1/4SE1/4 sec. 23, T. 1 S., R. 3 E. (Fig. 6).

Significance:

- Asphalt-impregnated limestones containing one of the world's oldest pristine aragonitic molluscan faunas.
- Original nacreous luster of shells and aragonite mineralogy may provide a regional and possibly global geochemical standard for isotope stratigraphy.
- Excellent outcrops in the area afford documentation for interpreting structural styles associated with the Arbuckle Mountains.

General Historical Background of the Area:

The rock-asphalt deposits about 3 mi (10 km) south of Sulphur are known as the Buckhorn asphalt district. The asphaltic rocks were eagerly sought in earlier days and extensively used for road surfacing. Mining was particularly active before refiner's asphalt was available in quantities, but even as late as 1943 the district produced slightly more than 100,000 short tons per year of asphaltic rock. Total cumulative production exceeded 1 million tons before mining ceased around 1962.

More than 300 occurrences of heavy-oil- and bitumen-impregnated rocks have been reported in Oklahoma (Harrison and others, 1981). Of these, about 20% occur in south-central Oklahoma, in Carter and Murray Counties (i.e., the Buckhorn asphalt district). Harrison and others (1981) estimated that four areas of heavy-oil-sand deposits in Carter and Murray Counties may contain as much as 800 million barrels of oil. This is assuming a 10% saturation by weight and a 40-ft-thick unit. The Sulphur area alone may contain as much as 50% of the reserve estimates.

The Buckhorn asphalt district (South Sulphur asphalt district, Mill Creek syncline district, etc.) has an area of about 30 mi^2 (Eldridge, 1901). Asphalt impregnated sediments occur throughout the area in Ordovician rocks (Oil Creek Sandstone), as well as in Pennsylvanian rocks (Deese Group, Boggy Formation). The Oil Creek Sandstone contains the bulk of the bitumen in the South Sulphur area.

The two major quarry areas, Sulphur and Dougherty have been known for many years; they were exploited as sources of road paving material until 1958 and 1960, respectively.

Sulphur Area

The Sulphur area contains about 10 major quarries. Most of the bitumen occurs in the sandstone member of the Ordovician Oil Creek Formation (Fig. 9). The thickness of the member ranges from 130 to 440 ft (39-122 m). The Sulphur area has been worked since about 1890 and has yielded at least 1.5 million short tons of bitumen-bearing sandstone. The bitumen constitutes between 0.4 and 13.0 wt.% of the rock. The material from the Sulphur deposit was mixed with that obtained from Dougherty to produce a superior-quality asphalt for paving. The Sulphur deposit sporadically has been of interest to industry and has been evaluated by at least two major companies.

Dougherty Area

The Dougherty area is about 3 mi (10 km) southwest of the Sulphur area and consists of two major quarries. At this location, the bitumen occurs in the Ordovician Viola Limestone (Fig. 9). The Dougherty area also was being actively worked as early as 1890 and was operated more or less continuously until 1960. The bitumen content of the Viola Limestone at this location varies between 3.0 and 3.5 wt.%. Approximately 800,000 short tons of bitumen-impregnated limestone was removed from the Dougherty area by 1943; it is reasonable to assume that total production probably exceeded a million short tons.

General Structure of the Area:

The South Sulphur asphalt deposits are located on the northwest flank of the Arbuckle Mountains. The Reagan fault, a major left-wrench fault, lies 2.5 mi (8 km) to the south. The Mill Creek fault defines the northern limit of the district. These two major faults delineate the Mill Creek syncline.

Gorman and others (1944) interpreted the faulting in the area as horst-and-graben faulting. According to Williams (1983,1986) the basic structure in the district is a NE-trending anticline, possibly plunging SW, broken by thrusts and extensive high-angle reverse faulting; superimposed upon this, a thrust sheet from the northwest has left an erosional remnant or klippe.

Structural trends in the South Sulphur area apparently are related to stress orientations characteristic of right-wrenching. However, regional folds and faults fit a left-wrench system. This suggests that two distinct periods of different stress orientation have occurred in southern Oklahoma. These distinct stress periods may have resulted from varied convergence along the Paleozoic continental margin of the southern and southeastern United States. Some geologic evidence suggests that dominant left-wrenching occurred before right-wrenching; this is the view of workers who support wrench tectonics as the principal mechanism for explaining major structural features in southern Oklahoma.

General Geologic History of the Area:

The Buckhorn asphalt district is of classic importance because of its excellent exposures, affording the opportunity to document some major geologic concepts regarding the Arbuckle Mountains. A homoclinal sequence of Middle Pennsylvanian rocks (Desmoinesian, dated by fusulinids) disconformably overlie Late Mississippian sediments. Younger sediments (Morrowan and Atokan) have been eroded as a result of epeirogenic uplift of the craton. The Hunton anticline (Stop 5) in the northern part of the Arbuckle Mountains, approximately 6 mi (19.6 km) to the northwest, underwent uplift and erosion throughout Desmoinesian time and periodically contributed pebble-cobble conglomerates to the shallow marginal basins.

Just south of the Buckhorn quarry, the lower Desmoinesian conglomerates consist mostly of limestone clasts from the Hunton Group (Silurian-Devonian), whereas the middle Desmoinesian conglomerates consist predominantly of Viola Limestone (Ordovician) clasts, indicating a stratigraphic inversion resulting from progressive uplift of the source area.

Desmoinesian and older beds were folded during the mid-Virgilian Arbuckle orogeny, and the structures were unconformably covered by a gently dipping blanket of late Virgilian Vanoss Conglomerate. The Vanoss in this area is composed chiefly of boulders and cobbles from the Arbuckle Group (Cambrian-Ordovician), together with all rocks of the Arbuckle Mountains down to and including Precambrian granite. Fusulinid studies have been extremely helpful in ascertaining stratigraphic ages and correlations. A generalized geologic map of the Buckhorn asphalt quarry region is shown in Figure 33.

Buckhorn Asphalt Quarry:

The Buckhorn quarry is located along the crest of a hill north of the Defratus-Heltzel ranch house (Fig. 33). The quarry (Fig. 34) trends along the NE-striking beds; it was originally about 600 ft (183 m) long, 70 ft (21 m) wide, and 20 ft (6 m) deep on the average (Fig. 34). Asphaltic rocks of Oklahoma were reported by Eldridge (1901), and the fossils of the Buckhorn asphalt quarry were described by Smith (1938). Unklesbay (1962) updated the cephalopod taxonomy, and geochemical data on the fauna were reported by Stehli (1956), Lowenstam (1961,1964), Fisher and Teichert (1969), Crick and Ottensman (1983), Sadd (1986), Sadd and others (1986), and Brand (1989). However, the principal study of the quarry was conducted by Richard L. Squires (1973) for a Ph.D. dissertation when he was a student at the California Institute of Technology under the supervision of H. A. Lowenstam, a pioneer worker in shell geochemistry. The quarry was re-excavated by Squires, by means of bulldozers, back-hoe tractor, and dynamiting, in order to expose fresh bedrock surfaces for collecting. More than 1.5 tons of material was collected from the richest fossil-bearing bed in the quarry.

Middle Desmoinesian limestones of the Deese Group, Boggy Formation, are impregnated with asphalt that has beautifully preserved marine invertebrate fossils. As a result, the molluscan shells of the limestones retain their original aragonitic mineralogy, and the cephalopods retain, in addition, their original iridescence.

Lithofacies:

The Deese Group consists of about 1,299 ft (396 m) of marine shales and limestones with interbedded conglomerates. The top of the Deese Group is eroded and unconformably overlain by blanketing conglomerates of Virgilian age (Figs. 33,35). Lithofacies

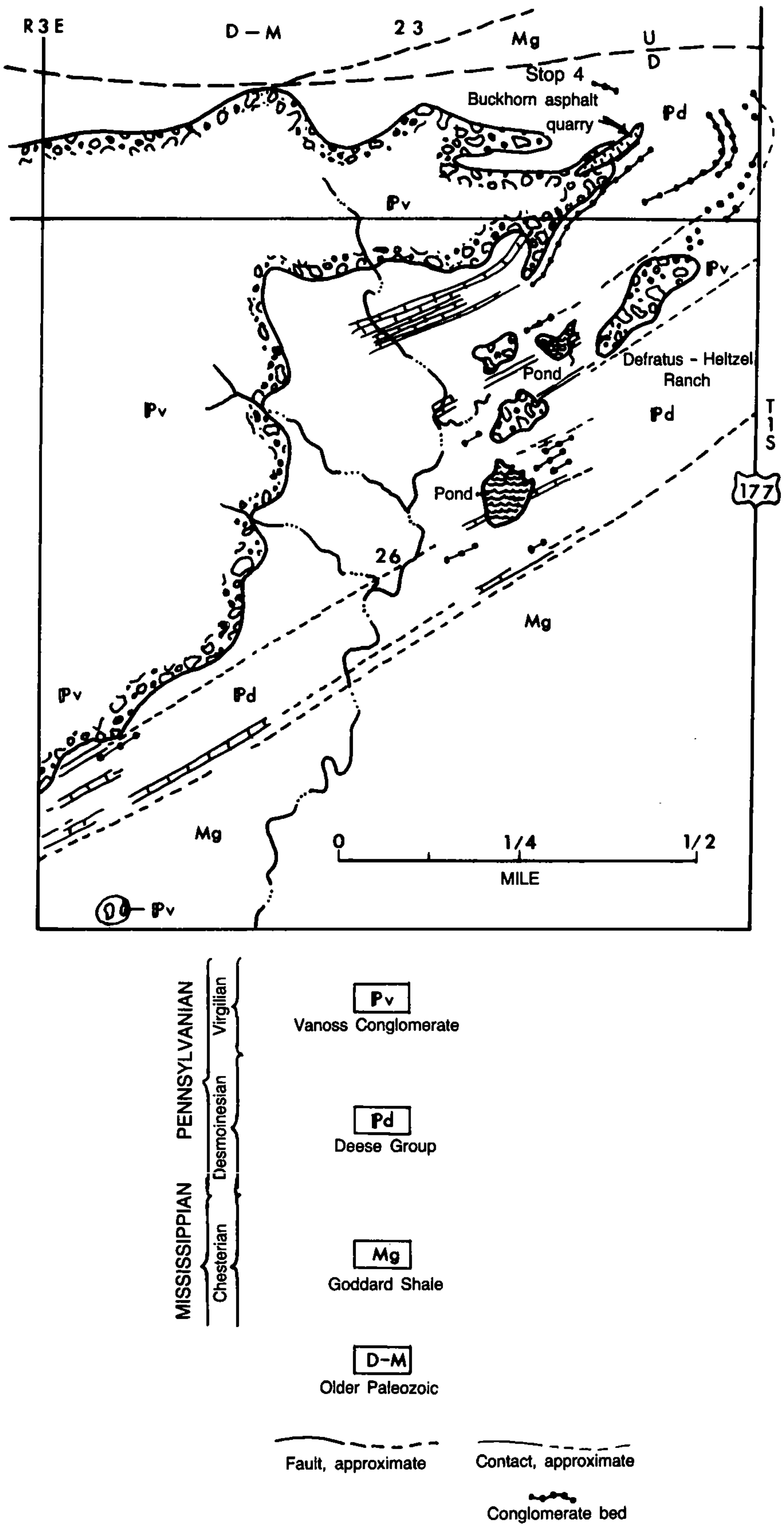

Figure 33. Generalized geologic map of the area around Buckhorn asphalt quarry. Stop 4. (Modified from Ham, 1969; Squires, 1973)

Figure 34. Buckhorn asphalt quarry, looking north, showing partial exposures of the asphalt-bearing Boggy Formation (Deese Group). Stop 4.

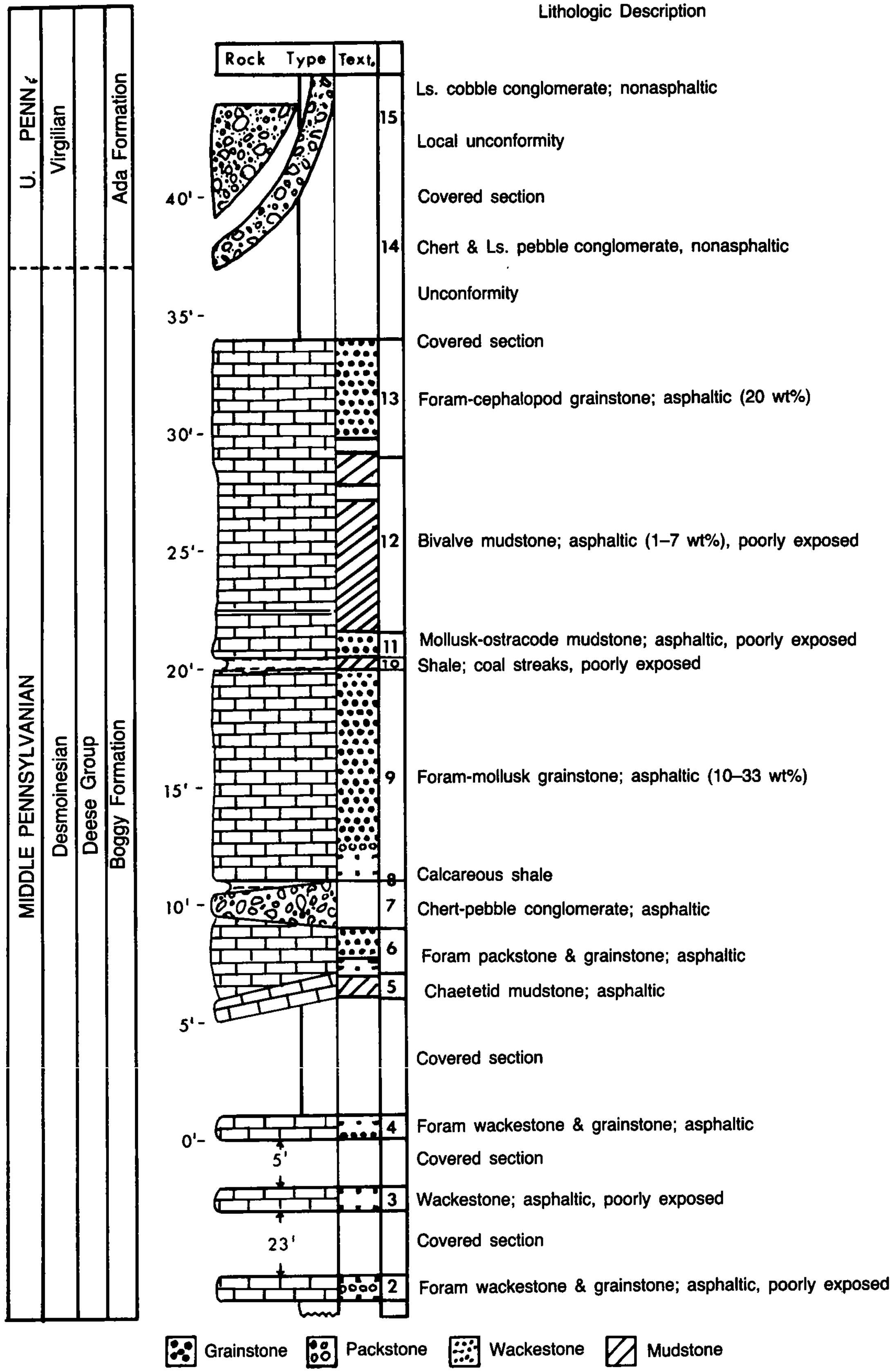

Figure 35. Generalized stratigraphic section of rocks exposed in the Buckhorn asphalt quarry. Stop 4. (Modified from Squires, 1973; Brand, 1989)

exposed in and near the quarry include (1) wackestones, (2) grainstones, (3) packstones, (4) mudstones, (5) calcareous shale, and (6) limestone-pebble conglomerates. A subordinate facies is represented by unit 10, a shale containing coaly streaks (Fig. 35). Most of the facies contain clasts composed of limestone and chert. Principal fossils present in most facies include mollusks, brachiopods, fusulinids, bryozoans, and plant remains. Orthocone cephalopods are particularly abundant. Other fossils reported include corals, ostracodes, sponge spicules, echinoderm fragments, and small foraminifera. Shell material is highly fragmented and preferentially aligned in one direction. The most fossiliferous unit is a foraminifera-mollusk grainstone/packstone found about 8 ft (2.4 m) above the base of the exposed section (Fig. 35, unit 6).

The main asphalt unit in the quarry is unit 9, a foraminifera-mollusk grainstone, for which Squires (1973) reported an asphalt content of 12 wt.%; Brand (1989) reported an asphalt content of 10-33 wt.% for the same unit. Figure 35 shows a generalized stratigraphic section of rocks exposed in the Buckhorn quarry; unfortunately, many of these units are now poorly exposed.

Depositional Environment:

Most of the fossils occur as fragments in predominantly skeletal grainstones, in the upper part of the section, which are inferred to be shallow, turbulent-water channel deposits (Squires, 1973). Underlying calcareous skeletal mudstones and wackestones were deposited in less-turbulent environments. A nearby terrestrial source is indicated by the rafted plant remains and logs in the quarry. Further evidence of marginal marine to nonmarine conditions is indicated by the admixture of marine and nonmarine fossils present in the channel-fill deposits. Periodic higher-energy conditions (e.g., storm surges) are suggested by abundant small-scale channels throughout the quarry cuts. In addition, some facies show definite evidence of cross-bedding.

Unit 7, a chert-pebble conglomerate, is probably a local channel deposit (Figs. 36, 37). The source for the chert clasts in the conglomerate may have been the Woodford chert (Devonian-Mississippian), based on lithologic similarity.

Probable Origin:

Asphalt-impregnated sediments of the Pennsylvanian Deese Group (Buckhorn asphalt) in the Buckhorn asphalt district, share some similarities with the nearby tar-sand bitumen of the Ordovician Oil Creek Formation. Both originated as oils emplaced during Middle to Late Pennsylvanian tectonic events (Arbuckle orogeny), when the two formations were juxtaposed by combined wrench and dip-slip faulting (Sadd and others, 1986). Biomarkers indicate that the two oils were generated from similar source rocks, both rich in terrestrial-plant organic matter, suggesting deposition in marine deltaic to shallow-shelf conditions. The absence of potential source rocks in the immediate area seems to favor migration, probably along faults, into the reservoir rocks, rather than local generation and accumulation. However, Deese asphalts (Buckhorn asphalt) differ from the Oil Creek bitumens in at least two important ways: (1) they are two to three times richer in asphaltenes (as much as 78%), and (2) they show considerable variation in sterane alteration at a given level of saturates and aromatics depletion. The variation in sterane alteration suggests that formation water-washing was more important to Deese alteration.

Figure 36. Exposure of Boggy Formation in quarry, showing slightly asphaltic chert-pebble conglomerate, unit 7, exposed along east wall of quarry; the overlying unit 9 consists of a highly asphaltic foraminifera-mollusk grainstone. Stop 4.

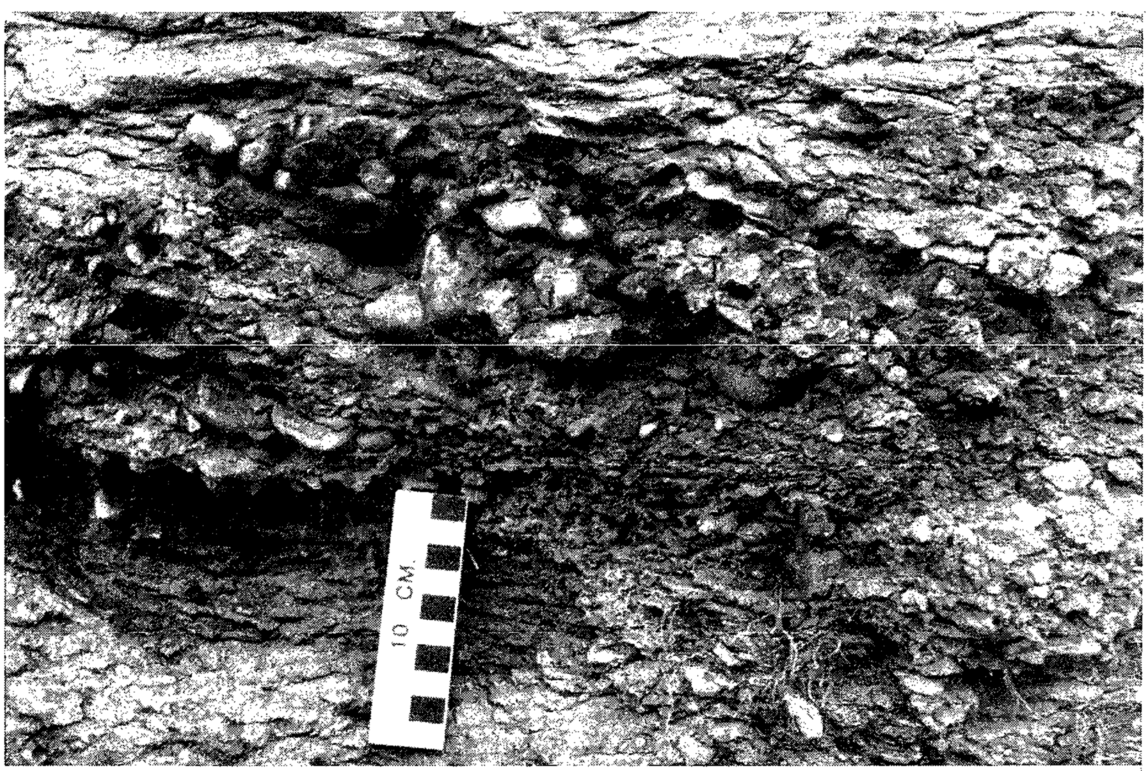

Figure 37. Closeup of chert-pebble conglomerate, unit 7; clasts are mostly chert, with some limestone.

General Preservation History/Geochemistry:

The fossiliferous rocks of the Boggy Formation are unusual because sealing of the unit by asphalt helped to preserve most of the fossils in their pristine state. Many fossil mollusks have retained their nacreous luster. Some shells show signs of chalkification or calcite replacement. These middle Desmoinesian rocks and fossils were impregnated with asphalt by the end of middle Virgilian time (Squires, 1973). This indicates that there was limited interaction between these rocks and fossils and either meteoric or marine waters in shallow and/or deep-burial environments. Squires (1973) noted the following diagenetic effects in the skeletal carbonates:

1) The amount of replacement calcite and degree of obliteration of shell microarchitecture in the skeletal aragonites increase with decreasing asphalt content;

2) Asphalt-impregnated skeletal calcites contain more Mg and usually less Sr than corresponding non-asphalt-impregnated specimens;

3) The Sr/Ca ratio for the best-preserved coiled nautiloids is similar to that for the modern *Nautilus*;

4) The Mg contents in the calcites of the foraminifera, bivalves, and ostracodes are similar to those in related Holocene forms; and

5) The shell walls of the extinct orthocone nautiloids have lower Sr contents than the cameral deposits.

Brand (1989) discussed the diagenesis of molluscan shells from the Buckhorn quarry based upon their geochemistry; he also related observed changes in shell mineralogy and microstructure to changes in biogeochemistry with increasing postdepositional alteration.

Stop 5
Hunton Anticline and Hunton Quarry

Hunton limestone quarry; Woodford Shale pit.

Location:

About 0.5 mi (0.8 km) east of Highway 110 and 0.5 mi (0.8 km) south of the dam of Lake of the Arbuckles, Murray County, Dougherty Quadrangle, C sec. 31, T. 1 S., R. 3 E. (Fig. 6).

Significance:

- Hunton-Woodford contact.
- Three-dimensional cross-sectional view of plunging anticline nose, with associated low-angle thrust fault and flank folds.
- Woodford Shale, an organic-rich shale that is an excellent petroleum source rock in the Anadarko basin.
- Small-scale model of tectonic style that influenced the Arbuckle anticline.

General Description:

At this stop, several interesting structures are exposed in the Silurian-Devonian Hunton Limestone (Figs. 38,39). The quarry provides a three-dimensional, cross-sectional view of a NW-plunging anticlinal nose with an associated low-angle thrust fault and many smaller flank folds. All of the structures developed during the Arbuckle orogeny (Late Pennsylvanian). Structures exposed here are typical of structures throughout the Arbuckle anticline (see Stop 1A).

The Hunton anticline is on the north flank of the Tishomingo uplift. The Reagan fault separates the uplift from the Mill Creek syncline to the north. On the south, the uplift is bounded by the Washita Valley fault and the Washita Valley syncline; both structures trend NW (N. 45° W. to N. 60° W.). Both the Tishomingo uplift and the Hunton anticline plunge NW. This small fold is one of several on the uplift whose axes are at 10-15° angles to the fault. Strata dip about 20° on both flanks of the anticline.

General Stratigraphy:

The units deformed in the Hunton anticline area range from the Viola Limestone (Ordovician) to the Woodford Shale (Devonian-Mississippian); however, the anticline is best developed in post-Sylvan rocks, namely, the Haragan-Bois d'Arc Formations (Hunton Group) of Early Devonian age and the Woodford Shale of Devonian-Mississippian age (Fig. 9). Some difference in the size of folds between the Bois d'Arc Formation and the Woodford Shale is shown at this stop. The size of the fold is simply related to the thickness of the more-competent layers that are folded: The Bois d'Arc Formation contains massive carbonate beds which form the major fold in the upper level of the quarry (Figs. 40,41); the Woodford Shale consists of thin, cherty layers interbedded with shale which form folds with much smaller amplitudes.

Although not well exposed at this stop, the Hunton-Woodford contact is an erosional unconformity. In places, the entire Hunton is absent. There is some evidence that thickness variations of the Hunton beneath the unconformity are controlled by the Reagan fault. The Woodford Shale lying unconformably on the Hunton Group in much of Oklahoma produces an ideal source-reservoir condition in many areas.

The Woodford Shale is an organic-rich unit that is at least in part lithostratigraphically equivalent to shales such as the Chattanooga, New Albany, Ohio, Antrim, and others in the central and northeastern parts of the U.S. In the Midcontinent region, the Woodford is exposed at relatively few localities but is widespread in the subsurface at depths as great as 27,000 ft (8,200 m). Typically, the Woodford Shale has organic-carbon values of 1-9 wt.% and extractable organic matter (EOM) yields as high as 6,000 ppm. Therefore, this unit is an excellent petroleum source rock.

Limestones in the Bois d'Arc Formation have been quarried from this site and used as rip-rap in building the Lake of the Arbuckles dam just 0.5 mi (0.8 km) north of the quarry (Fig. 39). The Woodford Shale has also been mined at this quarry as base material for county roads in the area.

Discussion:

The Hunton anticline is developed abruptly above the Arbuckle Group and is well

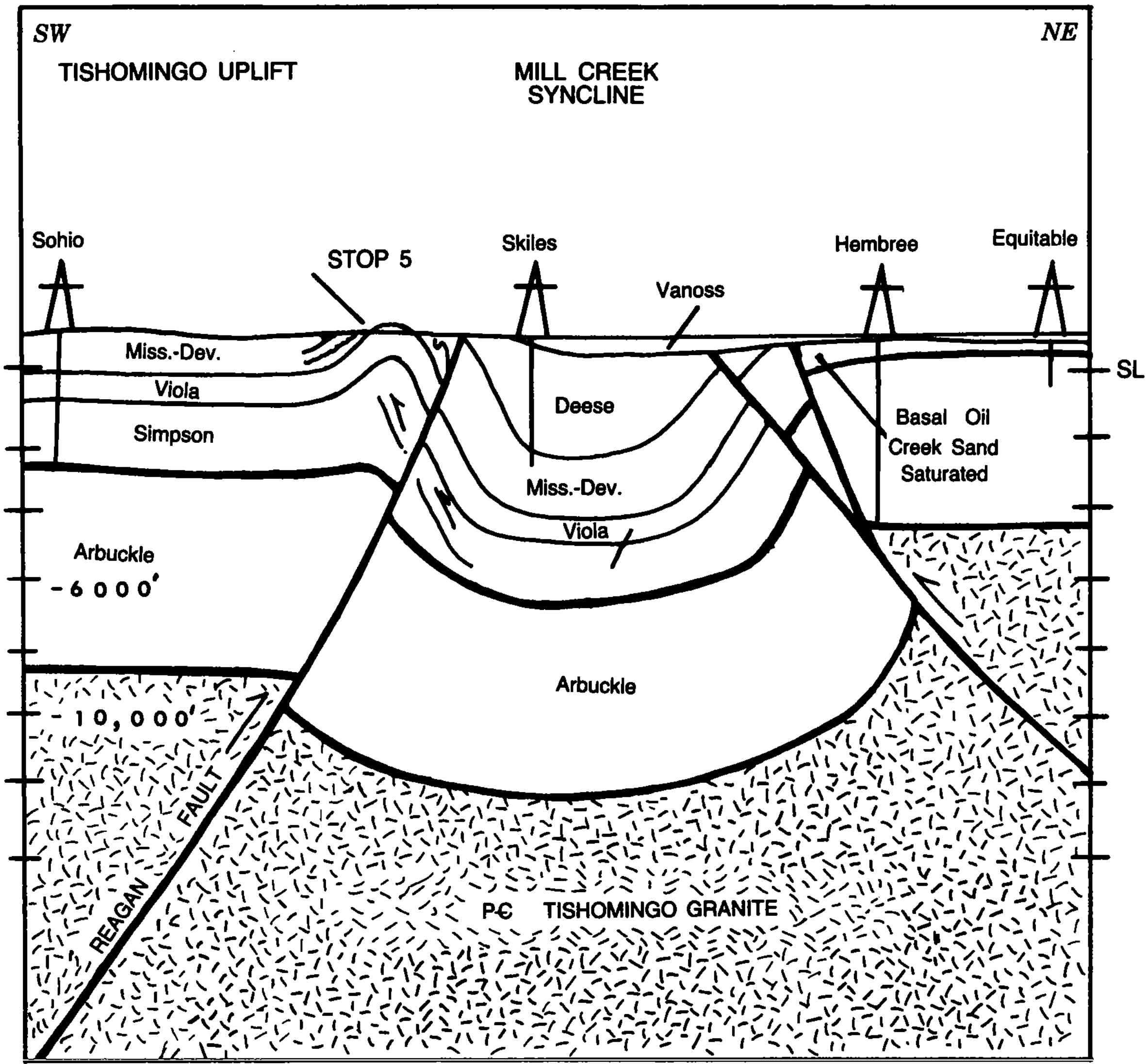

Figure 38. Structural cross section across the north flank of the Tishomingo uplift; note location of the Hunton quarry in the Hunton anticline on the hanging wall of the Reagan fault. Stop 5. (Brown, 1984)

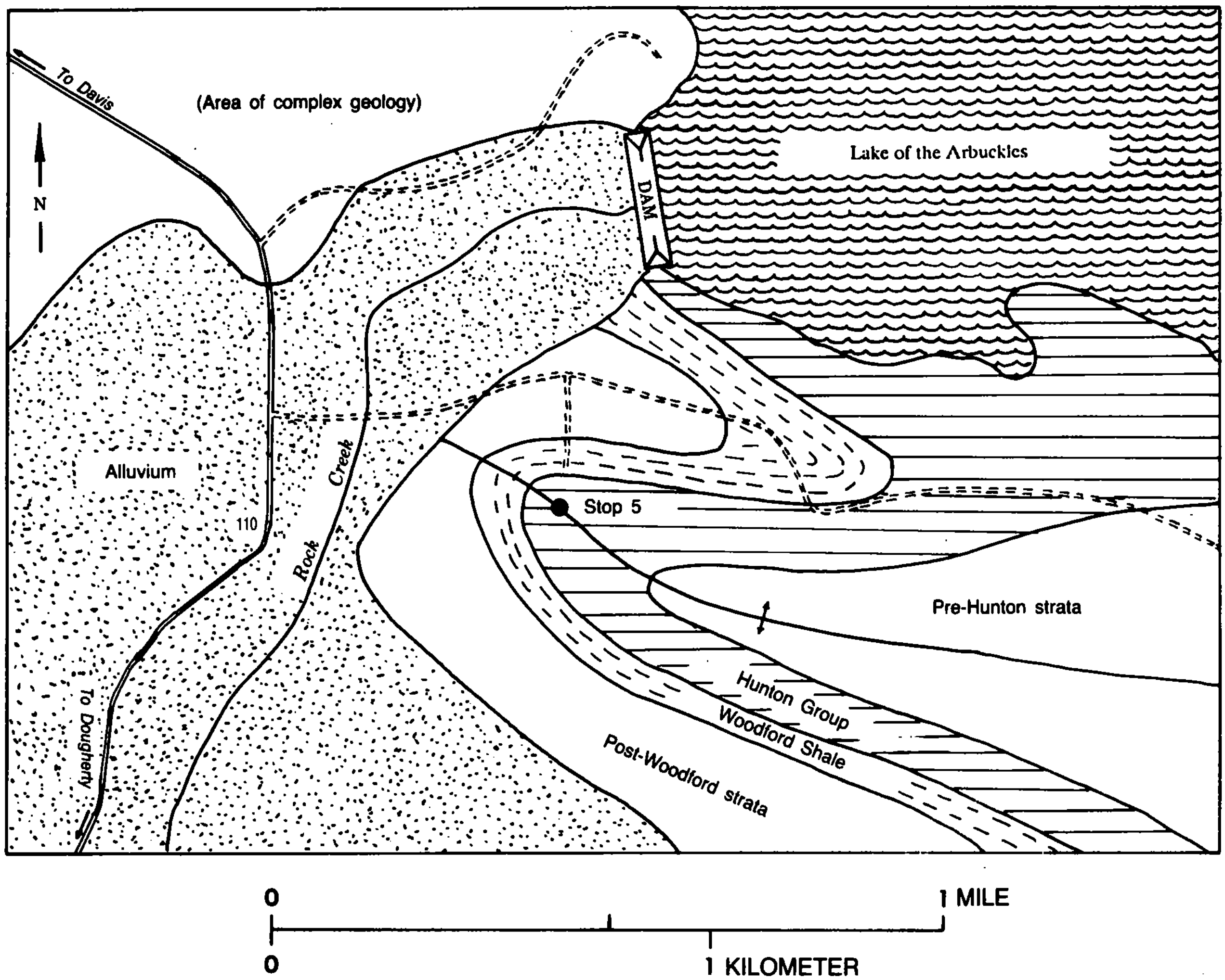

Figure 39. Generalized geologic map for Stop 5, showing the location of the quarry along the axis of the NW-plunging Hunton anticline. (Modified from Johnson and others, 1984)

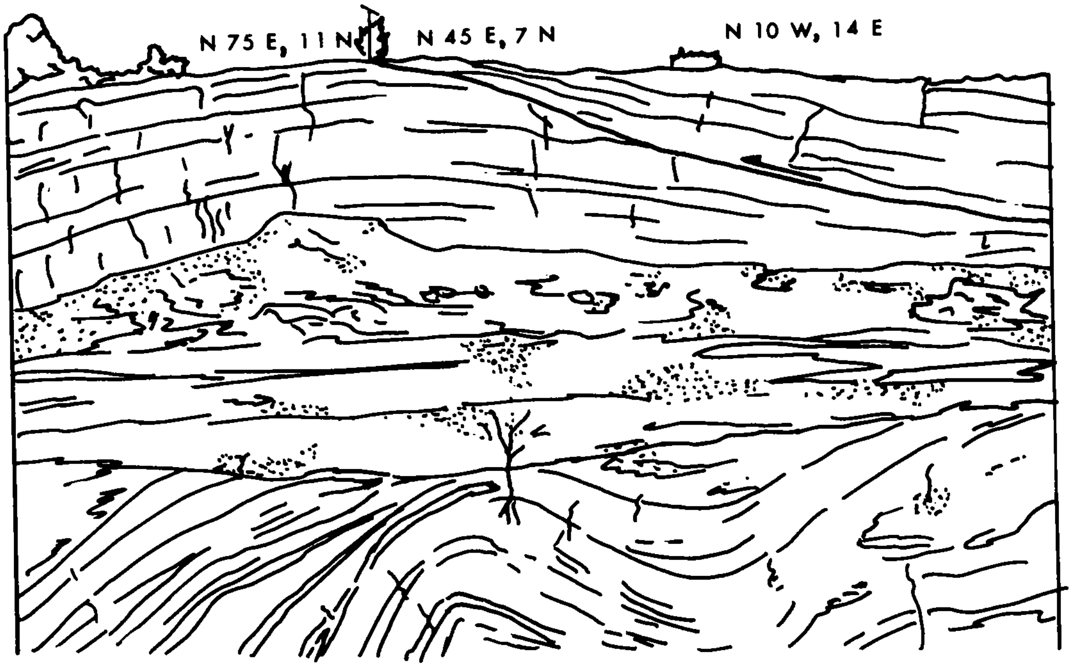

Figure 40. Diagrammatic sketch of quarry showing the low-angle thrust fault in the upper level of the quarry and typical Arbuckle-type folding style of beds in the lower level of the quarry (see Figs. 41,42). Stop 5.

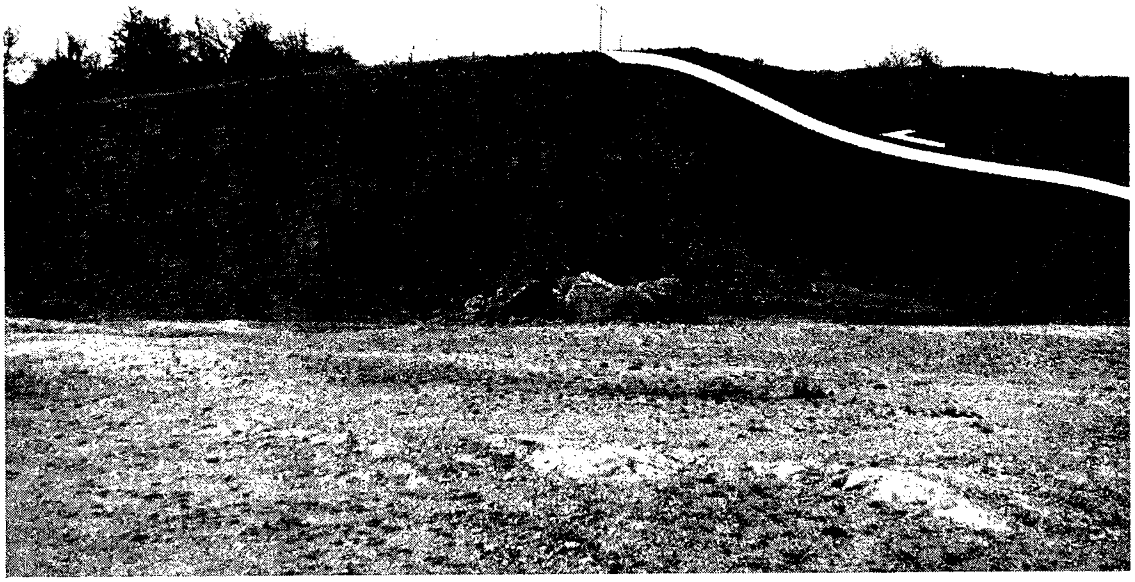

Figure 41. Upper level of the quarry, looking southeast along the axis of the anticline. Thrust fault dips about 30° S (right) and cuts the top of the quarry wall. Stop 5.

Figure 42. Typical Arbuckle-type folding in the Hunton Group, lower level of the quarry. Stop 5.

expressed in the Viola and younger sediments. Brown (1984) suggested that local detachment faulting in the shales of the Simpson Group aided in the growth of the fold. He stated that in foreland regions local bedding-plane slippage developed out of adjacent synclines where major structures plunge at rates exceeding 20°. The Tishomingo uplift is a major structure whose NW plunge increases from 10° to 15° in the southeast to a plunge of 25° or more in the northwest. Evidence of this bedding-plane slippage comes from the flank folds in the Hunton and overlying Woodford Shale, which can be seen in the lower quarry walls and surrounding areas. The small "drag folds" on the northeast flank of this anticline (lower quarry walls) and along the Reagan fault, attest to bedding-plane slip on the northeast flank of the structure (Fig. 42). Further evidence is provided by the small, low-angle thrust fault in the Hunton which is exposed on the upper quarry walls (Figs. 40, 41). This fault is directed obliquely up and across the axis of the south limb of the local anticline. The thrust dips about 30° toward the south, has a throw of about 30 ft (10 m), and passes through the axis of the fold at the top of the quarry face.

Brown and Islam (1984) suggested that the thrust fault is related to the growth of the syncline adjacent to and southwest of the Hunton anticline. The box-like form of the syncline dictates upward tightening of the units involved. This is a concentric (parallel) fold and results in flexural slip and bedding-plane thrusts.

The Hunton anticline appears to be a "rabbit ear" fold described by Tomlinson (1952) for the volume adjustment which takes place due to bedding-plane slip out of a syncline as a result of compressional stresses. This could be the result of a NE-SW compressional stress system in the Arbuckle Mountains. Figure 38, a cross section across the north flank of the Tishomingo uplift, demonstrates this relationship. Although this interpretation stems from the proposal of reverse dip-slip movement along the Reagan fault (Brown, 1984), the nature and amount of displacement along the fault remains a debatable subject.

Brown's thrust theory is supported by Austin (1970), who described the Reagan fault as having at least 10,000 ft (3,050 m) of reverse dip-slip movement, but the theory has been challenged by others, such as Ham (1954), Tanner (1967), Wickham (1978), and Haas (1981). Ham (1954) proposed that there is about 3 mi of strike-slip movement along the fault. Wickham (1978) noted that the relationship between the trends of folds such as the Hunton anticline and the trend of major, through-going faults such as the Reagan is important in distinguishing between wrench-fault tectonics and structures produced by horizontal compression or vertical uplift alone. Trends of folds associated with wrench faults occur at angles ranging from 10° to 40° to the trend of the wrench-fault zone. That pattern is evident along the Reagan fault where the folds, including the Hunton anticline, converge with the Reagan fault and commonly do not parallel it. The direction of convergence, to the northwest, indicates that the relative movement along the Reagan fault is left-lateral, consistent with the type of displacement indicated by the offset stratigraphic facies boundaries along the Washita Valley fault. Tanner (1967) and Haas (1981) concluded that the folds are an en echelon system suggestive of a left-lateral strike-slip fault zone.

It is quite apparent that more-detailed studies of the structures in the Arbuckle Mountains region are needed in order to determine the true nature of the movement along the faults, and therefore, the relationship of folding to faulting during the Arbuckle orogeny.

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