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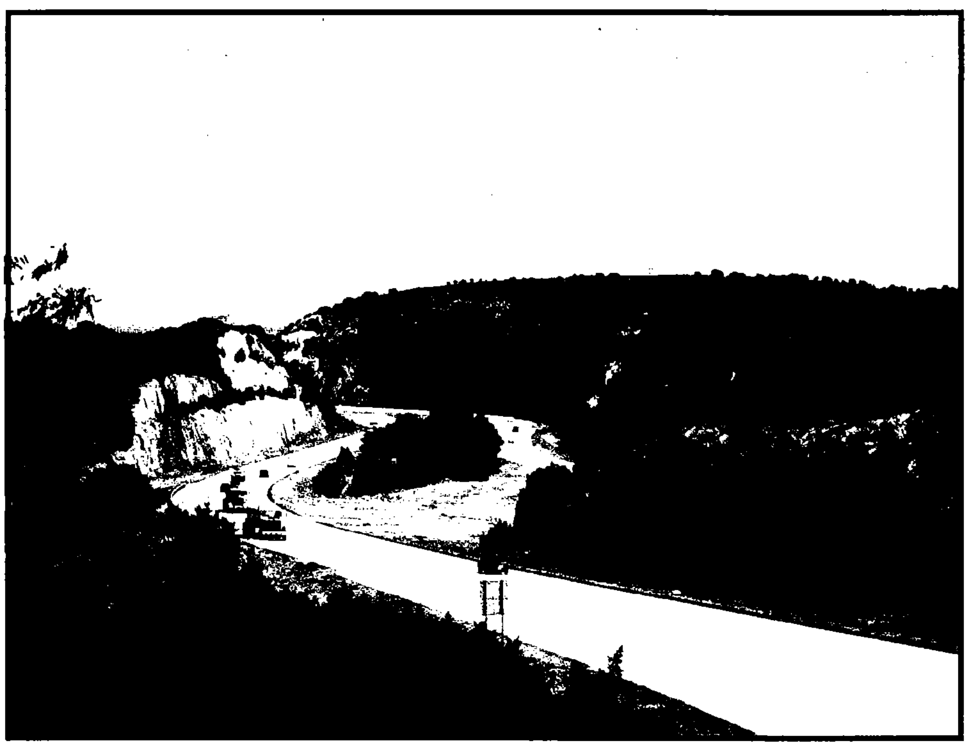
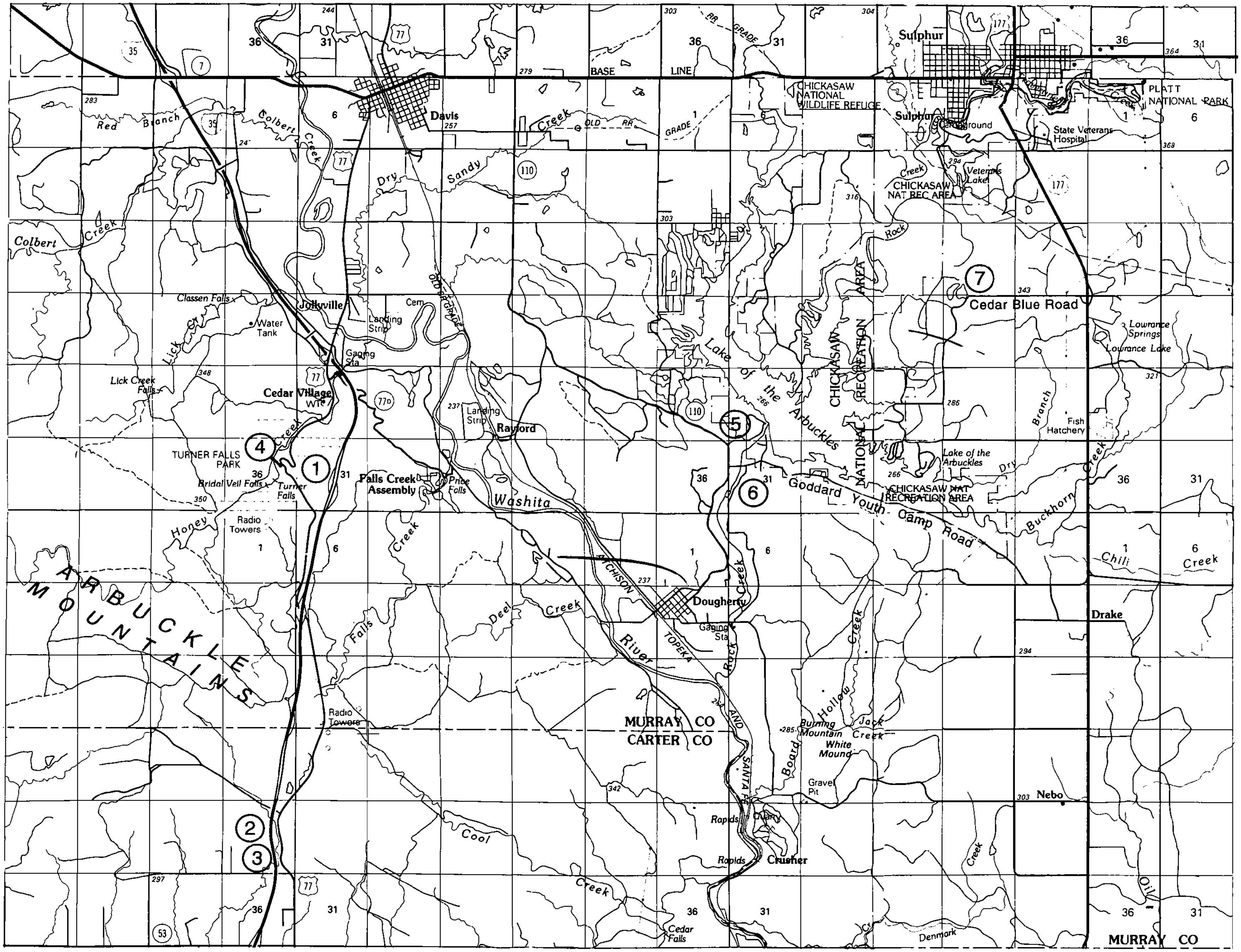
Guidebook for Selected Stops in the Western Arbuckle Mountains, Southern Oklahoma

Brian J. Cardott and James R. Chaplin





Road map showing stops for western Arbuckle Mountains field trip.

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Brian J. Cardott and James R. Chaplin

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Front Cover

Stop 1 view, looking north, of Interstate 35 and exposures of Collings Ranch Conglomerate, Viola Group, and Simpson Group.

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PREFACE

This guidebook has been prepared for the 10th annual meeting of The Society for Organic Petrology (TSOP) field trip to the western region of the Arbuckle Mountains on October 13, 1993.

Organic petrology is the branch of earth science dealing with the origin, occurrence, thermal maturity, composition, and utilization of sedimentary organic matter. Organic petrology includes coal petrology, kerogen petrology, organic geochemistry, petroleum geochemistry, palynology, and paleobotany. Therefore, the emphasis of this field trip is the organic petrology of selected rock units in the western Arbuckle Mountains.

The Arbuckle Mountains uplift geologic province, named for Brigadier General Matthew Arbuckle, is located in south-central Oklahoma as part of the Osage Plains of the Central Lowland physiographic province. The formations that comprise the Arbuckle Mountains have been extensively studied for hydrocarbon source rock and reservoir rock characteristics that can be applied to the subsurface in the adjacent Anadarko and Ardmore basins. The western Arbuckle Mountains region is an important petroleum region in its own right. More than 17,000 oil and gas wells have been drilled in each of Stephens and Carter Counties.

Numerous reports and guidebooks have been written about the Arbuckle Mountains. General publications include Ham (1969), Johnson and others (1984), Brown and Grayson (1985), Fay (1988,1989), Perry (1989), Ham and others (1990), and Keller and Reed (1993). The most detailed report on the regional geology of the Arbuckle Mountains is by Ham and others (1973).

Brian J. Cardott and James R. Chaplin

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We thank G. Eric Michael, Carolyn L. Thompson-Rizer, and Roger A. Woods of Conoco, Inc., Ponca City, Oklahoma, for geochemical data of the Viola Springs Formation along Interstate 35 (stop 2), the Woodford Shale along Interstate 35 (stop 3) and at the Hunton quarry (stop 6), the Viola Group limestone at the Dougherty district asphalt area (stop 5), and the Oil Creek sandstone at the Sulphur district asphalt area (stop 7).

We thank Gwen Sutton and Randy Kirby for permission to visit the Dougherty district and Sulphur district asphalt areas, respectively. We thank James D. Lance for permission to visit the Hunton quarry and Woodford Shale pit.

We thank Jane L. Weber, organic chemist at the Oklahoma Geological Survey, for critical review of portions of this guidebook and many helpful discussions on the organic geochemistry of field-trip samples.

Guidebook for Selected Stops in the Western Arbuckle Mountains, Southern Oklahoma

BRIAN J. CARDOTT AND JAMES R. CHAPLIN

GENERAL GEOLOGIC SETTING

Portions of the following sections are adapted from Ham (1969) and Ham and others (1973).

The Arbuckle Mountains are located just north of the Texas/Oklahoma border in south-central Oklahoma (Fig. 1). The Arbuckle Mountains region offers some of the best exposures of lower Paleozoic rocks in the North American Midcontinent. The Paleozoic outcrops (Cambrian–Pennsylvanian) along Interstate 35 (formerly U.S. Highway 77) have become classic geologic exposures in that they are exceptional in their thickness, lateral continuity, and excellent exposure. Reference to the Arbuckle outcrops as the Arbuckle Mountains is somewhat misleading since ~80% of the province consists of gently rolling plains. Only in the western part of the province is reference to the Arbuckle outcrops as "mountains" perhaps warranted; there the Arbuckle anticline attains an altitude of 1,377 ft (420 m), the highest elevation in the Arbuckle Mountains, with a total relief of 607 ft (185 m).

The Arbuckle Mountain geologic province consists of ~1,000 mi^2 of outcrop composed of a huge inlier of folded and faulted Precambrian rocks and ~30,000 ft (9,200 m) of fossiliferous Paleozoic sedimentary rocks ranging in age from Cambrian through Late Pennsylvanian. The sedimentary rocks are composed mostly of carbonates that constitute the best outcrops and greatest area of exposure of this marine sequence in all of the Midcontinent and perhaps the world. The sedimentary-rock column within the southern Oklahoma aulacogen (SOA) is about seven times thicker than coeval rocks on the adjacent craton. The Arbuckle Mountains are covered on the east, north, and west by gently westward-dipping Pennsylvanian and Permian strata, and on the south by gently southward-dipping Lower Cretaceous sediments of the Gulf Coastal Plain province (Fig. 1).

GENERAL GEOLOGY

The oldest rocks in the Arbuckle Mountain region are igneous rocks exposed in the core of the Tishomingo anticline (Fig. 2), which are dated to be ~1.35 b.y. old. The 150 mi^2 exposure of Precambrian granites in the eastern Arbuckle Mountains is the largest and best outcrop of such rocks in the central United States between the Llano region of Texas and the Black Hills of South Dakota. In some parts of southern Oklahoma (e.g., Arbuckle anticline), the basement rocks are unique in that they are exposed around the margin of a profound aulacogen, and are composed of igneous flows and intrusives of Cambrian (525 m.y. old), rather than Precambrian age.

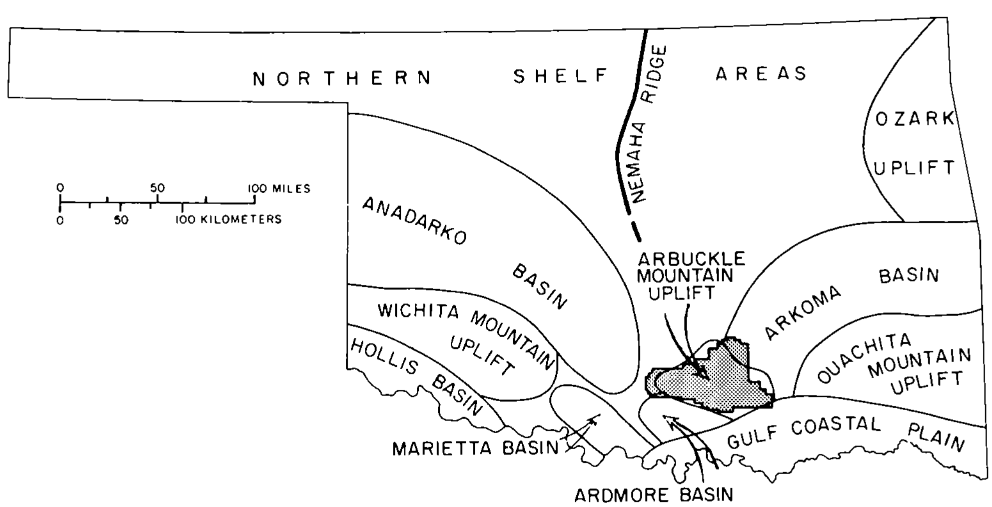


Figure 1. Geologic provinces map of Oklahoma (from Ham and others, 1990). The shaded area is illustrated in detail in Figure 2.

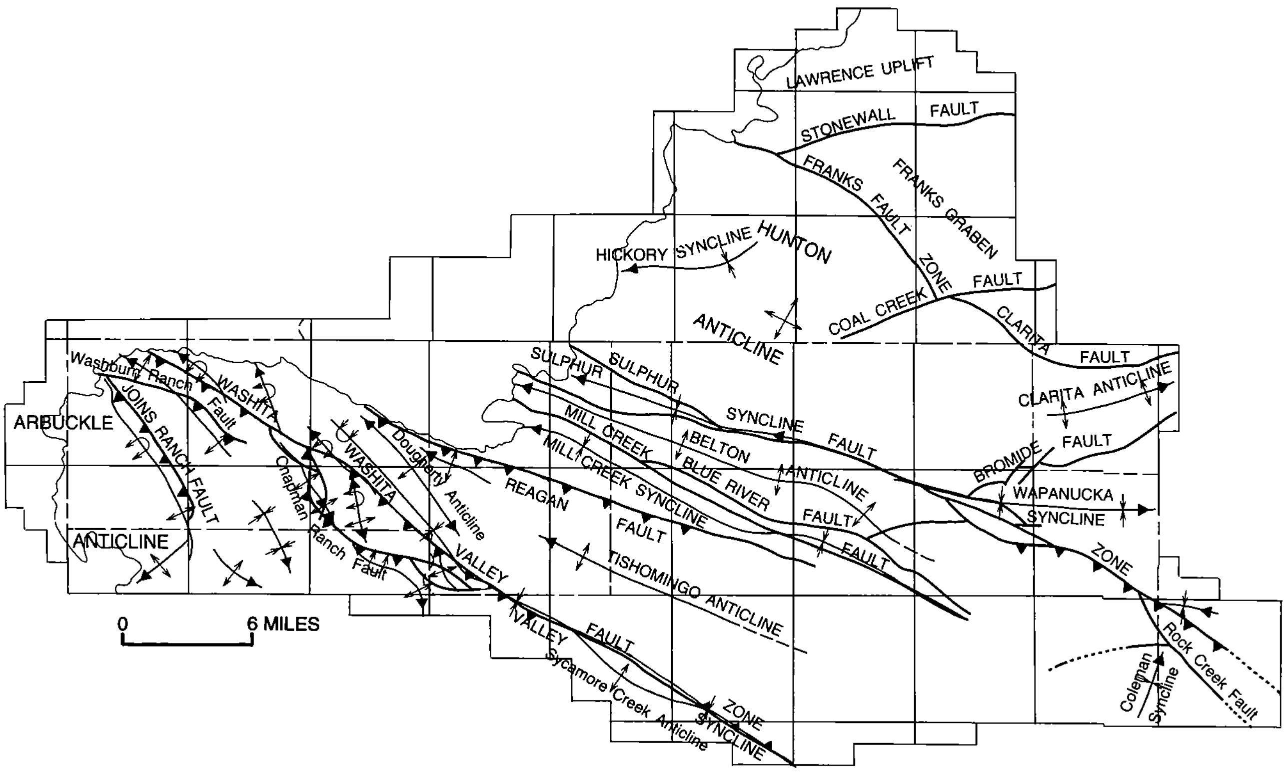


Figure 2. Index map of Arbuckle Mountains showing principal structural features (from Ham and others, 1990). Location of this area is shown (shaded) in Figure 1.

Pre-Devonian sedimentary rocks of the Arbuckle Mountains primarily comprise a thick (11,000-ft [3,400-m]) sequence of cyclic platform carbonates interbedded with minor clastics of the Gondwana passive margin (Fig. 3). Because of late Paleozoic structuring of the Gondwana margin, present-day exposures occur in updip shelfal positions and lack internal stratal geometries across depositional strike. The pre-Devonian rocks are dominantly limestones in the aulacogen and dolomites upon the craton.

The younger rocks of the lower Paleozoic carbonate sequence in southern Oklahoma are those of the Hunton Group of Late Ordovician, Silurian, and Early Devonian age. The Hunton Group has an average thickness of about 100–350 ft (30–110 m) at most localities in the Arbuckle Mountains. The group is much thinner than older sequences, in part because of the numerous unconformities within and at the top of the sequence. The thickness of the Hunton Group is related more closely to the position of isolated cratonic basins and to the effectiveness of the several unconformities, than to the localization within a through-going trough. Depositional patterns of Silurian and Devonian strata differ from those of older and younger sequences of the southern Oklahoma aulacogen. Neither the Hunton Group nor the overlying Woodford Shale are appreciably thicker in most parts of the aulacogen than upon the craton (Ham, 1969).

Late Paleozoic strata (Woodford Shale, Sycamore Formation, Delaware Creek Shale, Goddard Formation, Springer Formation), of Late Devonian–Mississippian age, are dominated by dark shales deposited in a deeper-water anoxic environmental setting. The dark-shale succession is 6,000 ft (1,800 m) thick in the southern Oklahoma aulacogen; slightly more than 5,500 ft (1,700 m) is Mississippian. On the craton, coeval Mississippian dark shales are ~650 ft (200 m) thick. The dark shales are commonly interbedded with poorly fossiliferous, silty limestones. Some of the impure limestones are thick and massive.

Southern Oklahoma was again the site of abnormally thick sedimentation during the Pennsylvanian. The southern Oklahoma aulacogen received locally as much as 15,000–17,000 ft (4,600–5,200 m) of shales, sandstones, and generally thin limestones. Equivalent beds upon the craton are ~3,000 ft (900 m) thick and consist of shales, sandstones, and a much greater relative thickness of limestones as compared to the SOA. Rocks of Pennsylvanian age crop out around most of the Arbuckle Mountains. Pre-Desmoinesian Pennsylvanian rocks within and adjoining the Arbuckle Mountains generally are non-conglomeratic; however, Desmoinesian and younger Pennsylvanian rocks are conglomerate-bearing and record the beginning and close of mountain-building in the Arbuckle Mountains (Fritz and others, 1993).

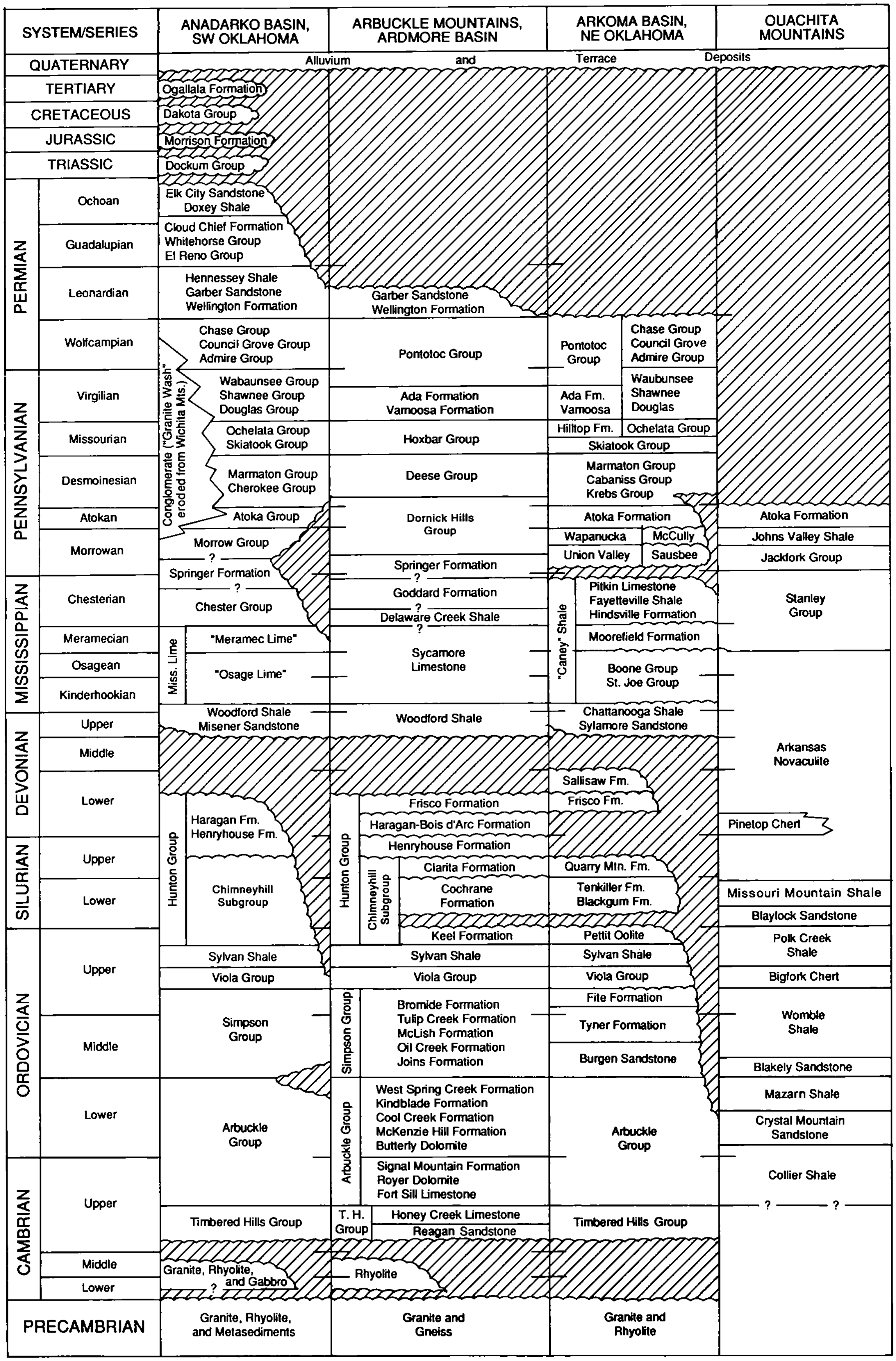


Figure 3. Generalized correlation of rock units in Oklahoma (from Johnson and Cardott, 1992b). Height of boxes is not related to thickness of rock units.

SOUTHERN OKLAHOMA AULACOGEN TECTONIC SETTING

Portions of the following section are adapted from Brown and Grayson (1985) and Tapp (1991).

Southern Oklahoma contains the most accessible, best exposed, and best understood aulacogen in the United States. The southern Oklahoma aulacogen (SOA) is the deepest sedimentary trough in North America, filled to a thickness of at least 45,000 ft (13,700 m) (Ham, 1969). The SOA trends N 60° W from southeastern Oklahoma ~250 mi (400 km) into the Texas Panhandle. Aulacogens preserve the igneous and sedimentary rocks that record the opening and closure of ocean basins. Rocks in the aulacogen are usually preserved without metamorphism, and thus they contain invaluable information about the evolution of continents. Nickolai Shatsky (1946) first defined the term "aulacogen" as a long-lived, fault-bounded trough in an otherwise stable platform that intersects a deformed belt or a continental margin at a high angle. Shatsky (1946) described the Dnieper–Donets basin of the Russian platform and the Arbuckle–Wichita system as type aulacogens. An aulacogen contains an abnormally thick, usually undeformed, section of continental and marine sediments. According to Shatsky (1947), aulacogens are distinct geotectonic features with complex evolutionary histories that are genetically related to geosynclines but are not easily explained by geosynclinal theory. Milanovsky (1981, p. 213) redefined the term "aulacogen" as "linear graben-like depressions of ancient platforms" and allowed for later inversions and cover of the structure.

Ham and others (1964) named this feature (SOA) the "southern Oklahoma geosyncline" and stated that the Arbuckle–Wichita trend evolved through three separate geosynclinal stages to reach its final configuration. According to Ham and others (1973), 17,000 ft (5,200 m) of Upper Cambrian through Mississippian sediment accumulated in the SOA. The combination of continued subsidence and periodic orogenic activity led to a further accumulation of 13,000 ft (4,000 m) of mostly terrigenous clastic sediment during the Pennsylvanian. This combined total of 30,000 ft (9,100 m) of sediment was folded and faulted during the deformation stage of the aulacogen to become the present-day Arbuckle Mountains.

The tectonic significance of the SOA was first recognized by Hoffman and others (1974) who presented evidence for the evolution of an aulacogen using the Athapuscow aulacogen and the SOA as examples. The evolution of an aulacogen is divided into three stages: (1) rifting, followed by (2) subsidence and infilling of the rift, and finally, (3) deformation of the rocks in the ancient rift.

The SOA apparently developed during Late Proterozoic–Early Cambrian rifting of the southern continental margin. This margin appears to be related to the Grenville suture formed when the Llano terrane was accreted to North America. The SOA is representative, as well as the best exposed, of a series of penecontemporaneous rifts along the southern and eastern margins of the North American plate. The only likely exposed boundary of the rift is the Washita Valley fault zone in the Arbuckle Mountains (Fig. 2); this structure juxtaposes Precambrian granite and the equivalent of the Carlton Rhyolite.

Pronounced Pennsylvanian structural inversion, at least in part, resulted in the formation of a series of linear uplifts, notably the Wichita, Arbuckle, and Criner uplifts (Fig. 4). The inversion lifted the igneous basal sections of this rift (SOA) to shallow crustal levels and exposed parts of it in the Wichita Mountains (Fig. 1). Contemporary basins filled with syntectonic sediments abut these uplifts. As much as 39,000 ft (11,900 m) of strata are preserved in the deep Anadarko basin, ~29,500 ft (9,000 m) in the Ardmore basin, and ~26,000 ft (7,900 m) in the southern parts of the Arkoma and Marietta basins (Fig. 1).

Deformation Stage of Southern Oklahoma Aulacogen Orogenic Conglomerates

Portions of the following section are adapted from Ham (1954,1968) and Brown and Grayson (1985).

The deformation stage of the SOA is evidenced by several orogenic conglomerates in the Arbuckle Mountain region (Table 1). These conglomerates are primarily Pennsylvanian in age; however, orogenic activity in this region began as early as Late Mississippian (Chesterian) time, as recorded by cherty conglomeratic limestones (Springer Formation) deposited in the Criner Hills region (Fig. 4). Several pulses of uplift indicated in the Pennsylvanian sediments suggest that the segments of southern Oklahoma were uplifted at different times.

Late Mississippian (Chesterian)

The initial orogenic stage of the SOA began in Late Mississippian to Early Pennsylvanian time and exposed a land mass along the Wichita Mountains–Criner Hills chain. Syntectonic cherty conglomeratic limestones within Late Mississippian sediments (Springer Formation) suggest that this activity began in the Chesterian. A syncline developed where the Ardmore basin and Arbuckle anticline are presently located.

Pennsylvanian (Morrowan and Atokan)

This synclinal basin accumulated sediments of the Dornick Hills Group, including syntectonic conglomerates of the Joliff (Morrowan) and Bostwick (Atokan) units (Table 1). The source area for these sediments is believed to have been the Criner Hills which underwent uplift separating the southeastern portion of the SOA into the Ardmore and Marietta basins. At the same time, uplift of the Hunton and Tishomingo anticlines occurred. A syncline developed between them during Atokan time and collected sediments now preserved in the Mill Creek syncline (Fig. 2).

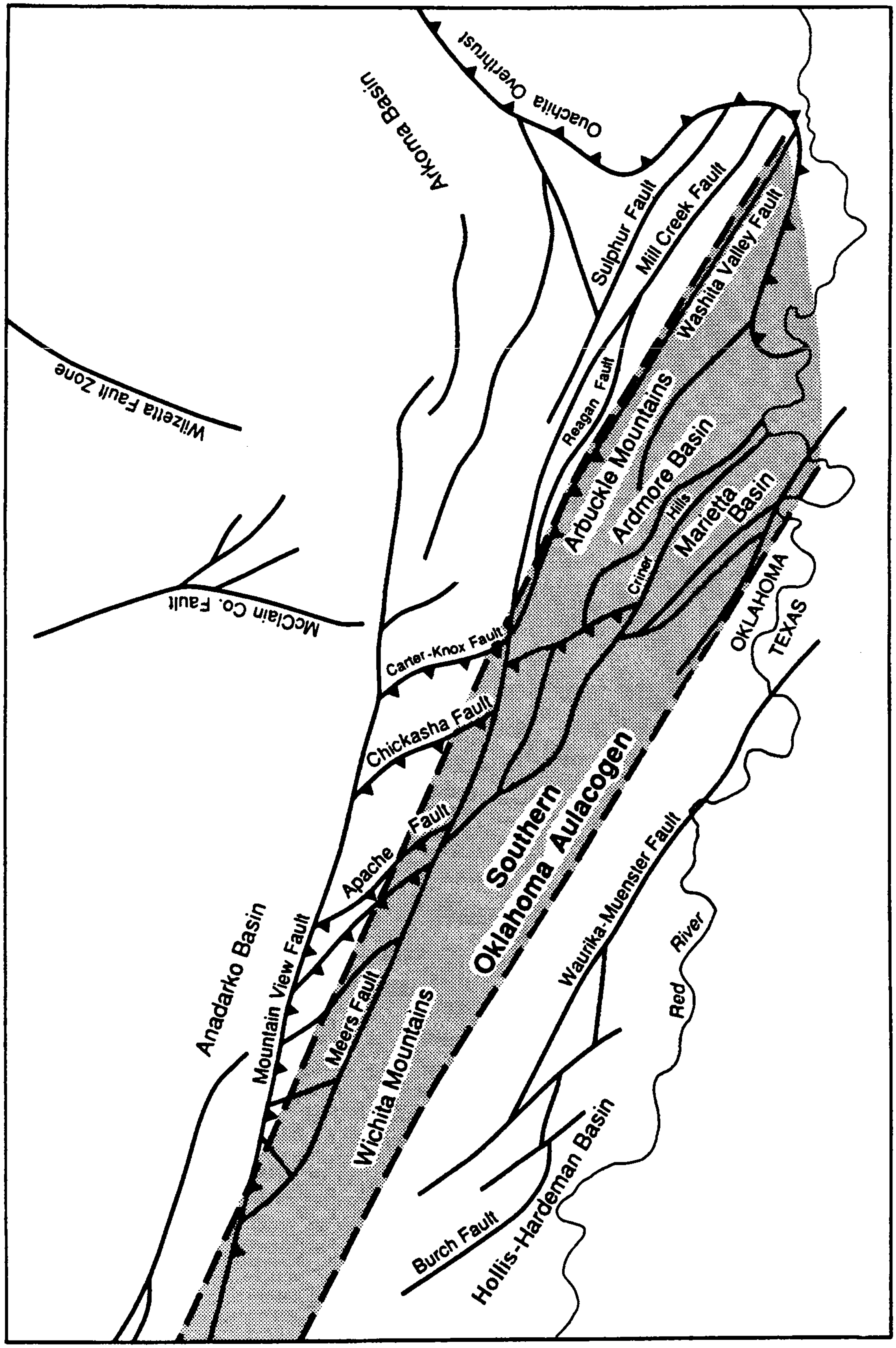


Figure 4. Major faults and structures of southern Oklahoma (adapted from Axtmann, 1983).

TABLE 1. — ASSOCIATION OF MAJOR TECTONIC/DEPOSITIONAL EVENTS IN THE SOUTHERN OKLAHOMA AULACOGEN

Geologic age	Tectonic event(s)	Depositional event(s)	Location	Preserved record
LATE PRECAMBRIAN/ EARLY CAMBRIAN	• initial rifting stage of aulacogen	• emplacement of both extrusive/ shallow intrusive rocks		Carlton (Colbert) Rhyolite Group
	• initial rapid subsidence stage of aulacogen	• volcanic field with original areal extent of 15,000 mi^2	core of Arbuckle anticline	
		• local thickness $\leq$4,500 ft		
		• development of passive continental margin	site of present-day Ouachita fold belt	
EARLY TO MIDDLE CAMBRIAN		• intrusion and extrusion of a bimodal suite of igneous rocks		Glen Mountain Complex Carlton (Colbert) Rhyolite Group
MIDDLE TO LATE CAMBRIAN	• initial zone of crustal mobility forming a WNW-trending rift presumably bounded by normal faults inherited from a Precambrian basement weakness			Carlton (Colbert) Rhyolite Group
LATE CAMBRIAN	• major marine transgression along the western margin of the opening Iapetus Ocean			Honey Creek Limestone
	• rapid subsidence of SOA relative to sedimentation rate	• initial siliciclastic pulse		Reagan Sandstone
LATE CAMBRIAN/ EARLY ORDOVICIAN	• subsidence of SOA approximately equaled by sedimentation rate	• major production of thick, cyclic shallowing-upward tidal flat/subtidal carbonate successions		Arbuckle Group
MIDDLE ORDOVICIAN	• subsidence of SOA approximately equaled by sedimentation rate	• short-lived periods of siliciclastic sedimentation in nearshore settings		Simpson Group
LATE UPPER ORDOVICIAN	• SOA begins to subside more rapidly	• lower and middle parts suggest deeper water sedimentation; upper part shows shallow-shelf sedimentation		Viola Group
LATE ORDOVICIAN/ LATE SILURIAN/ EARLY DEVONIAN	• subsidence of SOA approximately equaled by sedimentation rate/minor vertical adjustments of SOA element	• transition from dominantly carbonate deposition to clastic deposition		Sylvan Shale
		• periodic emergence events produce several local unconformities		Hunton Group
LATE DEVONIAN/ EARLY MISSISSIPPIAN	• renewed rapid subsidence of SOA	• deeper water, black, siliceous organic-rich shale sedimentation		Woodford Shale
	• major transgression with associated long-lived anoxic event	• deposition of micritic limestone		Sycamore Limestone
MISSISSIPPIAN/ EARLY PENNSYL-VANIAN	• dismemberment of the craton begins			
	• continued rapid subsidence of SOA maintains deeper water conditions			Delaware Creek & Goddard Shales
Late Mississippian (Chesterian)	• initial orogenic state of SOA	• deposition of synorogenic cherty conglomeratic limestones	Criner Hills	Springer Formation
PENNSYLVANIAN/ EARLY PERMIAN	• periodic, but significant, deformation of the SOA			Vanoss Conglomerate
	• areas of Precambrian granites uncovered for the first time in Early Pennsylvanian	• major orogenic pulses recognized by deposition of several tectonic conglomerates		Collings Ranch Conglomerate

	• reactivation of old faults bounding the Cambrian rift • partial inversion of SOA forming the Wichita, Criner, and Arbuckle uplifts • partial enhancement of SOA to form the Anadarko, Ardmore, and Marietta basins			Warren Ranch Conglomerate Devil's Kitchen & Rocky Point Conglomerates Franks Conglomerate Bostwick Conglomerate Joliff Conglomerate
PENNSYLVANIAN Morrowan/Atokan	• separation of southeastern portion of SOA into the Ardmore and Marietta basins	• deposition of syntectonic conglomerates sourced from the Criner Hills	preserved in synclinal basin (present-day Ardmore basin/Arbuckle anticline region)	Dornick Hills: Bostwick Conglomerate (Atokan) Joliff Conglomerate (Morrowan)
early Atokan	• main Wichita orogeny • uplift along Amarillo/Wichita/Criner trend • exposure of Cambrian igneous basement rocks			
early Desmoinesian	• initial epeirogenic uplift of Arbuckle area • first emergence of Hunton anticline • folding and faulting along Ouachita front	• deposition of syntectonic conglomerate sourced from Hunton, Tishomingo, and Belton landmasses • deposition of syntectonic conglomerates in synclinal graben sourced from Ouachita front	Franks graben and Mill Creek syncline Lake Murray region	Franks Conglomerate (Deese Group) Devil's Kitchen & Rocky Point Conglomerates (Deese Group)
late Desmoinesian/ early Missourian	• sediment shed from uplift of Hunton anticline	• deposition of syntectonic conglomerate in synclinal graben from cannibalism of uppermost Arbuckle Group through Hunton Group	Arbuckle Mountain region	Warren Ranch Conglomerate (Deese Group)
late Missourian/ early Virgilian	• major Arbuckle orogeny • rejuvenation of folds in Wichita system • continued uplift/faulting of Hunton, Tishomingo, and Belton anticlines	• early Virgilian beds presumably were eroded leaving no preserved record in the Ardmore basin		
middle Virgilian	• late phase of Arbuckle uplift, chiefly faulting; probably the strongest pulse of Arbuckle orogeny • folding and overturning of Deese conglomerates	• deposition of syntectonic conglomerate in synclinal graben from cannibalism of middle and upper parts of the Arbuckle Group • first and thickest orogenic deposit of the Arbuckle anticline	northern part of the Arbuckle anticline region	Collings Ranch Conglomerate
late Virgilian	• termination of major deformation in the Arbuckle Mountain region • first unroofing of the Precambrian granites in the Arbuckle Mountains	• deposition of posttectonic conglomerates that contain arkose, granite, feldspar, and vein quartz from Precambrian granites • final detrital products of Pennsylvanian deformation	northern margin of Arbuckle Mountains	Vanoss Conglomerate
PERMIAN	• Arbuckle Mountains buried slowly beneath their own clastic detritus • fossil landscape was preserved	• deposition of red shales, sandstones, and halite-gypsum evaporites		Permian redbeds
CRETACEOUS	• marine transgression locally • extensive peneplanation of Arbuckle Mountain area	• deposition of unconsolidated sands, gravels, and limestones		

Pennsylvanian (Early Atokan)

The main Wichita orogeny took place in early Atokan time and was marked by a period of strong folding and uplift along the Amarillo–Wichita–Criner trend. This uplift exposed Cambrian igneous basement along the mountain chain, and lifted the Criner Hills 10,000–15,000 ft (3,000–4,600 m) structurally higher than the Ardmore basin.

Pennsylvanian (Early Desmoinesian)

Uplift continued in the Wichita system and the initial uplift of the Arbuckle area probably occurred during Desmoinesian time. Sediments shed from the Hunton and Tishomingo landmass were preserved as the Franks Conglomerate (Deese Group) in the Franks graben and in the Mill Creek syncline. The Ardmore basin continued to receive sediments shed from the Criner Hills area. However, chert pebbles preserved in the Devil's Kitchen and Rocky Point Conglomerates (Deese Group) near Lake Murray may have been sourced from folding and thrusting along the Ouachita front.

Pennsylvanian (Late Desmoinesian–Early Missourian)

In late Desmoinesian and early Missourian time, sediments shed from uplift of the Hunton anticline were preserved as the Warren Ranch Conglomerate (Deese Group) in the Arbuckle Mountain region. Pebbles and cobbles in the Warren Ranch Conglomerate record cannibalism of the uppermost Arbuckle Group through the Hunton Group.

Pennsylvanian (Late Missourian–Early Virgilian)

In late Missourian and early Virgilian time, the major Arbuckle orogeny began. During this period of deformation, the folds of the Wichita system were rejuvenated, the Hunton and Tishomingo anticlines underwent further uplift and faulting, and the basin between these two structural systems was compressed, folded, and faulted to become the Ardmore basin and Arbuckle anticline.

Pennsylvanian (Middle Virgilian)

Sediments shed from this uplift include the syntectonic Collings Ranch Conglomerate (middle Virgilian) which is preserved along the northern part of the Arbuckle anticline region (stop 1). The Collings Ranch Conglomerate consists of clasts primarily sourced from the middle and upper Arbuckle Group. The Late Pennsylvanian Arbuckle orogeny appears to have been the last mountain-building pulse in the SOA. The Collings Ranch Conglomerate was folded and faulted during the final stages of deformation along the Arbuckle anticline.

Pennsylvanian (Late Virgilian)

The post-tectonic Vanoss Conglomerate (late Virgilian), preserved in the Mill Creek syncline (stop 7), is the chief depositional product of the Arbuckle orogeny and marks the termination of major deformation in the Arbuckle Mountain region. The Vanoss Conglomerate is generally undeformed except for some minor folding, which suggests that only minor, if any, deformation of the Arbuckle Mountain region occurred after late Virgilian time. As evidenced by arkose in the Vanoss Formation and by the presence of granite, feldspar, and vein quartz from Precambrian granites in the Vanoss Conglomerate, the first unroofing of the Precambrian granite in the Arbuckle Mountains occurred only after the highest uplift and deepest erosion of the Arbuckle Mountains in Late Pennsylvanian time.

ARBUCKLE MOUNTAINS TECTONIC SETTING

Portions of the following section are adapted from Ham (1969), Ham and others (1973), Wickham (1978), Brown and Grayson (1985), and Tapp (1988).

The structural styles of the Arbuckle Mountain region of southern Oklahoma have developed as a result of the late Paleozoic Wichita, Ouachita, and Arbuckle orogenies. The location and trends of many of these structures, however, were predetermined by the initial rifting in the late Precambrian and Early Cambrian during the development of the southern Oklahoma aulacogen (Table 1). The Arbuckle Mountains show a variety of structural styles and intensity. Changes in deformation style and intensity may be related, in part, to competency contrasts of the deforming medium. Interpretation of the surface structures has generated significant controversy. Deformation in the region has been related to: (1) wrench tectonics, (2) thrust tectonics, or (3) distinct phases of both.

Structural uplifts in the Arbuckle Mountains region consist of three prominent anticlines of differing deformation, separated from each other by high-angle faults that strike approximately N 60° W. These anticlines are the Hunton and Tishomingo, both on the platform, and the Arbuckle anticline in the aulacogen.

The Hunton anticline, composed of gently deformed lower Paleozoic carbonates, is separated from the Tishomingo anticline by the Sulphur fault, Mill Creek fault, and Reagan fault (Fig. 2). The style of deformation in this area is consistent with a wrench fault model.

The Arbuckle anticline, the principal part of the Arbuckle Mountains to be visited on this trip, is the most intensely deformed part of the mountains. Structurally, it is a faulted anticline, overturned to the north. This asymmetric, extremely complex, structure is bounded on its northern flank by the

Washita Valley fault zone and on its south flank by the Ardmore basin (Figs. 1,2). Results of the tectonic activity of the Arbuckle orogeny, including karstification and collapse, can best be observed on the structurally more complex northern flank. The stratigraphy along the southern flank of the Arbuckle anticline controls the topography in that area. Carbonates, particularly cyclic shallowing-upward sequences of the upper Arbuckle Group, form prominent hogback ridges (referred to as tombstone topography); shales form valleys, and sandstones form smaller hogbacks.

The Arbuckle anticline and its associated minor folds have been interpreted as forming in two major events: (1) the first formed the main anticline and its secondary folds in the middle Virgilian, and (2) the second event formed the Dougherty anticline in the late Virgilian (Ham, 1969). The Arbuckle anticline is within the range of axial orientation proposed for a primary fold in a left-lateral wrench system (Tapp, 1988).

The northern flank of the Arbuckle anticline is bounded by the Washita Valley fault zone. The exposed length of the fault zone is 35 mi (56 km). It extends for another 50 mi (80 km) to the southeast beneath the Cretaceous cover. Some evidence suggests that the Washita Valley fault zone may link up with the Meers fault in the Wichita Mountains to the northwest (Fig. 4). Deformation in the vicinity of the Washita Valley fault zone in the uniform and competent Arbuckle Group is restricted to a narrow zone of shear, folding, and fractures at the edge of the open Arbuckle and Sycamore Creek anticlines. However, deformation in the overlying interlayered sandstones, shales, and carbonates of the Simpson Group and younger rocks is in a broader zone of folding and thrusting north of the fault.

Ham (1969) proposed that the Washita Valley fault zone marks the northern limit of the Cambrian rift valley. The fault zone is thought to be a rejuvenated northeastern edge to the aulacogen; it separates the Arbuckle Mountains into a western block, in which the basement is the Cambrian Colbert (Carlton) Rhyolite, and an eastern block floored by the Tishomingo and associated Precambrian granites. The fault zone probably represents the only likely exposed margin to the Precambrian rift system. The present Washita Valley fault zone was reactivated during the Pennsylvanian and may have been rejuvenated during the Quaternary (Cox and Van Arsdale, 1988).

Many different interpretations of the Washita Valley fault zone have been published. The most popular is that it is a horizontal, left-lateral strike-slip (wrench) fault. Estimates for the amount of left-slip range from 3 mi (5 km), based on stratigraphic offsets (Ham, 1956; Cox and Van Arsdale, 1988), to 40 mi (64 km), based on the offset of the erosional edge of the basal Oil Creek Formation in the Simpson Group (Tanner, 1967). Carter (1979) estimated 20 mi (32 km) of left-slip based on the offset of Hunton isopachs. An alternative interpretation for the fault zone, based on subsurface evidence, has been proposed by Brown (1984), who interpreted the southwest-dipping Washita Valley fault zone to be an imbricate of the Arbuckle thrust. The asymmetric Arbuckle anticline was uplifted and its northeast flank was overturned along the Arbuckle thrust. Brown (1984) has demonstrated that apparent left-lateral offset, cited by proponents of wrench fault tectonics, can be completely accounted for by the development of reverse dip-slip movement on the Arbuckle thrust. Accordingly, Brown suggests that the fault zone is subordinate to the Arbuckle thrust and that the entire zone is a left oblique-slip reverse fault having a dip-slip component of 8 mi (13 km) and a strike-slip component of 3 mi (5 km).

Field Trip Road Log and Stop Descriptions

ROAD LOG

A road map of the field trip region is printed inside the front cover. Figure 5 is a generalized geologic map of the western Arbuckle Mountains showing the location of seven field-trip stops. A NE–SW cross section through the field-trip region is shown in Figure 6.

0.0 Road log begins at rest area (milepost 59) along southbound lanes of Interstate 35 (52 mi south of Norman).

2.7 Bridge at State Route 7 (exit 55); marks the northern limit of the Arbuckle Mountains.

5.2 Weigh station.

6.7 Milepost 52.

7.3 Highway 77 (exit 51; Turner Falls exit).

7.9 Mississippian Sycamore Limestone exposure, 221 ft thick, on north flank of Arbuckle anticline.

8.0 Bridge over U.S. Highway 77D. Hunton Group and Woodford Shale.

8.2 Viola Group exposure.

8.7 Milepost 50. Bromide Formation (Simpson Group) exposure.

8.8 Collings Ranch Conglomerate/Bromide Formation/Viola Group angular unconformity.

8.9 Marker No. 17 (Fay, 1989; Station No. 2630 + 14 ft). Upper Bromide, 36 ft below Viola (Ardmore Geological Society and Oklahoma Geological Survey [AGS&OGS]) and Collings Ranch Conglomerate.

9.2 Turn right at scenic turnout.

9.5 ***STOP 1:*** Parking lot at top of scenic turnout. Geologic sign (Ardmore Geological Society and Ardmore Lions Club [AGS&ALC]) (Fig. 7): "Cross section of Arbuckle anticline along east lane of Interstate 35." Granite marker: "Oklahoma, where reflection seismograph was born." Collings Ranch Conglomerate, West Spring Creek Formation (upper Arbuckle Group), and Kindblade Formation (upper Arbuckle Group).

9.8 Milepost 49.

10.8 Milepost 48.

11.0 Exit 47 (U.S. Highway 77; Turner Falls exit).

11.8 Milepost 47. Royer Dolomite (lower Arbuckle Group) outcrop.

12.4 Scenic turnout. Tombstone topography in Cool Creek Formation (upper Arbuckle Group).

12.8 Milepost 46.

13.0 Carter County sign. Kindblade Formation (upper Arbuckle Group) outcrop.

13.3 Spectacular view to the south looking into the Ardmore basin. The Ardmore basin, located just south of the Arbuckle Mountains, is a downwarped remnant of the southern Oklahoma aulacogen containing ~35,000 ft (10,700 m) of Late Cambrian through Late Pennsylvanian (Missourian) sedimentary rocks. The basin has an average width of 15 mi (24 km) and a length of ~50 mi (80 km).

13.8 Milepost 45.

14.2 ***STOP 2:*** Viola Springs Formation (Viola Group) exposure.

14.4 Small oil seep in exposure of upper part of Viola Group.

14.5 Small exposure of south-dipping beds of the Silurian-Devonian Hunton Group (Henryhouse, Haragan/Bois d'Arc Formations).

14.6 ***STOP 3:*** Woodford Shale. Marker No. 2 (Fay, 1989; Station No. 2329 + 70 ft), 9 ft below top (located below trees).

14.8 Milepost 44. Sycamore Limestone exposure.

14.9 Southern extent of Arbuckle Mountains.

15.7 Turn right at exit 42, then left (east) onto State Route 53.

16.6 Stop sign. Turn left (north) onto U.S. Highway 77.

17.9 Geologic sign (AGS&ALC): "This rock is the Woodford Chert and bituminous shale, Early Mississippian age. Produces oil in a few southern Oklahoma fields from fracture porosity."

18.0 Geologic sign (AGS&ALC): "This rock is the Chimneyhill Limestone, also known as the lower Hunton lime, Silurian age. This limestone produces oil and gas in many Oklahoma fields. Six miles to the southwest of the Caddo anticline oil and gas is produced at a depth of 4,200 ft."

18.2 Geologic sign (AGS&ALC): "This rock is the Viola Limestone, Ordovician age. This limestone is quarried and crushed for road material and aggregate for cement work. One large quarry [stop 5] is seven miles to the northeast. It produces oil and gas in some fields of Oklahoma."

18.5 Geologic sign (west side of road) (AGS&ALC): "This rock is the Tulip Creek Sand, Simpson

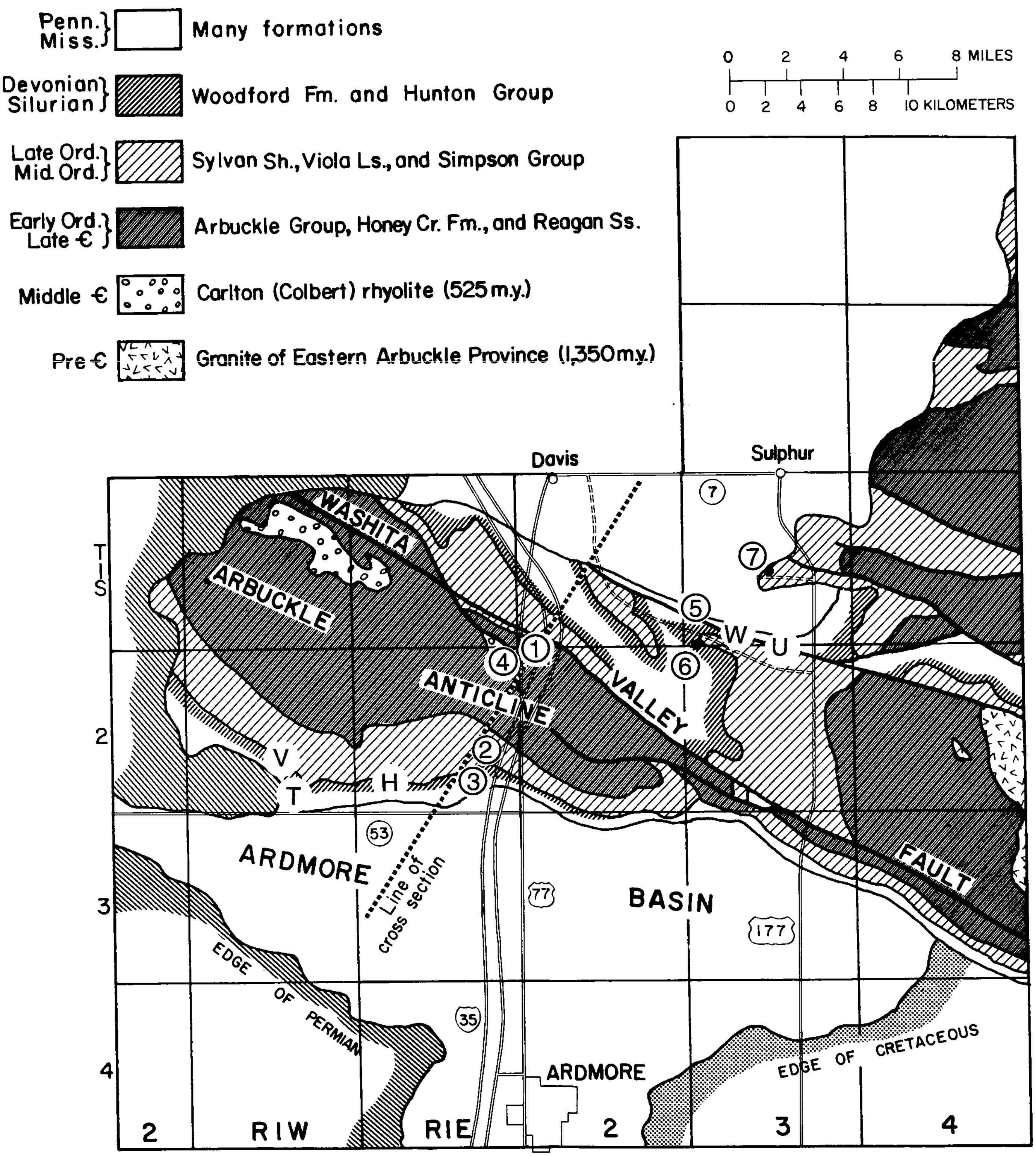


Figure 5. Generalized geologic map of the western Arbuckle Mountains showing location of seven field-trip stops (adapted from Johnson and others, 1984). Cross section is shown in Figure 6. ① = Field trip stops. H = Henry House Falls quarry (Kirkland and others, 1992); T = Woodford Shale type locality (Taff, 1902); U = palynologic investigation of Woodford Shale by Urban (1960); V = palynologic investigation of Woodford Shale by Von Almen (1970); W = approximate location of Williams asphaltite prospect (possibly under water; Hutchison, 1911).

Group, Ordovician age. May be called lower Bromide Sand. Produces oil in many Oklahoma fields. Gas condensate is produced in fields of Oklahoma from this sand at a depth greater than 16,000 ft or in excess of three miles below the surface."

18.7 Geologic sign (AGS&ALC): "This rock is the basal McLish Sand, Simpson Group, Ordovician age. This sandstone is one of the major oil and gas producing zones of Oklahoma."

19.1 Tombstone topography in Kindblade Formation.

19.8 Murray County sign and radio tower.

21.4 I-35 bridge. Royer Dolomite exposure.

22.2 East Timbered Hills on left (west).

23.6 ***STOP 4:*** Turner Falls overlook/Cool Creek Limestone.

23.7 Collings Ranch Conglomerate.

24.1 Geologic sign (AGS&ALC): "This rock is the Collings Ranch Conglomerate, Late Pennsylvanian age. This conglomerate is composed of limestone boulders washed down from the Arbuckle Mountains when they were much higher. The boulders are quite rounded from tumbling against each other in the streams."

24.4 Entrance to Turner Falls Park.

24.8 Bridge over Honey Creek.

25.5 Nearly complete exposure of strata from the Upper Ordovician Sylvan Shale (southern end of outcrop) through the Silurian–Devonian Hunton Group (northern end of outcrop).

25.6 Turn right (east) onto Highway 77D.

25.8 Stop sign. Turn right (south) onto Arbuckle Wilderness access road.

26.4 Entrance to Arbuckle Wilderness Exotic Animal Theme Park.

28.6 Highway 77D.

30.0 Woodford Shale exposure.

31.7 Bridge over Washita River.

32.3 City of Dougherty.

32.4 Railroad tracks. State Route 110 north sign.

33.4 Woodford Shale outcrop.

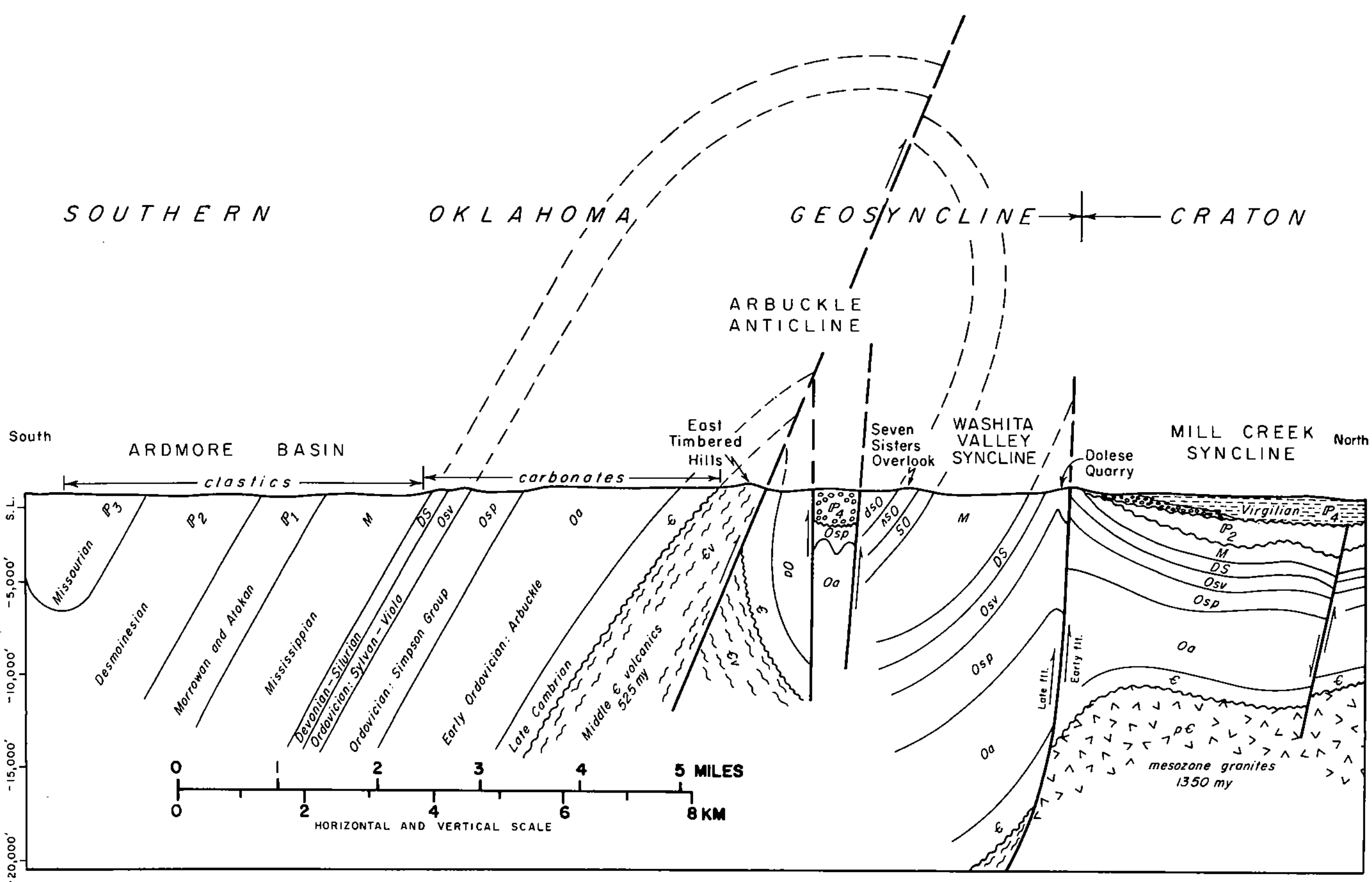


Figure 6. Structural cross section of Arbuckle Mountains in vicinity of Interstate 35 (from Johnson and others, 1984). Location of cross section is shown in Figure 5.

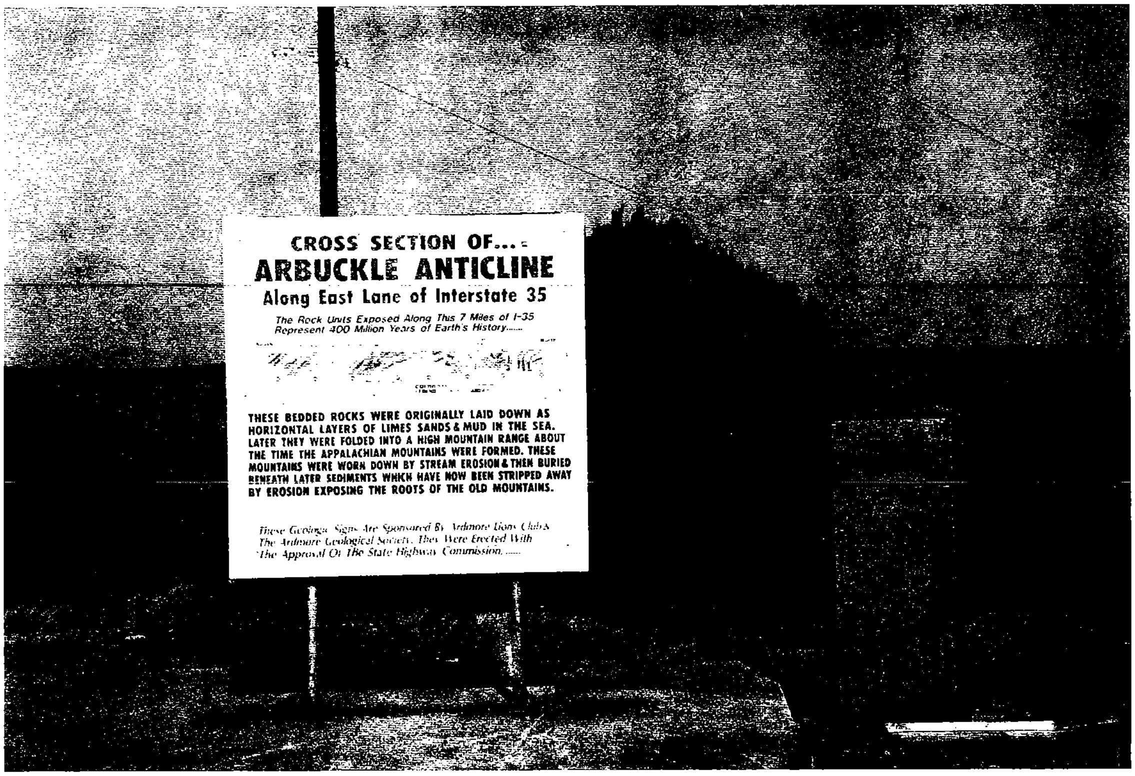


Figure 7. Geologic sign and granite marker at stop 1.

35.5 Turn right onto access road to Lake of the Arbuckles overlook.

36.2 Lunch stop at overlook.

36.8 ***STOP 5:*** Dougherty asphalt quarry.

36.9 Turn left (south) onto State Route 110.

37.2 Turn left (east) onto Goddard Youth Camp Road.

37.6 ***STOP 6:*** Hunton quarry; turn right at entrance.

37.9 Turn right (east) onto Goddard Youth Camp Road.

40.0 Goddard Youth Camp entrance.

42.8 Stop sign. Turn left (north) onto U.S. Highway 177.

44.3 Bridge over Buckhorn Creek.

46.7 Turn left (west) onto Cedar Blue Road.

48.1 ***STOP 7:*** Sulphur asphalt quarry; park on road shoulder.

48.4 Turn around at Five Lakes entrance.

50.1 Stop sign. Turn left (north) onto U.S. Highway 177.

52.4 Junction with State Route 18.

52.5 Sign for Chickasaw National Recreation Area.

53.5 Stop sign. Turn left (west) on State Route 7. City of Sulphur.

55.9 Chickasaw Turnpike.

59.7 Conoco–Davis terminal.

60.4 Junction with State Route 110.

60.7 City of Davis.

62.5 Junction with U.S. Highway 77.

63.4 Bridge over Washita River.

65.2 Turn right (north) onto Interstate 35.

68.2 Road log ends at rest area (north of milepost 58) along northbound lanes of Interstate 35.

STOP 1
Collings Ranch Conglomerate

Location

Stop 1 is a scenic turnout from the southbound lanes of Interstate 35, ~2.0 mi (3.2 km) south of U.S. Highway 77 (exit 51). Detailed location: Located ~0.5 mi (0.8 km) north of milepost 49 on Figure 8 (Pcr) at the SE¼SE¼NW¼ sec. 31, T. 1 S., R. 2 E. on the Turner Falls Quadrangle map (7.5′ series), Murray County. Marker No. 29 (Fay, 1989; Station No. 2604 + 50 ft) is 70 ft (21 m) north of a fault in the Washita Valley fault zone; the Washita Valley fault zone separates the Arbuckle anticline and Tishomingo anticline (Fig. 2).

CAUTION: Please do not walk on the roadway. If we cross the southbound lanes of I-35, please do this in groups of five.

Significance

- The first, thickest, and coarsest orogenic product following Pennsylvanian folding.
- Next to the last synorogenic conglomerate deposited during the deformation of the southern Oklahoma aulacogen.

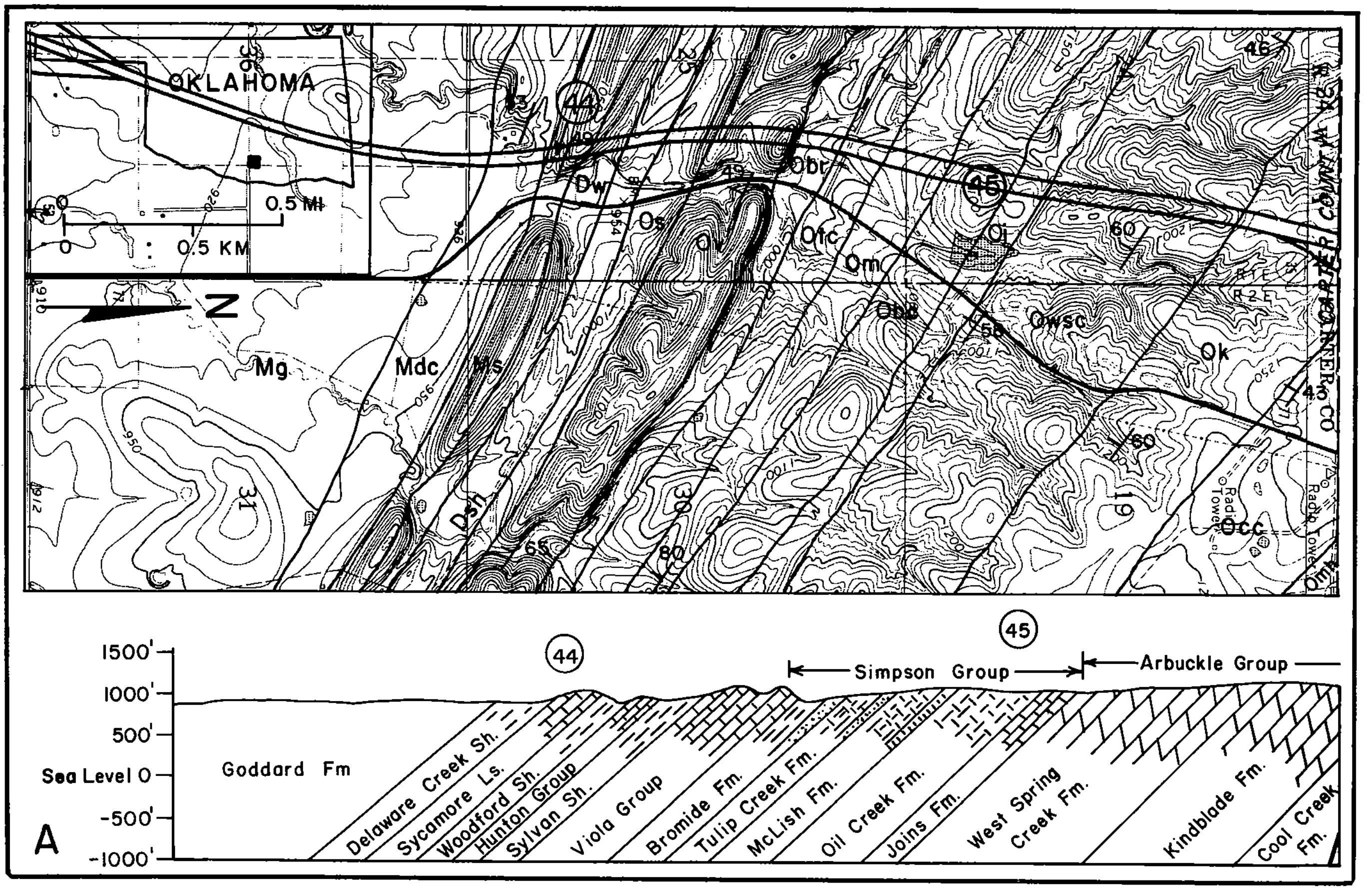


Figure 8 (this and facing page). Geologic map and profile of Arbuckle Mountains along Interstate 35 (from Fay, 1988). *A* is to the south; *C* is to the north. Circled numbers 44–51 are mileposts.

Qal = Quaternary alluvium
Pcr = Pennsylvanian Collings Ranch Conglomerate
Mg = Mississippian Goddard Formation
Mdc = Mississippian Delaware Creek Shale
Ms = Mississippian Sycamore Limestone
Dw = Devonian–Mississippian Woodford Shale
Dsh = Ordovician–Devonian Hunton Group
Os = Ordovician Sylvan Shale
Ov = Ordovician Viola Group
Obr = Ordovician Bromide Formation
Otc = Ordovician Tulip Creek Formation
Om = Ordovician McLish Formation
Ooc = Ordovician Oil Creek Formation
Oj = Ordovician Joins Formation
Owsc = Ordovician West Spring Creek Formation
Ok = Ordovician Kindblade Formation
Occ = Ordovician Cool Creek Formation
OCms
Omh = Ordovician McKenzie Hill Formation
Obu = Ordovician Butterly Dolomite
Csm = Cambrian Signal Mountain Formation
Cro = Cambrian Royer Dolomite
Cfs = Cambrian Fort Sill Limestone
Chc = Cambrian Honey Creek Limestone
Cre = Cambrian Reagan Sandstone
Cc = Cambrian Colbert Rhyolite

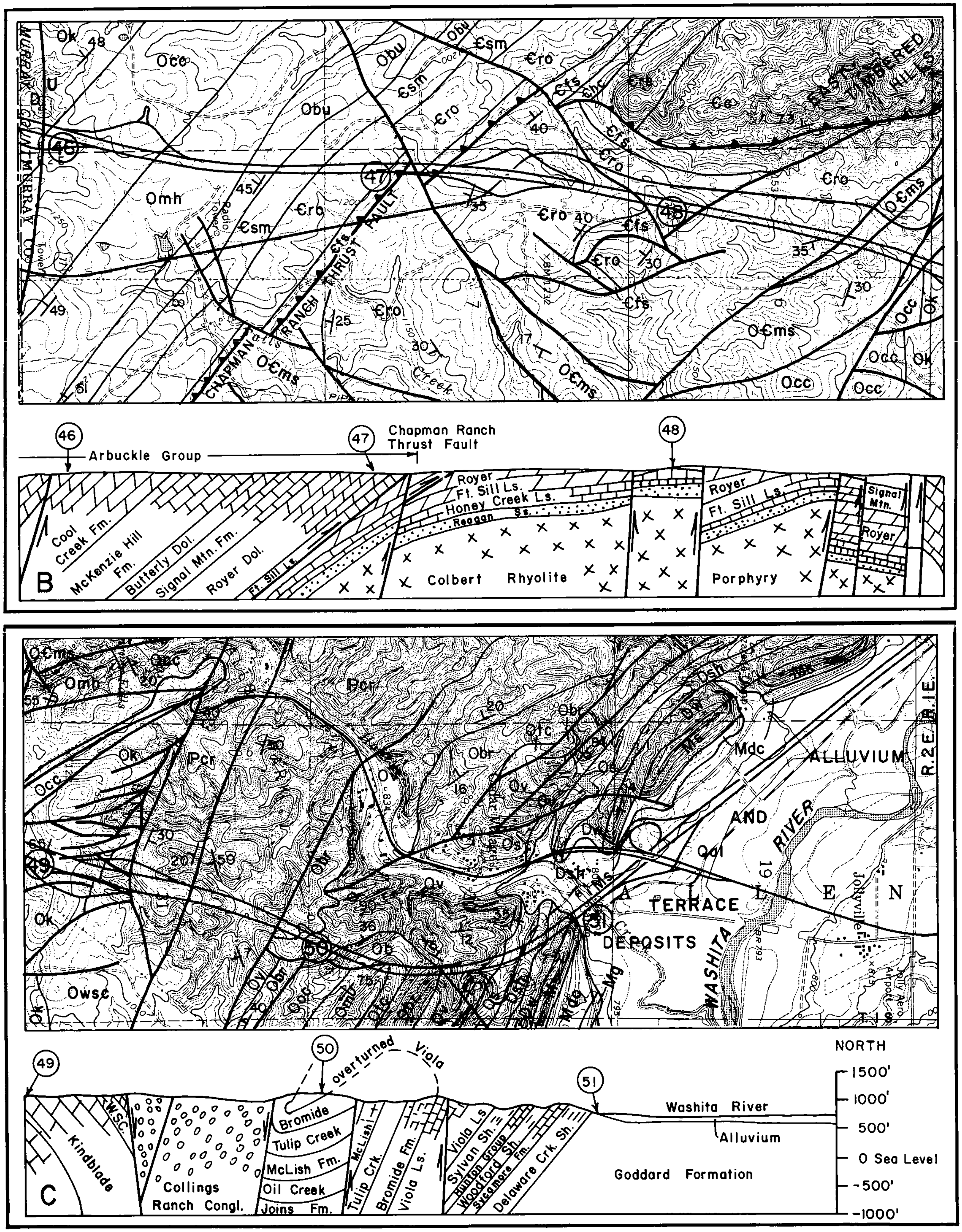


Figure 8. *Continued.*

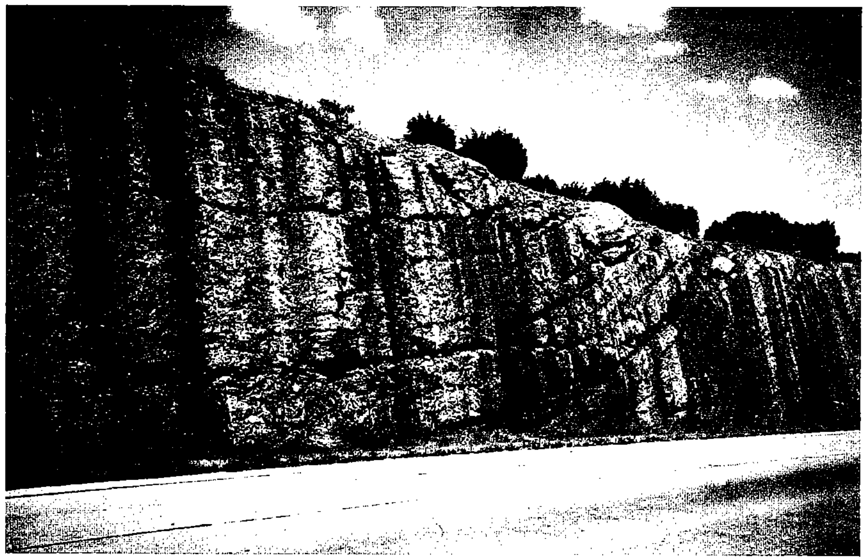


Figure 9. Exposure of Collings Ranch Conglomerate preserved in an asymmetric synclinal fold within a faulted graben along northbound lanes of Interstate 35 at stop 1. The conglomerate is the first, thickest, and principal depositional product of the Arbuckle orogeny. Faulting occurs at the north (right) boundary of the synclinal fold.

- Profound angular unconformity between conglomerate and underlying strata.
- A polymict conglomerate primarily composed of rock fragments cannibalized from the Cambrian–Ordovician Arbuckle Group.
- Orogenic product deposited in proximal part of an intramontane alluvial fan complex.
- An example of syndepositional deformation with the preservation of the orogenic product.

Description

Portions of the following section are adapted from Ham (1954), Brown (1984), Brown and Reneer (1985), and Donovan and Heinlen (1988).

The Collings Ranch Conglomerate, well exposed on the northern edge of the Arbuckle anticline along the Washita Valley fault zone in the Turner Falls area, is a massive limestone boulder conglomerate deposited during the Late Pennsylvanian (middle Virgilian). The Collings Ranch Conglomerate was the next to the last synorogenic conglomerate deposited during the deformation of the southern Oklahoma aulacogen. The conglomerate, ~3,000 ft (900 m) thick, was deposited in a northwest–southeast trough with sediments spread over a wide area in irregular sites of deposition while the Arbuckle Mountains were still actively rising. As a result, most of the conglomerate was uplifted, eroded, and lost. The only area where the conglomerate has been preserved extensively is in a synclinal graben (Fig. 9) bounded by the Arbuckle anticline on the southwest and the Tishomingo anticline on the northeast.

The conglomerate rests, with pronounced angular unconformity, on rocks of the Bromide and Viola Springs Formations (Ordovician) in the northern part of the outcrops at this stop (Fig. 10). These rocks, which are progressively younger to the north, were folded steeply during the culmination of the Arbuckle orogeny. Bedding in the Bromide Formation is overturned and dips ~85° to the south. The Viola Group shows a wide range of structural dips. The dip of the conglomerate is slight.

The Collings Ranch Conglomerate is composed of pebble- to boulder-size limestone clasts sourced primarily from Ordovician rocks, particularly the Arbuckle Group, of the Arbuckle and Tishomingo anticlines (Fig. 11). Provenance of the clasts can be correlated, by petrographic, isotopic, and rock magnetic methods, to the underlying tectonically deformed lower Paleozoic section that forms the Arbuckle uplift. Most of the rock fragments derived from the Cambrian–Ordovician Arbuckle Group consist of micritic limestone clasts. Probable sources of the carbonate clasts include the McKenzie Hill, Cool Creek, Kindblade, and West Spring Creek Formations (Arbuckle Group) as well as limestones in the Viola and Hunton Groups. Sandstone clasts consist primarily of mature quartz arenites from the Simpson Group (Ordovician). There are no clasts of the Colbert Rhyolite (Middle Cambrian) in the Collings Ranch Conglomerate, which suggests that either the igneous core of the Arbuckles was not unroofed at the time the conglomerate was being deposited, or that the Colbert Rhyolite did not outcrop within the drainage basin of the conglomerate. The average composition of the conglomerate is a pebble to boulder, clay to sandy, unsorted, clast-supported lithrudite. The stratigraphic sequence generally coarsens up from the base. The pinkish-gray conglomerate comprises stacked-pebble and cobble conglomerates forming lenticular beds whose contacts are either erosional scour-and-fill

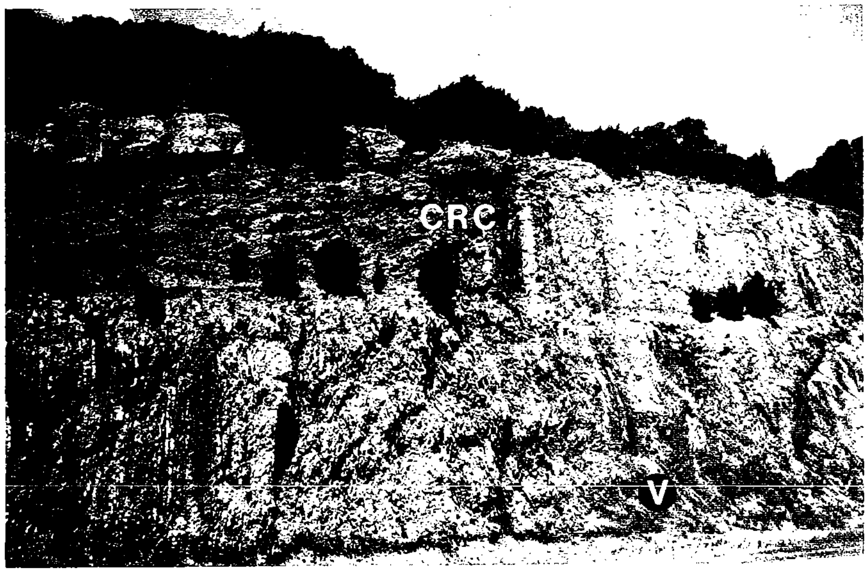


Figure 10. View, looking southwest from stop 1 along Interstate 35, of the Pennsylvanian Collings Ranch Conglomerate (CRC) overlying, with pronounced angular unconformity, the upturned and slightly overturned edges of the Ordovician Viola Limestone (V). Note the lenticular geometry of the conglomerate.

structures, or are defined by discontinuous surfaces of red calcareous mudstone. Compositionally, the deposit is immature due to the predominant percentage of carbonate rock clasts.

Depositional Environment

The nature and distribution of the Collings Ranch Conglomerate suggests that it is an orogenic product deposited in the proximal part of an intramontane alluvial fan complex. This synorogenic deposit accumulated in the southern Oklahoma aulacogen at the base of the actively rising Arbuckle and Tishomingo anticlines. Depositional facies of an alluvial fan complex recognized in outcrops at this stop include: (1) debris flows (channel or sheet geometries), (2) braided stream-channel fills, and (3) mudflow deposits.

Debris flows, either in channel geometries or spread laterally in sheet/lobe geometries, represent the principal depositional facies at this stop (Fig. 11). The channelized debris-flow deposits consist of poorly sorted, graded, clast-supported deposits with larger rock fragments randomly arranged. Channelized debris-flow deposits are more common at the southern end of the outcrops. Massive sheet/lobe deposits are more common at the northern end. These deposits consist of poorly sorted, clast-supported rock fragments exhibiting normal- or inverse-grading.

Figure 11. Collings Ranch Conglomerate exposed at stop 1 along the west side of the southbound lanes of Interstate 35. Three stacked cycles of debris flows show graded bedding of rock fragments from boulder-sized at the base to pebble-sized at the top. The rock fragments were cannibalized primarily from the Cambrian/Ordovician Arbuckle Group. The polymict conglomerate records some of the latest tectonic events in the evolution of the southern Oklahoma aulacogen. It was deposited in the proximal part of an intramontane alluvial-fan complex.

Braided stream-channel fills, diagnostic of the proximal facies of an alluvial-fan complex, also are common throughout the series of outcrops at this stop. These deposits are characteristically poorly to moderately sorted, contain less clay matrix, show thin-to-lenticular geometries, and fine upward. The numerous shallow channel fills present in these outcrops suggest the rapid and continuous shifting of channels. Many of the deposits appear to have formed as gravel bars deposited by flashy streams. Where present, erosional channels show imbricate structure.

Mudflow deposits consist of finer grained deposits ranging from sand to clay, but clay is the dominant composition. These deposits, laid down as widespread sheets in non-channel areas, represent either a waning sediment supply due to the lowering or shifting of the source area, or overbank deposits from periodic flooding events.

The alternating of normal- and inverse-graded bedding recorded in the Collings Ranch Conglomerate suggests gentle, episodic uplift of the Arbuckle Mountains. Each bed, grading from debris flow to mudflow, may, in fact, record an individual tectonic pulse, that is, a single sedimentation event (Brown and Reneer, 1985). The overall coarsening-upward sequence is the result of the progradation of the alluvial fan complex as uplift and erosion of the source area continued.

Discussion

The Collings Ranch Conglomerate was deposited in a graben-like basin, trending WNW–ESE, which was several miles in length and as much as 0.5 mi (0.8 km) in width. Faulting occurs at both the north and south boundaries of the graben-like basin in which the conglomerate is preserved. The south-bounding, Washita Valley, fault is one of the principal through-going faults of the Arbuckle Mountains (Fig. 2). The Washita Valley fault zone is a long, straight fault system trending northwest to the western edge of the Arbuckle Mountains, where it is covered by the Late Pennsylvanian (Virgilian) Vanoss Conglomerate; this relationship demonstrates that the Vanoss is younger than the Collings Ranch Conglomerate. The fault is nearly vertical at the surface, but dips either north or south at various points along its length. There is some evidence that the fault was active at least as far back as the Cambrian and as recently as the Quaternary (Cox and Van Arsdale, 1988).

Tanner (1967) interpreted the Washita Valley fault to be a major left-lateral fault having ~40 mi (66 km) of slip. Evidence cited includes the numerous subordinate en echelon faults and folds, and the apparent offset of stratigraphic units across the Washita Valley fault zone. The preservation of the conglomerate has very interesting implications if, in fact, the fault was a left-lateral wrench system during deposition of the conglomerate.

Wickham (1978) noted that the basin in which the conglomerate was deposited is intimately associated with the major Washita Valley fault zone. According to Wickham, the aulacogen theory predicts that such a major fault system originated as a normal fault along which intermittent dip-slip displacement occurred throughout the subsiding phase of the aulacogen. Wickham suggested that the fault system formed as a left-lateral wrench pull-apart depression located along a bend or leftward step in the major fault. If this is the case, then the apparent maximum thickness of 3,000 ft (900 m) assigned to the conglomerate (Ham, 1954) may be incorrect, particularly as the maximum vertical thickness that can be measured at any one locality is only 300 ft (90 m). The Collings Ranch Conglomerate may, in fact, consist of a series of small, stacked-up (imbricate) fan complexes 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 offset position as the anticline tightened. This explanation is more compatible with Ham's (1954) original explanation and estimated thickness of the conglomerate.

Subsequently, the fault system was rejuvenated and transpressed the basin fill, which caused 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.

STOP 2
Viola Springs Formation

Location

Stop 2 (Fig. 12) is a road-cut exposure along the east side of the southbound lanes of Interstate 35, ~3 mi (5 km) south of exit 47 (U.S. Highway 77) to the Turner Falls area. Detailed location: Located 2,400 ft (730 m) south of milepost 45 on Figure 8 (Ov) at the NE¼SW¼NE¼ sec. 25, T. 2 S., R. 1 E. on the Springer Quadrangle map (7.5′ series), Carter County. Marker No. 6 (Fay, 1989; Station No. 2353 + 15 ft) is 1 ft (0.3 m) below the top of the Bromide Formation.

CAUTION: Pull off the road to the far right. Be extremely careful when crossing the southbound lanes of I-35. Large groups should seek permission from the Oklahoma Highway Department.

Significance

- Hydrocarbon source rock.
- Graptolite-bearing rock. Use of graptolite reflectance as a thermal maturity indicator.

Description

The Viola Group (Middle to Upper Ordovician) is divided into two formations: the Viola Springs Formation (proposed by Amsden, 1983) and the Welling Formation (proposed by Amsden, 1979) (Fig. 13). Both formations are present at stop 2. However, the graptolite-bearing and best hydrocarbon source potential zone is in the lower and middle parts of the Viola Springs Formation. The type section of the Viola Springs Formation is in the eastern Arbuckle Mountains at the NW¼NE¼ sec. 19, T. 2 S., R. 8 E., Johnston County, Oklahoma (Amsden, 1983). Figure 14 shows the extent of the Viola Springs Formation in Oklahoma.

Stop 2 is on the south flank of the Arbuckle anticline (Fig. 2). The strike of the Viola Springs Formation is N 62° W and the dip is 43° SW (Fay, 1989). The Viola Springs Formation is divided into two lithologically distinct units (Pollard and Williams, 1985; Finney, 1988). The lower part comprises white to dark-gray, planar-bedded, siliceous, laminated calcareous mudstones and bedded cherts (Amsden, 1983). It was deposited under anaerobic conditions in relatively deep water during the stable-shelf carbonate phase of the southern Oklahoma aulacogen. The upper part comprises light-gray, wavy-bedded, medium- to coarse-grained skeletal wackestones and packstones with nodular chert and thin shale interbeds (Amsden, 1983; Finney, 1988). Deposition under dysaerobic to aerobic conditions resulted in an overall shallowing-upward sequence. Figure 15 illustrates a stratigraphic column of stop 2 (Finney, 1986). The upper contact of the Viola Group with the Sylvan Shale and the lower contact with the Bromide Formation are disconformities.

The maximum thickness of the Viola Group is 1,070 ft (326 m) in the depocenter of the Oklahoma basin (Pollard and Williams, 1985). The maximum thickness of the Viola Springs Formation in the western Arbuckle Mountains is ~800 ft (244 m)(Amsden, 1983). The thickness of the Viola Group at stop 2 is reported to be 735 ft (224 m) by Pollard and Williams (1985), 715 ft (218 m) by Finney (1988), and 684 ft (208 m) by Fay (1989).

The massive carbonate sequence of the Viola Group has undergone significant diagenesis locally. Major events in altering primary rock texture include phosphatization, pyritization, dolomitization, silicifi-

Figure 12. Exposure of Viola Springs Formation (Viola Group) along east side of southbound lanes of Interstate 35 at stop 2.

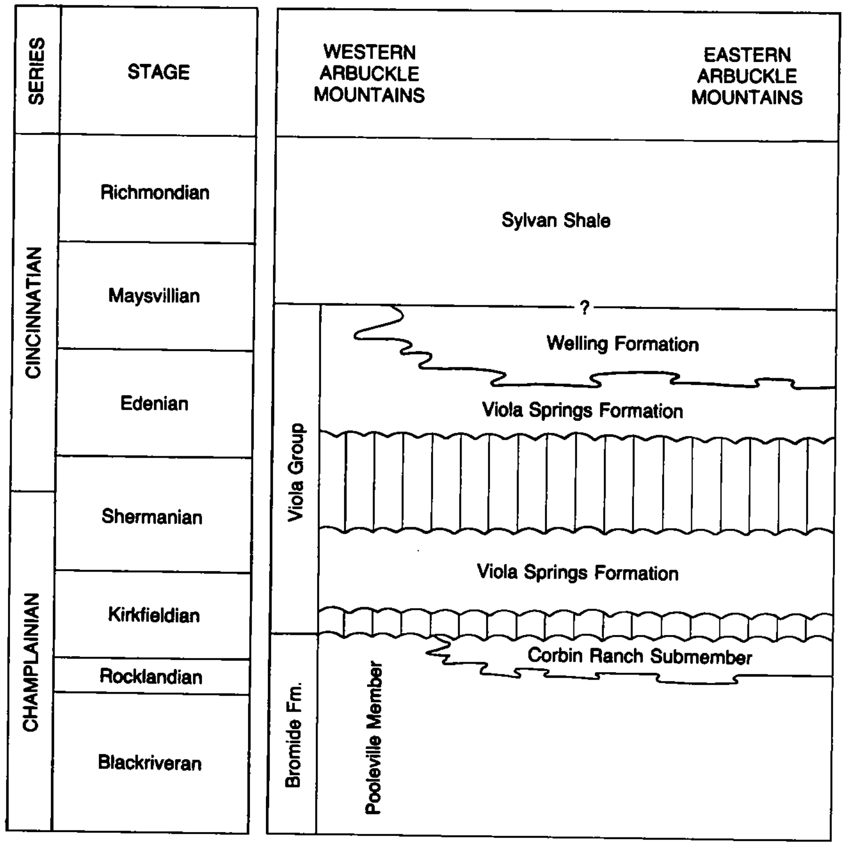


Figure 13. Upper Ordovician stratigraphy in Arbuckle Mountains (from Amsden, 1983).

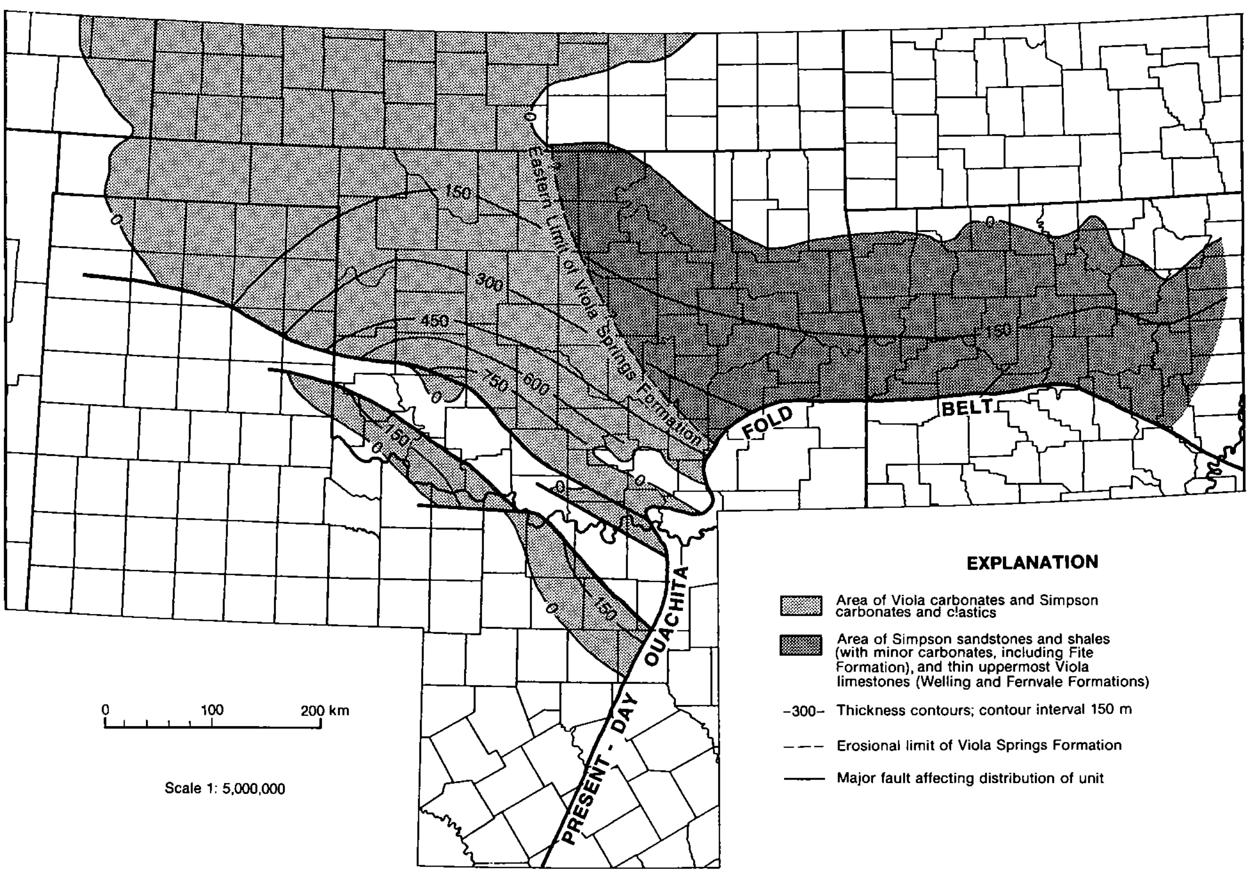


Figure 14. Thickness and dominant lithologies of Simpson and Viola Groups (from Johnson and others, 1988).

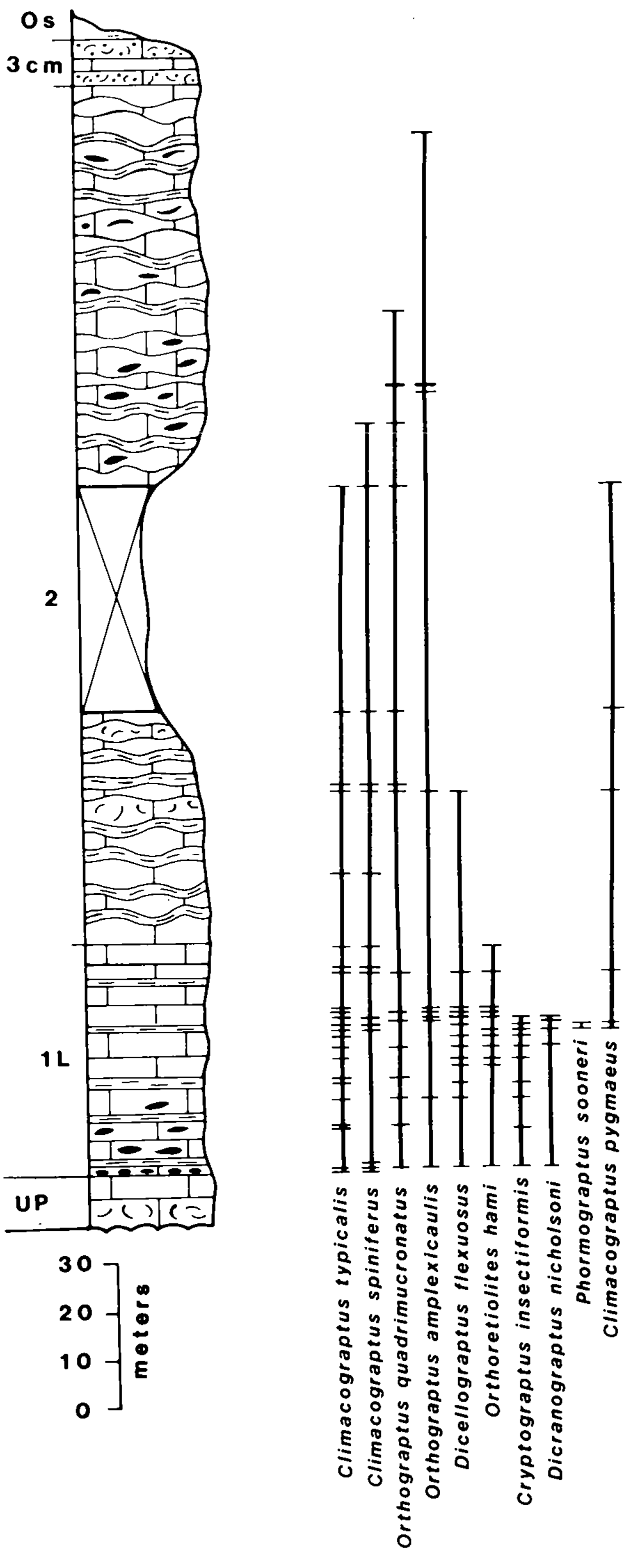


Figure 15. Stratigraphic column and graptolite range chart for stop 2. UP refers to upper Bromide Formation; 1L and 2 are microfacies of the Viola Springs Formation; 3cm refers to the Welling Formation; Os refers to the Sylvan Shale (from Finney, 1986, section U).

cation, cementation, neomorphism, and pressure solution (Al-Shaieb, 1993).

The fauna of the Viola Group includes graptolites, trilobites, brachiopods, nautiloid cephalopods, conulariids, cephalopods, bryozoans, ostracods, and echinoderms (Glaser, 1965; Alberstadt, 1973; Finney, 1988; Finney and others, 1984). Microfossils recognized in the Viola Group include chitinozoans, conodonts, sponge spicules, trilete spores, dinoflagellates, scolecodonts, acritarchs, and vascular plant tissue (Oberg, 1966; Jenkins, 1969; Nygreen, 1970; Sweet, 1983).

Hydrocarbon Source Rock

Jones and others (1987), Michael and others (1989), and Jones and Philp (1990) concluded that Viola Group limestones are the source and reservoir of oil in the Pauls Valley area of the Anadarko basin (north–northwest of the Arbuckle Mountains) based on biomarker analysis of oils and source-rock extracts. Michael and others (1989) indicated that the algae *Gloeocapsomorpha prisca* is the probable oil source. Zemmels and Walters (1987) found that Viola oil from Love County, Oklahoma, (south of the Arbuckle Mountains) was typical Ordovician oil. End-member Type D oils of Wavrek (1992) occur in Viola Group reservoirs, particularly in the Marietta basin (south–southwest of the Arbuckle Mountains) (Fig. 16). Wavrek (1992, p. 188) stated: "Type D oils have an increased abundance of mid-range n-alkanes that contain a moderate odd-carbon preference in the nC_{11}–nC_{20} range. They contain a moderate amount of aryl-isoprenoids and typical values for Pr/Ph, Pr/nC_{17}, and Ph/nC_{18} are 1.10, 0.31, and 0.51, respectively.

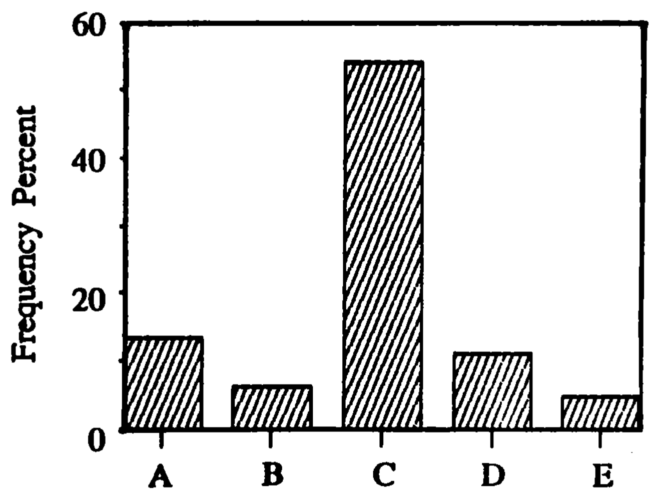


Figure 16. Frequency distribution of oil types in reservoirs in the Ardmore and Marietta basins. Oil types A through E tentatively correlate with source facies in the Pennsylvanian (Atoka Formation?), Mississippian (Goddard, Caney, and Sycamore Formations), Devonian–Mississippian (Woodford Shale), middle Upper Ordovician (Viola Group), and Middle Ordovician (Simpson Group) rocks, respectively (modified from Wavrek, 1992).

The per mil carbon-isotope values for two of these oils averaged −31.1, −31.3, and −30.9 for the whole oil, saturate, and aromatic fractions, respectively. The hydrocarbons that make Type D oils unique include the anomalously high concentrations of alkylated cyclic compounds (e.g., n-alkylcyclohexanes and n-alkylbenzenes) with an odd-carbon preference, and moderate concentrations of alkylated sulfur compounds."

Asphalt (active oil seep) occurs in the upper part of the Viola Group at stop 2 ~200 ft (61 m) from the top of Viola, on the eastern side of southbound Interstate 35 (Ham and others, 1973; Fay, 1989) and in the lower to middle part of the Viola Group at the Sooner Rock and Sand quarry in the northern Arbuckle Mountains (secs. 11 and 14, T. 1 S., R. 1 E.) (Bagley and others, 1992). These seeps indicate the presence of hydrocarbons and suggest potential petroleum production under proper subsurface conditions. Oil production from the Viola is due primarily to porosity from fractures, developed best at the hinges of folds (Allen, 1983; Pollard and Williams, 1985). The degree of fracturing throughout the section is dependent on the silica content. The most highly fractured units correlate well with high silica content.

Kerogen Type: G. E. Michael, C. L. Thompson-Rizer, and R. A. Woods (1993, personal communication) reported the visual kerogen composition of a Viola Springs Formation carbonate sample from stop 2 to be 80% amorphous type A (fluorescing, oil prone; Thompson and Dembicki, 1986), 20% herbaceous (includes acritarchs), and a trace of vitrinite-like graptolites.

Wang (1993) found that the lower and middle units of the Viola Group in the southeastern part of the Anadarko basin contain type II (oil-prone) kerogen with good oil generation potential. The total organic carbon (TOC) content was 0.2–2.7 wt%, and averaged 0.8 wt% for 29 samples. Kirkland and others (1992) analyzed Viola shale samples from stop 2 and reported 2.5–3.5 wt% total organic carbon content. A thin shale at the base of the Viola had a hydrogen index (HI) of 300–580 mgHC/g OC.

Table 2 summarizes the Rock-Eval pyrolysis data of a Viola Springs Formation carbonate sample from stop 2. The total organic carbon content of ~0.7 wt% indicates fair hydrocarbon source potential. The hydrogen index of 548 mgHC/g OC and the oxygen index of 48 mgCO_2/g OC indicate type II kerogen. The kerogen-type indicator value of ~11 suggests that the kerogen is oil-prone. The production index of 0.06 indicates that the sample is immature. The T_{max} of 432°C indicates that the sample is marginally mature (vitrinite reflectance equivalent of 0.5–0.7%).

Graptolite-Bearing Rock: Graptolites are an extinct class of colonial marine invertebrates found in carbonate and clastic rocks of Cambrian to Pennsylvanian age (Bulman, 1970). The Viola Springs Formation is one of several graptolite-bearing Ordovician-

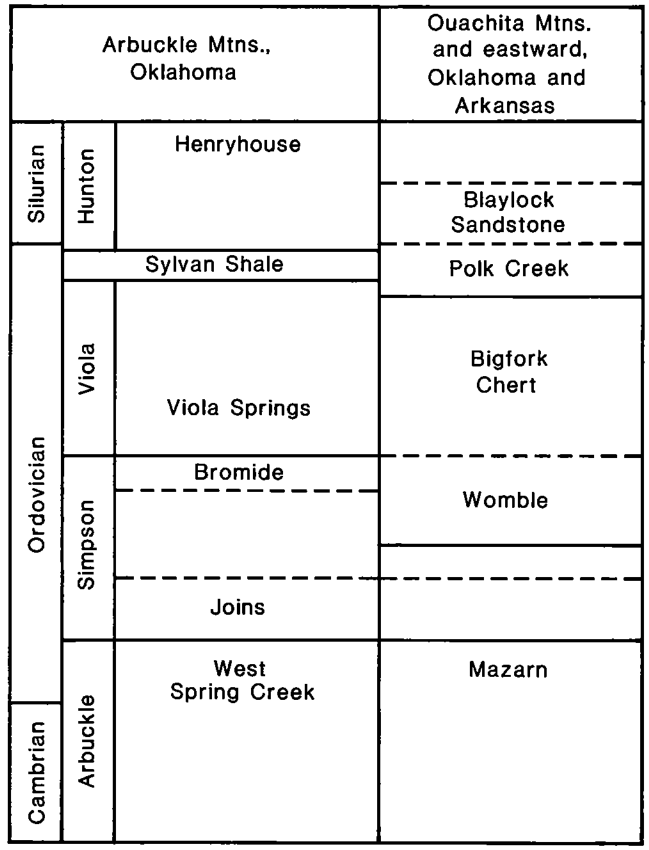


Figure 17. Graptolite-bearing strata of Oklahoma (from Cardott and Kidwai, 1991).

age rocks of Oklahoma (Decker, 1959) (Fig. 17) where graptolites are abundant at its base (Gentile and others, 1984; Finney, 1986). Ruedemann and Decker (1934) provided a faunal list of 26 graptolite species for the Viola Springs Formation. Finney and others (1984) indicated that this list should be reduced to 11 species. Finney (1986) illustrated 10 species, all from the Order Graptoloidea (Fig. 15).

Graptolite reflectance, the measurement of the percentage of white light reflected from polished graptolite periderm, is known to be an important thermal maturity indicator for pre-Devonian strata. Cardott and Kidwai (1991) summarized the potential of this maturity indicator and gave examples from Oklahoma. The correlation of graptolite reflectance with vitrinite reflectance is not definitive. Bertrand (1990) indicated that, at the same maturity level, graptolite reflectance is slightly less than vitrinite reflectance. Goodarzi (1990) and Goodarzi and others (1992) showed that graptolite reflectance is greater than vitrinite reflectance at the same maturity level (e.g., "oil window" is 1.1–2.2% graptolite reflectance compared to 0.5–1.3% vitrinite reflectance).

Cardott and Kidwai (1991) reported the mean maximum graptolite reflectance from this exposure to be 0.69%. The conodont color alteration index (CAI) is 1. Both values indicate an early stage of maturity with respect to the generation of liquid hydrocarbons.

STOP 3
Woodford Shale

Location

Stop 3 (Fig. 18) is a road-cut exposure along the west side of the southbound lanes of Interstate 35, ~0.5 mi (0.8 km) south of stop 2. Detailed location: Located 650 ft (198 m) north of milepost 44 on Figure 8 (Dw) at the SE¼NW¼SE¼ sec. 25, T. 2 S., R. 1 E. on the Springer Quadrangle map (7.5′ series), Carter County. Marker No. 2 (Fay, 1989; Station No. 2329 + 70 ft) is 9 ft (3 m) below the top of the Woodford Shale.

CAUTION: Pull off the road to the far right. Stay on the west side of the road, away from traffic. Large groups should seek permission from the Oklahoma Highway Department.

Significance

- Records a major regional anoxic event.
- Woodford Shale as major hydrocarbon source rock.
- May prove to be a significant reservoir rock in the Anadarko basin.
- Oldest rock in the Arbuckle Mountains that contains vitrinite.
- Sample collecting locality of early hydrous pyrolysis experiments.

Description

The Upper Devonian–Lower Mississippian Woodford Shale (Fig. 3) occurs in Oklahoma, Texas, and New Mexico (Conant and Swanson, 1961). It was named Woodford Chert by Taff (1902) for outcrops north of the town of Woodford, ~8 mi (13 km) west of stop 3 (Morgan, 1924; Gould, 1925; Jordan, 1957). The type locality is at sec. 34, T. 2 S., R. 1 W. (T on Fig. 5).

Hass and Huddle (1965) determined a Late Devonian (Frasnian) age for most of the formation and based the Early Mississippian (Kinderhookian) age of the uppermost portion on conodonts. They indicated that conodonts were not abundant in the samples they collected from Carter, Murray, Pittsburg, and Pontotoc Counties in Oklahoma. New radiolarian and conodont faunas recovered from the upper part of the Woodford Shale indicate a considerably higher chronostratigraphic position (Osagean–Meramecian) for the top of this unit than previously assigned (Schwartzapfel, 1990; Schwartzapfel and Holdsworth, 1991). Age-equivalent rocks of the Woodford Shale in Oklahoma include, in part or in entirety, the Woodford Shale of New Mexico and Texas; the Chattanooga Shale in the Eastern Interior of the United States; the New Albany, Ohio, and Sunbury Shales of the central United States; the Arkansas Novaculite in southeastern Oklahoma and Arkansas; the Antrim Shale in the Michigan basin; the Bakken Formation in the Williston basin; the Kettle Point Formation of Ontario; and the Pilot Shale of Utah (Conant and Swanson, 1961).

Stop 3 (Fig. 18) is on the south flank of the Arbuckle anticline (Figs. 2,8). The strike of the Woodford Shale is N 60° W and the dip is 44° SW (Fay, 1989).

The Woodford Shale is a marine, carbonaceous and siliceous, fissile to blocky, dark-gray to black shale containing chert, subordinate amounts of green-greenish-gray shales, phosphate nodules, and pyrite.

Figure 18. Exposure of Woodford Shale along west side of southbound lanes of Interstate 35 at stop 3.

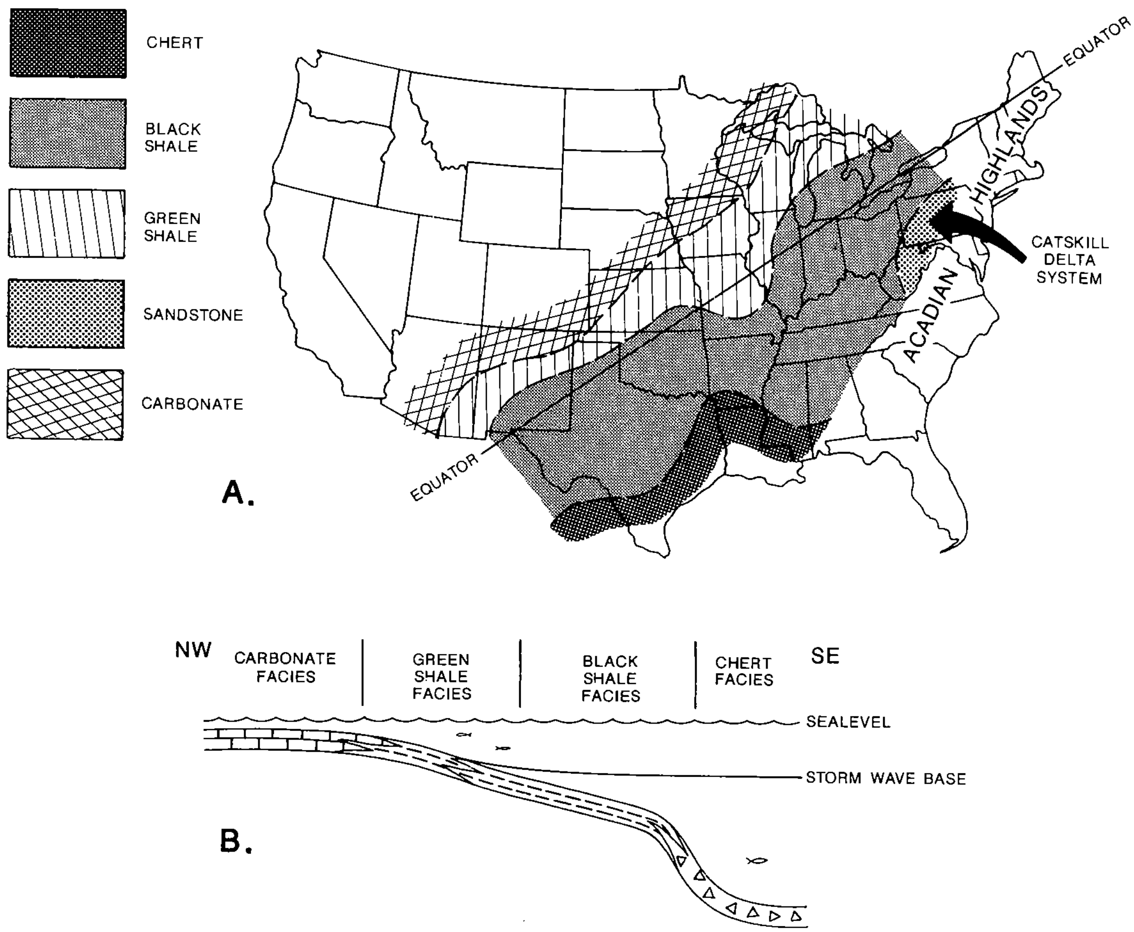


Figure 19. (*A*) Paleogeography and facies distribution in the Late Devonian. (*B*) Northwest–southeast cross section through the Woodford depositional basin showing the relationship of facies to relative water depth (from Kirkland and others, 1992).

It marks a transition from predominantly carbonate deposition in the early Paleozoic to primarily clastic deposition in the late Paleozoic (Ham and others, 1973). Figure 19 illustrates paleogeography and facies distribution in the Late Devonian. Black shale was deposited below storm wave base over most of Oklahoma. A chert facies occurs within the Woodford, primarily in southern and southeastern Oklahoma. A major unconformity at the base of the Woodford Shale is the result of uplift and erosion during the late Early to Middle Devonian (Maxwell, 1959). Brown to green shale occurs at the base of the Woodford Shale at stop 3 (Barrick and Klapper, 1990). The upper contact with the Sycamore Limestone is gradational.

The Woodford Shale attains a maximum thickness of >700 ft (213 m) in the southern Oklahoma aulacogen (Amsden, 1975) (Fig. 20). The shales of the southwest flank of the Arbuckle Mountains are part of a thick basin sequence, nearly four times as thick as the equivalent cratonic succession on the northeastern flank. Fay (1989) reported the thickness of the Woodford Shale at stop 3 to be 290 ft (88 m). The upper 102 ft (31 m) and lower 51 ft (15 m) is exposed; the middle 137 ft (42 m) is covered. Figure 21 is a measured section of stop 3 (Ellis and Westergaard, 1985). Roberts and Mitterer (1992) indicated that the upper 72 ft (22 m) of the Woodford Shale at stop 3 contains black to blackish-brown laminated shales, 0.04–11 in. (0.1–29 cm) thick, and black to blackish-brown cherts, 0.2–13 in. (0.5–32 cm) thick.

Hester and others (1990) subdivided the Woodford Shale in northwestern Oklahoma into three informal stratigraphic units based on log-derived characteristics. Higher total organic carbon content of the middle member was the physical basis for the subdivision. Urban (1960) recognized three depositional facies in the Woodford Shale based on microfossil content of an outcrop ~3 mi (5 km) east of stop 6 (sec. 3, T. 2 S., R. 3 E.; U on Fig. 5). The upper and lower facies indicate a nearshore-marine environment, whereas the middle facies indicate a more open-marine environment. Von Almen (1970) identified three depositional facies composed of marine transgressive and regressive cycles, based on palynomorphs identified from 55 outcrop and core chip samples from south-central Oklahoma. The zones were not correlative across the region. The primary outcrop in the Arbuckle Mountains used by Von Almen (1970) was along Hickory Creek (sec. 27, T. 2 S., R. 1 W.; V on Fig. 5), ~1 mi (2 km) north of the type locality.

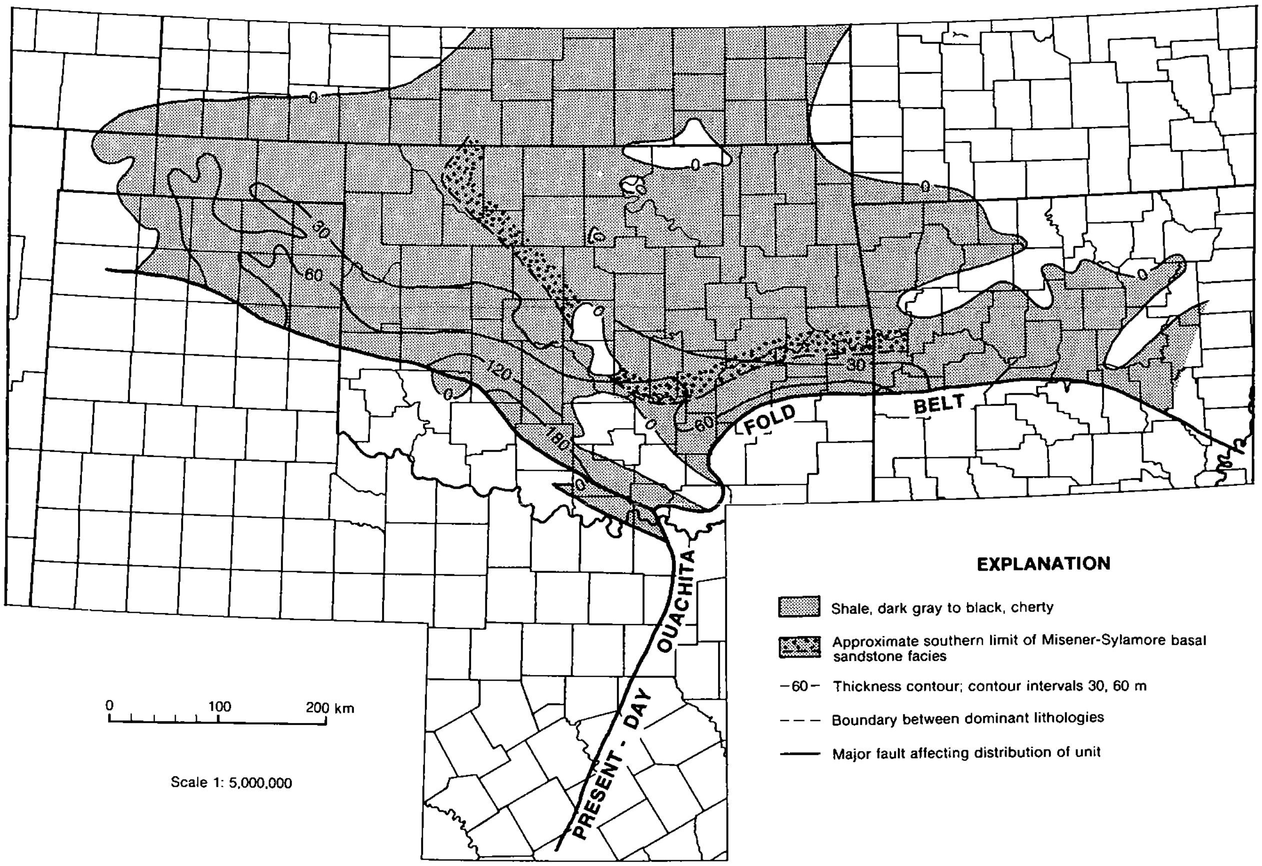


Figure 20. Thickness and dominant lithologies of the Woodford–Chattanooga Shale (from Johnson and others, 1988).

Microfossils recognized in the Woodford Shale include miospores, acritarchs, algae (*Tasmanites*, *Quisquilites*, *Foerstia*), scolecodonts, conodonts, radiolarians, and sponge spicules (Cooper, 1931a,b; Urban, 1960; Wilson and Urban, 1963,1971; Hass and Huddle, 1965; Wilson and Skvarla, 1967; Von Almen, 1970; Orth and others, 1988; Barrick and Klapper, 1990; Over, 1990; Schwartzapfel, 1990; Schwartzapfel and Holdsworth, 1991; Kirkland and others, 1992; Siy, 1993).

Macrofauna reported in rare occurrences from the Woodford Shale include brachiopods (*Lingula*, *Productella*, *Spirifer*, *Strophomena*), arthropods (crustacean), gastropods, and cephalopods (*Probleoceras*, *Mooreoceras*) (Girty, 1909; Reeds, 1927; Roth, 1929; Cooper, 1932; Green, 1972; Kirkland and others, 1992).

The progymnosperm *Archaeopteris* (organ genus *Callixylon*) and the gymnosperm Cordaitales (form genus *Dadoxylon*) are the most common vascular flora observed in the Woodford Shale, especially in the lower portion (Reeds, 1927; Arnold, 1934,1947; Wilson, 1958; Huffman and Starke, 1960; Von Almen, 1970; Kirkland and others, 1992). Silicified *Callixylon* logs are in the basal Woodford Shale at the Henry House Falls (HHF) quarry, ~5 mi (8 km) west of stop 3 (H on Fig. 5; secs. 30 and 31, T. 2 S., R. 1 E.); measured section in Hass and Huddle (1965) and Kirkland and others (1992).

The Woodford Shale at stop 3 was deposited in the southern Oklahoma aulacogen; the Washita Valley fault is the craton/aulacogen bounding fault zone (Fig. 4). The black, organic-rich composition of the shale (organic carbon concentrations as much as 25 wt%) and the occurrence of phosphate nodules and chert suggest that the upper part of the Woodford, at least, was deposited in relatively deep water (200–500 ft [60–150 m]) (Tucker, 1991; Kirkland and others, 1992) near the oxygen-minimum zone (Heckel and Witzke, 1979; Spesshardt and Barrick, 1986; Siy, 1993). Kirkland and others (1992) argued against an upwelling model and preferred a thermocline model for anaerobic conditions. Based on an abundance of radiolarians (siliceous microfossils), Roberts and Mitterer (1992) concluded that the chert was of primary origin. Radiolarians and sponge spicules were also a major source of silica for the shale (Kirkland and others, 1992). Siy (1993) described the inorganic petrography and geochemistry of the Woodford Shale in the Arbuckle Mountains and indicated that the nodules are 14.97–38.4 wt% P_2O_5, classified as phosphorites.

O'Brien and Slatt (1990) described the whole-rock mineral composition (wt%) of a Woodford Shale sample from Carter County as containing 63% quartz, 3% plagioclase feldspar, 10% calcite, 6% dolomite, 5% pyrite, and 14% total layer silicates. Kirkland and others (1992) reported the mineral composition of several

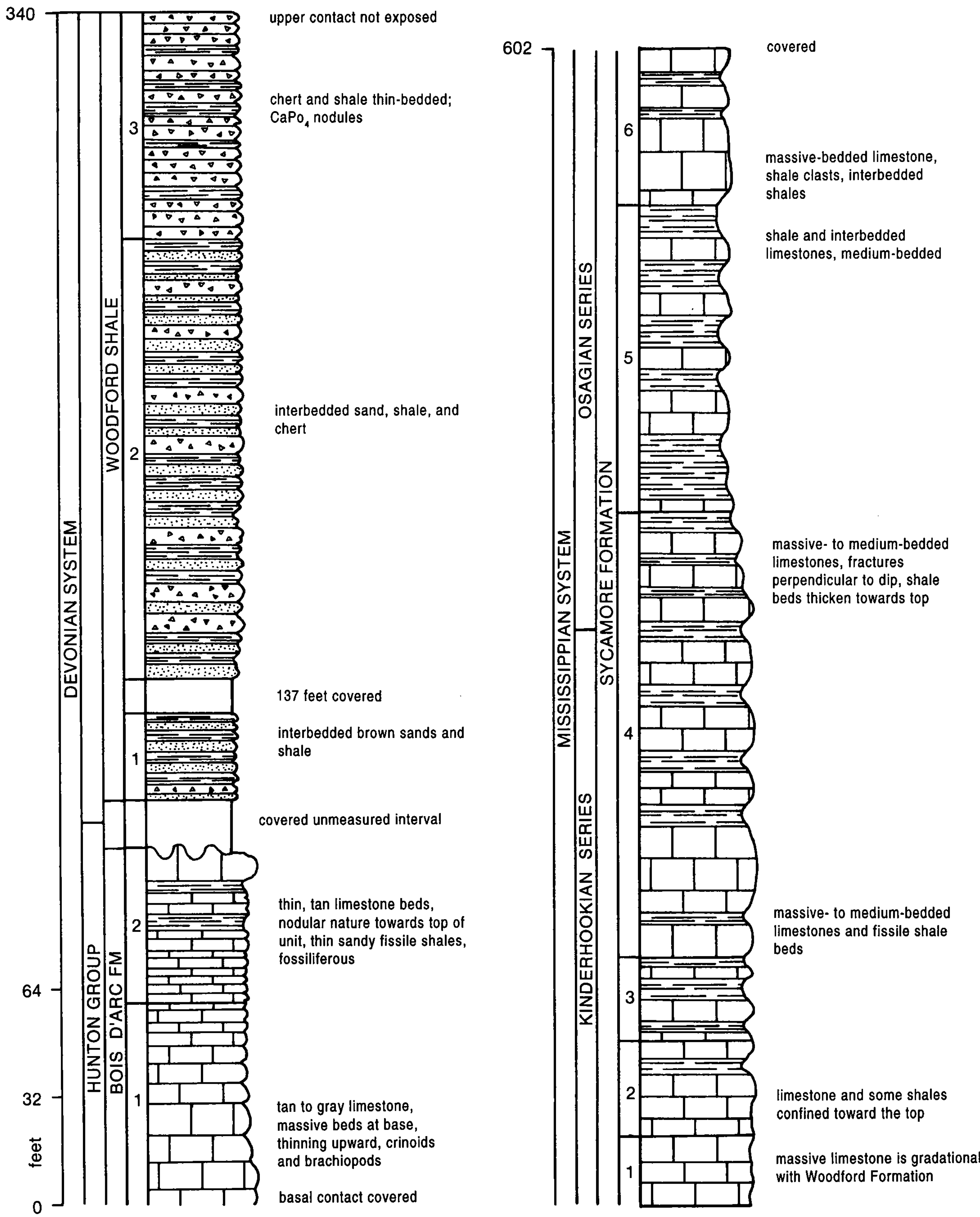


Figure 21. Measured section of the Bois d'Arc, Woodford, and Sycamore Formations at stop 3 (modified from Ellis and Westergaard, 1985).

Woodford Shale samples from the HHF quarry as having 55–87% quartz, 0–7% K-feldspar, 0–3% dolomite, 0–1% apatite, 0–1% pyrite, 8–34% illite, and 3–7% kaolin. The percentage of chert increases toward the top of the formation, and the lower portion contains black fissile shale (Siy, 1993). Kirkland and others (1992) described the occurrence and origin of phosphate nodules, pyrite concretions, and calcite concretions in the Woodford Shale in southern Oklahoma.

Orth and others (1988) described the geochemistry of the Woodford Shale from the Hass G section (SE¼ SW¼ sec. 35, T. 3 N., R. 6 E., Pontotoc County, Oklahoma) and reported that Ir (0.25 ppb), Pt, Au, V, Ni, U, and all measured chalcophiles (Cu, Zn, As, Se, Mo, Ag, Sb, and Hg) are highly enriched in the top 1 m of the Woodford Shale at that locality.

Cardott (1992) provided an extensive bibliography of the Woodford Shale of Oklahoma through 1991. Additional research papers are in Johnson and Cardott (1992a).

Hydrocarbon Source Rock

Organic geochemistry studies suggest that the Woodford Shale is an important hydrocarbon source rock in Oklahoma (Comer and Hinch, 1987; Cardott, 1989). Comer and Hinch (1987) and Comer (1992) reported that 70–85% of the oil produced in central and southern Oklahoma was generated by the Woodford Shale. Based on gas chromatography and biomarker analysis, Zemmels and Walters (1987) and Zemmels and others (1987) concluded that the Woodford Shale was the source of oils produced from the Arbuckle Group, Simpson Group, Bois d'Arc Formation, Woodford Shale, and Deese Group in the vicinity of the Arbuckle Mountains (Fig. 3). Wavrek (1992) attributed 55% of oil sample types in Ardmore-basin and Marietta-basin reservoirs to the Woodford Shale (Fig. 16, oil type C).

Kerogen Type: Based on bulk geochemical composition, the organic matter in the Woodford Shale is classified as type II (oil-prone) kerogen (Johnson and Cardott, 1992b; type IID kerogen of Hunt and others, 1991). Lewan (1983) and TSOP (1989) indicated that >90% by volume of the organic matter at stop 3 is amorphous kerogen. G. E. Michael, C. L. Thompson-Rizer, and R. A. Woods (1993, personal communication) reported the visual kerogen composition of the Woodford Shale at stop 3 to be 80% amorphous type A (fluorescing, oil prone) (Thompson and Dembicki, 1986), 15% herbaceous (includes *Tasmanites* and acritarchs), and 5% solid bitumen; fluorescence intensity from the herbaceous kerogen was strong, and fluorescence intensity from the amorphous kerogen was weak. Thompson-Rizer and others (1988) reported the results from a sample exchange study that included a Woodford Shale sample from the Arbuckle Mountains, Carter County. They concluded that more work is needed to obtain consensus on quantitative fluorescence values of dispersed organic matter in sedimentary rocks.

Tables 2 and 3 summarize the organic geochemistry of the Woodford Shale for stop 3. Total organic carbon (TOC) contents from ~2 to 14 wt% indicate very good hydrocarbon source potential. Concentrated zones contain as much as 25 wt% TOC. Roberts and Mitterer (1992, p. 333) indicated that "lower organic carbon content of the cherts is inferred to be due to sedimentary dilution of organic matter during periods of high siliceous productivity rather than to differences in type of organic matter." The atomic H/C content is 1.14–1.24; the atomic O/C content is 0.07–0.08. The ratios were used by Horsfield (1989) and Comer (1992) to classify the organic matter in the Woodford Shale as type II kerogen. The hydrogen index, ranging from 377 to 763 mgHC/g OC, suggests oil-prone potential. The oxygen index is 18–35 $mgCO_2/g$ OC. Figure 22 is a Van Krevelen-type diagram of the hydrogen and oxygen indices showing the type II kerogen at stop 3 (G. E. Michael, C. L. Thompson, and R. A. Woods, 1993, personal communication). The kerogen-type indicator value of ~18 suggests that the kerogen is oil prone. The production index of 0.02 indicates that the sample is immature.

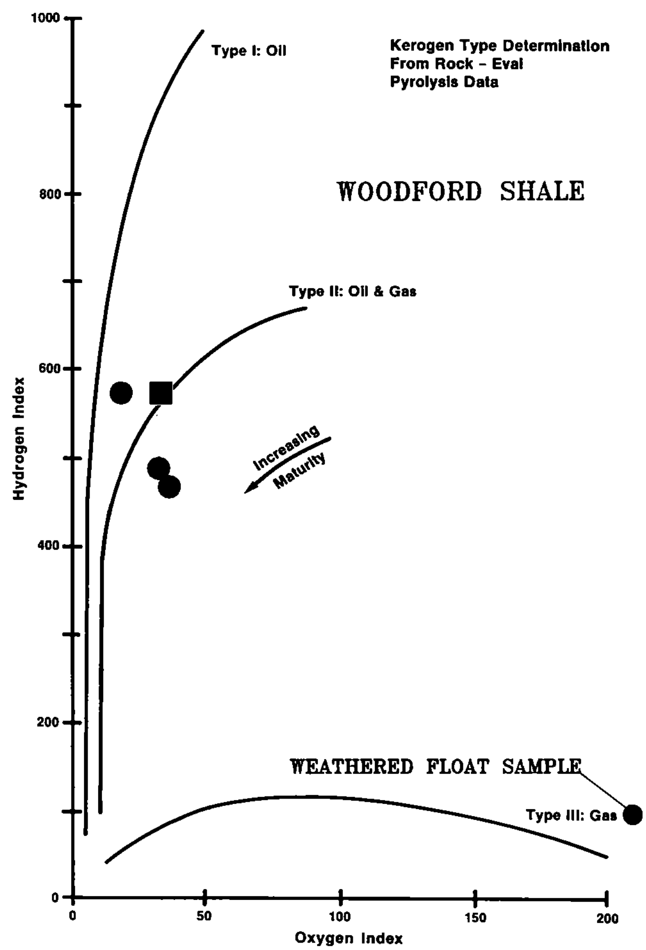


Figure 22. Van Krevelen-type diagram of Rock-Eval pyrolysis data showing the kerogen type of the Woodford Shale at stop 3 (■) and stop 6 (●). Data is in Table 2.

TABLE 2. — ROCK-EVAL PYROLYSIS DATA[a]

Stop no.	Unit	TOC[c] (wt%)	S_1[d]	S_2[e]	S_3[f]	S_4[g]	HI[h]	OI[i]	S_2/S_3[j]	PI[k]	T_{max}[l] (°C)
2	Viola	0.67	0.22	3.67	0.32	3.5	548	48	11.47	0.06	432
3	Woodford	2.13	0.29	12.25	0.67	11.0	575	31	18.28	0.02	435
5	Viola	6.23	20.47	38.12	0.76	14.3	—	—	—	0.35	426
6	Woodford[b]	3.68	0.06	3.40	7.91	34.0	92	215	0.43	0.02	418
	Woodford	7.80	0.89	44.89	1.22	40.5	576	16	36.80	0.02	416
	Woodford	8.17	0.68	40.11	2.45	48.3	491	30	16.37	0.02	417
	Woodford	8.57	0.73	40.31	2.94	52.0	470	34	13.71	0.02	418
7	Oil Creek	8.61	45.27	41.77	2.86	14.7	—	—	—	0.52	416

[a]Data from G. E. Michael, C. L. Thompson-Rizer, and R. A. Woods (1993, personal communication); parameter explanation after Peters and Moldowan (1993).

[b]Weathered float block from the quarry floor.

[c]Total organic carbon content. TOC = $[0.82(S_1+S_2)+S_4]/10$. Considered to have hydrocarbon source potential if >0.5 wt%.

[d]S_1 (mgHC/gROCK). The amount of free (extractable) bitumen in a sample.

[e]S_2 (mgHC/gROCK). The amount of hydrocarbons released during pyrolysis.

[f]S_3 ($mgCo_2$/gROCK). The amount of carbon dioxide released during pyrolysis.

[g]S_4 (mgC/gROCK). The amount of residual carbon released during the final, high-temperature stage of pyrolysis.

[h]Hydrogen index (mgHC/gOC). HI = (S_2/TOC). In general, gas-prone if <200 and mainly oil-prone if >300.

[i]Oxygen index ($mgCO_2$/gOC). OI = 100 (S_3/TOC).

[j]Kerogen-type indicator. Gas-prone if <5, oil-prone if >10, and mixed if between 5 and 10.

[k]Production index. PI = $S_1/(S_1+S_2)$. In general, immature if <0.1, in oil window if between 0.1 and 0.4, and in gas window if >0.4. Higher PI values may indicate contamination and/or oil stain.

[l]The temperature at the apex of the S_2 peak. In general, a T_{max} range of 435–470°C corresponds to the oil window.

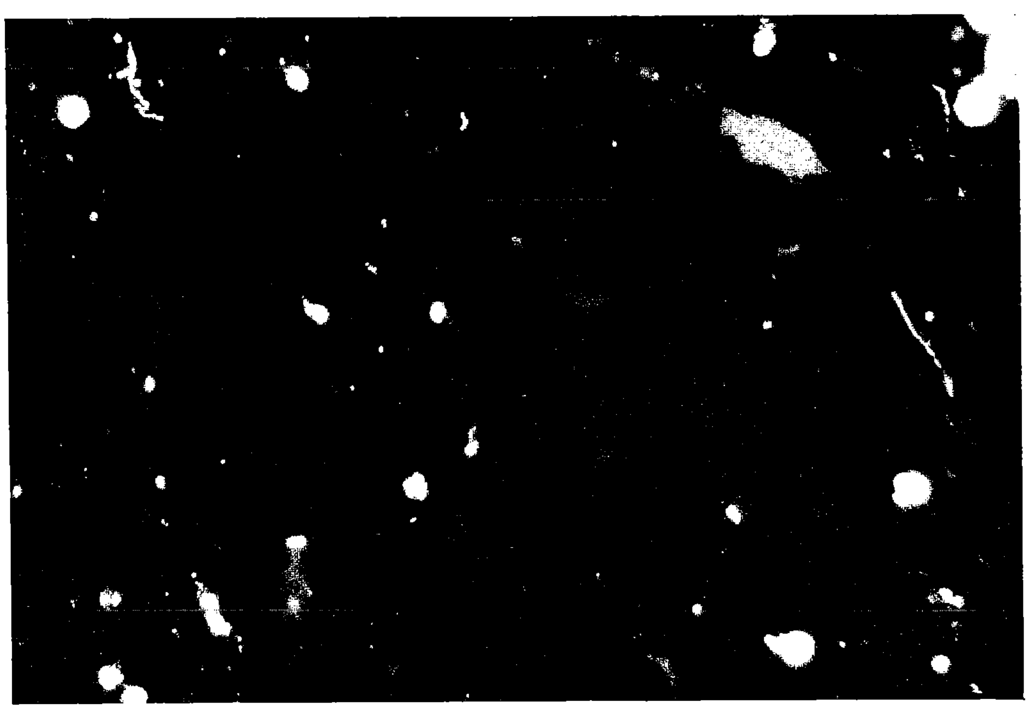


Figure 23. Photomicrograph of low-reflecting bitumen (on left; 0.36% R_o) and vitrinite (0.52% R_o) from Woodford Shale type locality (T on Fig. 5; reflected white light, oil immersion, 200×, field width is 140 μ).

TABLE 3. — ORGANIC GEOCHEMISTRY OF THE WOODFORD SHALE AT STOP 3

Source	TOC[a] (wt%)	Atomic[b] H/C	Atomic[c] O/C	HI[d]	OI[e]	T_{max}[f] (°C)	R_o[g] (%)
Lewan (1987)	4.3–14.0	1.14–1.21					0.35–0.44
Horsfield (1989)		1.24	0.08	460	35		0.38
TSOP (1989)	5.4–9.2			377–763	18–25	413–421	0.3
Comer (1992)	8.4	1.19	0.07				0.52
Roberts and Mitterer (1992)							
black shale	10–25					431	
chert	3–9						

[a]Total organic carbon content (see Table 2).

[b]Hydrogen/carbon atomic ratio. ([% H/1.008]/[% C/12.011]).

[c]Oxygen/carbon atomic ratio. ([% O/15.999]/[% C/12.011]).

[d]Hydrogen index (see Table 2).

[e]Oxygen index (see Table 2).

[f]The temperature at the apex of the S_2 peak (see Table 2).

[g]Vitrinite reflectance (oil immersion). In general, values <0.4% are immature, 0.4–0.6% are marginally mature, 0.6–1.3% are early to middle mature ("oil window"), 1.3–2.0% are late mature, and >2.0% are postmature with respect to the generation of liquid hydrocarbons.

The T_{max} of 413–435° C indicates that the samples are marginally mature (vitrinite reflectance equivalent of 0.5–0.7%). An additional Woodford Shale sample from stop 3 contains 5,823 ppm extractable organic matter (EOM) (by Soxhlet extraction using 2:1 toluene-isopropanol) (Jane Weber, unpublished data).

Vitrinite Reflectance: The Woodford Shale is the oldest rock in the Arbuckle Mountains that contains vitrinite (Wilson, 1958; Ham and others, 1973) and was deposited prior to the Middle to Late Pennsylvanian Arbuckle orogeny. Therefore, the Woodford Shale has less high-gray (recycled) vitrinite than younger rocks and records the thermal history of the Arbuckle orogeny.

Cardott and others (1990) indicated that the Woodford Shale in the Arbuckle Mountains is immature to marginally mature with respect to the generation of oil based on mean random (nonpolarized light, stationary stage, kerogen concentrate) vitrinite reflectance values of 0.35–0.77% and a weighted average of 0.54%. The reported vitrinite reflectance values of the Woodford Shale at stop 3 range from 0.3 to 0.52% (Table 3). The wide range in values is attributed to the occurrence of low-reflecting (0.25–0.47%) vitrinite-like bitumen, overlapping the vitrinite reflectance range. Jacob (1985,1989) developed a regression equation that related bitumen reflectance to vitrinite reflectance and indicated that bitumen has a reflectance lower than vitrinite when both are <1.0%. In reflected light, the bitumen in the Woodford Shale at stop 3 can have granular or nongranular texture, can be weakly fluorescing to nonfluorescing, often is translucent, and has internal reflections from pyrite. Lewan (1987) concluded that petroleum-filled fractures in the Woodford Shale at stop 3 contained exogenous oil rather than indigenous bitumen. Excluding bitumen reflectance values, the mean random (whole rock) vitrinite reflectance of the Woodford Shale at stop 3 is 0.50% (79 measurements with 0.43–0.66% reflectance range), which suggests that the sample is marginally mature.

Vitrinite reflectance values of Woodford Shale samples from the continuous outcrop belt to the west of stop 3 are similar to the value at stop 3. The Woodford Shale at the type locality (T on Fig. 5; sec. 34, T. 2 S., R. 1 W., ~8 mi [13 km] west of stop 3) contains abundant bitumen (1.72% EOM by Soxhlet extraction using dichloromethane) and has a mean random (whole rock) vitrinite reflectance of 0.49% (70 measurements with 0.40–0.62% reflectance range) (Fig. 23). Bitumen (tar) balls are found in the Woodford Shale at the McAlester quarry in the Criner Hills (sec. 36, T. 5 S., R. 1 E.; Kirkland and others, 1992) and at the type locality.

The Woodford Shale at the Henry House Falls (HHF) quarry (H on Fig. 5) has a mean random vitrinite reflectance of 0.50% (48 measurements with 0.43–0.64% reflectance range). Comer (1992, sample OK23) reported 0.65% R_o at the HHF quarry. Kirkland and others (1992) described the geology and organic geochemistry of the Woodford Shale at the HHF quarry.

Hydrous Pyrolysis: Lewan (1983,1985,1987,1992) used Woodford Shale samples from this exposure for hydrous pyrolysis experiments. Hydrous pyrolysis involves isothermally heating aliquots of crushed rock in contact with liquid water at temperatures ranging 300–360°C for 72 hours. Geochemical analysis of expelled oil-like pyrolysate, bitumen, and kerogen revealed that hydrous pyrolysis simulates the natural oil-generating process. Results were related to the stages, kinetics, and indices of petroleum generation.

Lewan (1983,1985) identified four stages of petroleum generation: pre-oil-generation, incipient oil-generation (bitumenization), primary oil-generation (expulsion), and post-oil-generation (gasification). Petroleum generation follows three basic reactions: (1) the thermal decomposition of kerogen to bitumen; maximum bitumen generation occurs at the end of the incipient oil-generation stage; (2) the thermal decomposition of bitumen to oil; maximum oil generation occurs at the end of the primary oil-generation stage; and (3) the thermal decomposition of oil to gas and pyrobitumen in the post-oil-generation stage.

The Woodford Shale at stop 3 was selected for hydrous pyrolysis study because it is in the pre-oil generation stage and contains amorphous type II (oil-generating) kerogen. Using kinetic parameters, Lewan (1985) showed that primary oil generation begins at a lower thermal stress for an amorphous type II kerogen with a high organic sulfur content (e.g., 9.0% normalized by mass) such as the Phosphoria Retort Shale than for an amorphous type II kerogen with a low organic sulfur content (e.g., 5.0% normalized by mass) such as the Woodford Shale. Lewan (1985, p. 128) stated: "It is conceivable that within a kerogen its carbon-sulfur bonds may cleave more readily to generate liquid hydrocarbons than its carbon-carbon bonds."

Lewan (1983) found that the atomic H/C ratio of amorphous type II kerogen may be a good index for the stages of petroleum generation, and that vitrinite reflectance measurement may be a good index for the magnitude of thermal stress experienced by kerogen.

Weathering: Lo and Cardott (1993) found that vitrinite reflectance of a surface grab sample was as much as 0.20% lower than that of shallow (19 ft [6 m]) corehole samples of the Woodford Shale taken along Highway 77D (NE¼ sec. 30, T. 1 S., R. 2 E.) in the Arbuckle Mountains. Some of the low vitrinite reflectance values in Cardott and others (1990) (e.g., sample no. 2, 0.35% R_o) may be attributed to weathering. Philp and others (1992) reported the effects of weathering on the geochemistry of Woodford Shale surface samples from the Arbuckle Mountains. Surface samples were divided into two groups based on changes in hydrocarbon and stable isotopic compositions. Both groups of surface samples were weathered compared to subsurface samples. Comparison of the two groups indicated that Group I samples had lower contents of n-alkanes and tricyclic terpanes, and higher contents of C_{21}–C_{22} steranes and $\alpha\beta\beta$ steranes than Group II samples, which suggests more extensive weathering by biodegradation of Group I samples.

STOP 4
Turner Falls Overlook

Location

Turner Falls overlook is located at the gift shop on U.S. Highway 77, ~3 mi (4.8 km) south of Davis, Oklahoma, and ~3 mi (4.8 km) north of the southernmost U.S. Highway 77 exit off of Interstate 35 (exit 47). Detailed location: The Turner Falls overlook is in the SW¼SE¼NE¼ sec. 36, T. 1 S., R. 1 E. on the Turner Falls Quadrangle map (7.5′ series), Murray County.

Significance

- Observation of Cambrian Carlton Rhyolite, which represents "basement" in this part of the Arbuckles.
- Traces of the Washita Valley and Chapman Ranch fault zones.
- Observation of active and inactive travertine and tufa deposits.
- Karstification in the Arbuckle Group.

Description

Portions of the following description and discussion are adapted from Ham (1969), Kidman (1985), Donovan and others (1988), Ragland and Donovan (1991), and Donovan and Ragland (1991).

Turner Falls, a popular tourist attraction in the Arbuckle Mountains, is the most impressive waterfall in Oklahoma (Fig. 24). It has a vertical drop of 77 ft (23 m). It is geologically unusual because the tumbling waters of Honey Creek have deposited a complex edifice of calcium carbonate (travertine and tufa) precipitated from the water. As a result, the waterfall scarp has advanced (prograded) downstream, rather than receding upstream like most waterfalls. This beautiful waterfall now is in a steady state stage; it receives about as much calcium carbonate in the form of stream-floor deposits as it loses through mechanical abrasion during flooding events. Blue-green algae assist in precipitating the calcium carbonate.

Discussion

The overlook is located on the south side of the trace of the Washita Valley fault zone, just south of

Figure 24. Turner Falls, viewed from scenic overlook (stop 4), U.S. Highway 77. The waters of Honey Creek flow over an active, fan-shaped travertine deposit; older, inactive travertine deposits tower above the falls. Behind the falls are the East Timbered Hills (microwave relay towers) composed of the Carlton Rhyolite (Cambrian basement rock). Between the Carlton Rhyolite and the overlook are complexly folded and faulted Late Cambrian/Early Ordovician rocks on the north limb of the Arbuckle anticline.

the outcrop of the Pennsylvanian Collings Ranch Conglomerate (Fig. 25). The tree-covered hill with the radio towers, immediately to the southwest of the overlook, is the crest of the East Timbered Hills anticline, topographically the highest point in the area (elevation of 1,377 ft [420 m]); the core of the East Timbered Hills anticline is the Cambrian Carlton Rhyolite (Fig. 24). Between the rhyolite and the overlook are complexly folded and faulted Upper Cambrian and Lower Ordovician rocks (Arbuckle Group) on the north limb of the Arbuckle anticline. Turner Falls is developed on outcrops of the Ordovician Cool Creek Formation (Arbuckle Group) which outcrops at this overlook. A fault trace parallels the valley of Honey Creek, separating the Cool Creek Formation at the overlook from the McKenzie Hill Formation, which is well exposed downstream and across the valley in a bold cliff face. Above the cliff and just behind it is a small lateral valley, occupied by a few deciduous trees, which marks the trace of the Washita Valley fault zone. North of this fault, the Collings Ranch Conglomerate outcrops. A number of faults have been mapped in this region. Several are splays off from the Washita Valley fault zone; but others are part of the Chapman Ranch thrust fault (Figs. 2,8), which crops out at the base of the East Timbered Hills, on the east and north sides (Fig. 25). The Washita Valley fault zone probably originated as a rift-forming normal fault in the late Precambrian to Early Cambrian during the formation of the southern Oklahoma aulacogen. The fault zone may have separated the subsiding aulacogen to the south, from the craton to the north. Approximately 4,500 ft (1,400 m) of Cambrian rhyolite flows are truncated against the south side of the fault zone and are absent beneath the basal Cambrian Reagan Sandstone on the north side. During the Pennsylvanian, southern Oklahoma underwent a period of uplift and compression. Folding and rejuvenation of the Washita Valley fault zone and other fault zones took place and the present Arbuckle anticline formed.

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 formation 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

- Calcite saturation and major travertine deposition as a result of warmer, drier climates.
- Formation, through deposition, of travertine cliff ~100 ft (30 m) high and 300 ft (92 m) wide.
- Local unconformities developed due to lithological contrasts, faults, and dip variations in the bedrock.
- Examples of thick travertine tubes, deposited around now-vanished tree logs.

Stage 3

- Evidence of speleothems (flowstone, crude stalactites, cave popcorn) developing within the older travertine deposits during a semiarid stage, when the flow of Honey Creek became diminished and intermittent.

Stage 4

- Cessation of carbonate precipitation due to a wetter, cooler climate.
- Honey Creek eroded its own deposit, forming the steep-sided gorge above the modern waterfall.

Stage 5

- Honey Creek reestablished its constructive mode, presumably during a warmer and drier climate.
- Modern travertine/tufa deposits at the falls are the products of this constructive mode.

The entire travertine/tufa edifice at Turner Falls is an excellent expression of how climatic variations—as opposed to tectonics or other base-level controls—can affect fluvial erosion.

Lower Ordovician Arbuckle Group (Cool Creek Formation)

Significance

- Superb preservation of sedimentary structures of peritidal carbonates including edgewise conglomerates, mud-cracked calcilutites, and a diversity of morphologic growth forms of algal stromatolites and thrombolites.
- Shallowing-upward parasequences (fifth-order carbonate cycles) typical of Arbuckle deposition.
- Recognition of potential reservoir interval(s) in carbonate cycles.
- Recognition of potential hydrocarbon source rock and identification of that part of the cycle that might provide the richest source rock (i.e., can Arbuckle rocks be self-sourcing)?

Arbuckle Group

Description

Portions of the following description and discussion are adapted from Ragland and Donovan (1985, 1991), Wilson and others (1991), and Lindsay and Koskelin (1993).

The Cool Creek Formation, upon which the overlook is situated, is part of the Cambrian–Ordovician Arbuckle Group, a thick accumulation (6,000+ ft [1,800+ m]) of cyclic peritidal carbonates. The Arbuckle Group was deposited upon an extremely broad, nearly flat carbonate ramp that formed the southern margin of the North American craton. Lithic equivalents, at least in part, include the Knox Group, southern Appalachians; the Ellenburger

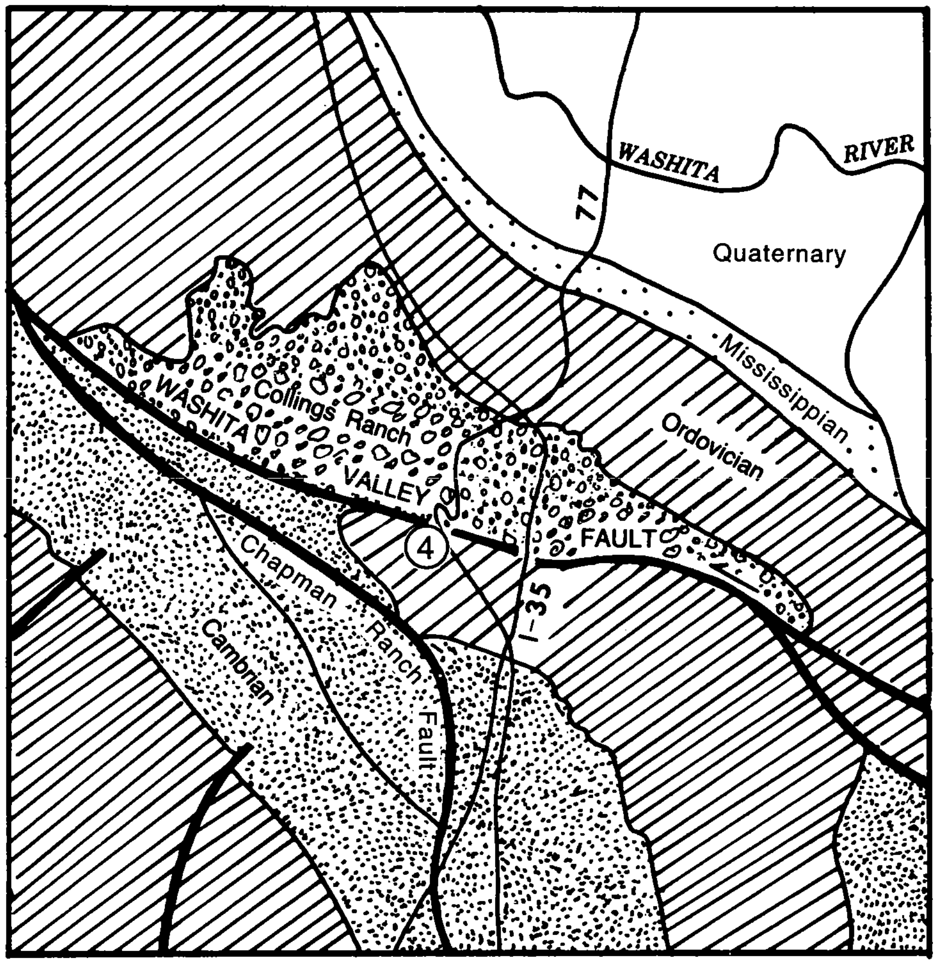


Figure 25. Generalized geologic map of Turner Falls area (stop 4). Modified from Brown and Grayson (1985).

Group, Llano uplift area, Texas; the El Paso Group, westernmost Texas; and the Pogonip Group along the western edge of the North American craton. The Cool Creek Formation is Early Ordovician in age (middle Canadian) and occurs stratigraphically ~3,300 ft (1,000 m) below the top of the Arbuckle Group (Fig. 3). The Arbuckle Group attains a maximum thickness of 8,000 ft (2,400 m) in the southern Oklahoma aulacogen. A nearly complete sequence consisting of eight formations of the Cambrian–Ordovician Arbuckle Group is exposed in road cuts along Interstate 35 and on the adjacent Chapman Ranch in the southern Arbuckle Mountains.

Arbuckle deposition consists of small-scale, relatively short-lived, fifth-order carbonate cycles. The predominant, peritidal carbonates of the Arbuckle Group are chiefly limestone but some dolomite, sandstone, and shale are present. In the subsurface, on the craton, the Arbuckle Group has been extensively dolomitized. After deposition and physical and chemical compaction, these shallowing-upward parasequences are 1–104 ft (0.3–32 m) thick (an average of 14 ft [4 m]). These cycles record abrupt transgressive events, caused by rapid sea-level rise, followed by progradation of a paleoshoreline as sea level gradually fell. Each cycle can be divided into subtidal and tidal-flat components. Subtidal and tidal-flat components may be equal in thickness, one component may be dominant and the other subordinate, or one component may be completely missing from a cycle. Only about half of all cycles are complete shallowing-upward sequences. The boundaries of these cycles often are disconformities or even local to subregional unconformities. Rates of subsidence nearly matched rates of carbonate deposition on the carbonate ramp, which permitted transgression and regression of the sea across vast distances on the southern margin of the North American craton. Some cycles record a deepening event at the top of individual parasequences; the next transgressive event then abruptly deposited a shallow-marine bed on top of the preceding back-stepping (drowning) deposit. Resulting incomplete shallowing-upward parasequences suggest that transgression and basin subsidence were not always related. Each parasequence is unique in its set of facies variations, in its thickness, and in its degree of completeness, which suggests that the rates of subsidence and rates of carbonate deposition were not always equal. An example of a shallowing-upward carbonate cycle of the Arbuckle Group is shown in Figure 26.

Cool Creek Formation

Description

Two excellent sections can be studied at this stop. The thicker, stratigraphically lower section (starts ~300 ft [90 m] above the base) is exposed along the cliff below the gift shop and formerly could be examined along the pathway leading down to the waterfalls. Unfortunately, deterioration of the steps has made the pathway extremely hazardous, and people have been injured on it. It is now barricaded. The second section is a road cut on U.S. Highway 77 directly across the highway from the gift shop. The Cool Creek is ~1,300 ft (400 m) thick and may contain as much as 118 shallowing-upward parasequences. Individual parasequences average 10.75 ft (3.3 m) in thickness. The Cool Creek is the least fossiliferous formation in the Arbuckle Group. The lower boundary of the Cool Creek with the McKenzie Hill Formation is marked by abundant quartz sand. The upper boundary with the Kindblade Formation is defined on paleontological criteria, namely, the earliest occurrence of the enigmatic gastropod genus, *Ceratopea.* Unfortunately, this gastropod genus is not always easily found in the field.

The following lithofacies are recognized in the Cool Creek Formation at this stop: (1) algal boundstones (dominant facies) (Fig. 27); (2) intraformational con-

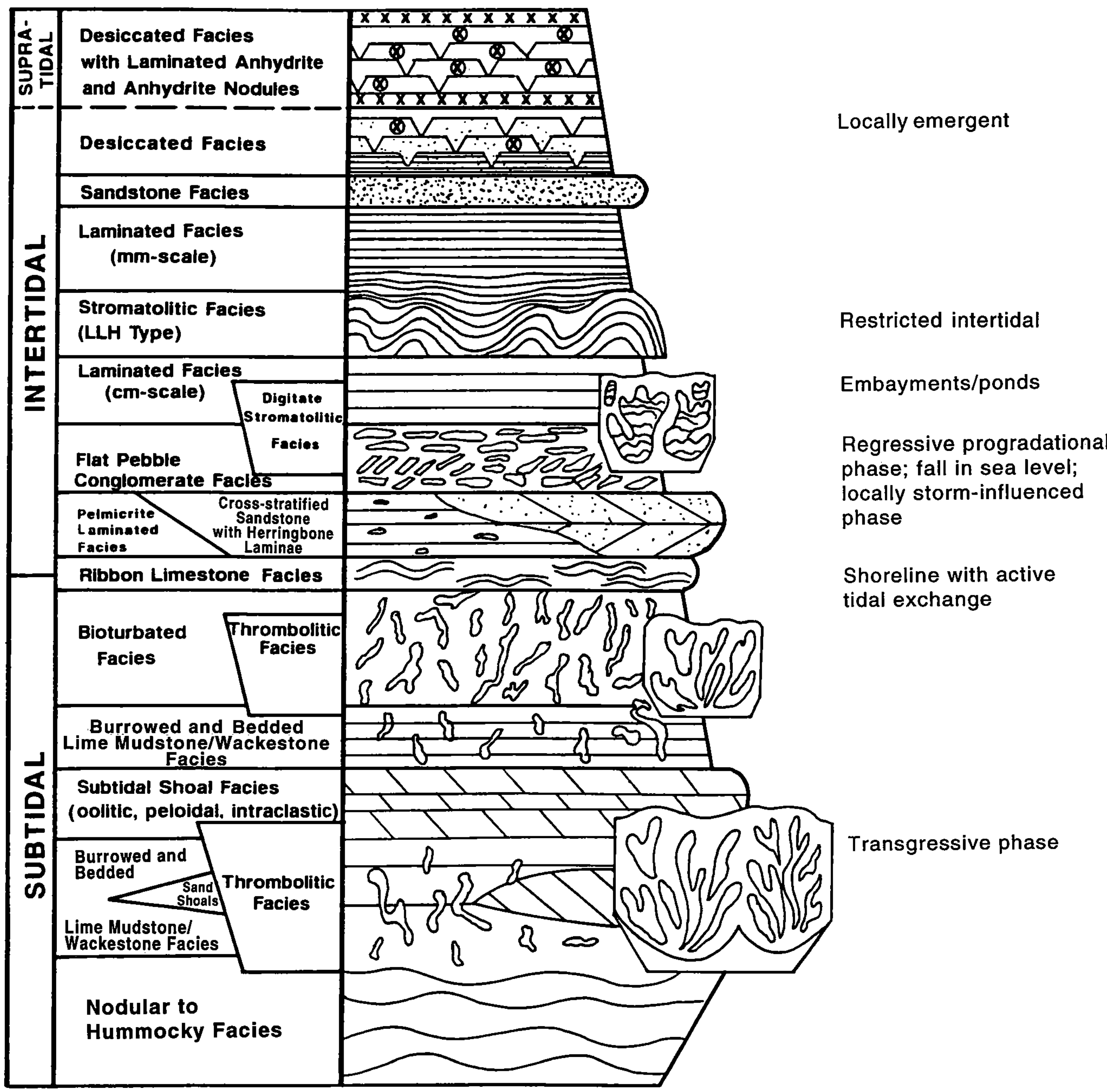


Figure 26. Example of a shallowing upward carbonate cycle of the Arbuckle Group. Modified after Wilson and others (1991).

glomerates (Fig. 28); (3) quartz-rich oolitic grainstones; (4) peloidal limestones; (5) lime mudstones; (6) cross-stratified quartz arenites; (7) bioturbated mudstones, wackestones, packstones; (8) heterolithic units (Fig. 29); and (9) cherty facies (Fig. 30). Chertification and dolomitization have affected these lithologies to varying degrees. However, the effects of dolomitization, which is so prevalent in many other Cambrian–Ordovician sequences, is minimal. Consequently, sedimentary structures diagnostic of peritidal carbonates, are exceptionally well preserved at this stop. The recognition of these different lithofacies is very important since facies associated with the well-developed subtidal parts of a parasequence can form reservoir intervals, whereas facies associated with the tidal-flat parts of a parasequence can form impermeable beds (seals). A brief description of the most common facies that can be observed at this stop follows.

Algal Boundstone Facies: Algal boundstones constitute the most common facies. External forms include encrustations, mats, mounds, and reefs. Internal organization into several morphologic growth forms of stromatolites and thrombolites (e.g., digitate, dendritic, cylindrical, columnar, turbinate) is apparent. The differing growth forms are thought to be a behavioral response to varying water depths and/or clastic influx.

Figure 27. Top view of thrombolitic mounds, broad domal stromatolitic growth forms of the algal boundstone facies, showing characteristic clotted texture; subtidal facies of a shallowing-upward cycle in the Cool Creek Formation. Opposite Turner Falls overlook (stop 4), U.S. Highway 77.

Figure 28. Block of limestone (intraformational conglomerate facies) from the Cool Creek Formation used as building stone in gift-shop wall, Turner Falls overlook (stop 4), U.S. Highway 77. The block was emplaced upside down (arrow indicates top of bed). The base of unit consists of intraformational conglomerate (IFC) composed of imbricate to vertical rod-shaped clasts of lime mud, quartz sand, and encrusting stromatolites. The upper part of the unit is composed of wavy-laminated micrite layers (algal-mat structures), alternating with quartz-rich laminae. Note the top planar erosion surface of IFC bed on which laminated micrite and encrusting algae were deposited. Example of tidal flat facies of shallowing-upward carbonate cycle.

Intraformational Conglomerate Facies: Intraformational conglomerates and flat-pebble conglomerates are abundant throughout the Cool Creek Formation. Most of the conglomerates are mud-supported and contain clasts of lime mud and subordinate amounts of algal desiccation chips. These clasts probably owe their origin to periodic storm events. The conglomerates usually occur in 1-ft (0.3-m) thick beds with eroded bases.

Quartz-Rich Oolitic Grainstone Facies: Grainstones are a common facies in the Cool Creek Formation. The principal allochems are lime-mud intraclasts and ooids; skeletal grains are uncommon. Some of the quartz-rich grainstones show crossbedding. This facies sometimes occurs as infill between algal mounds and in heterolithic units interbedded with lime mudstone.

Quartz Arenite Facies: Varying amounts of quartz sands are common throughout the Cool Creek Formation. The bedded quartz arenites are thin and commonly show small-scale trough crossbedding. The abundance of detrital quartz and the overall paucity of sponge spicules in the Cool Creek suggest that the detrital quartz may be the principal source for the abundant chert in the section.

Bioturbated Mudstone/Wackestone/Packstone Facies: Mudstones, wackestones, and packstones are also common facies in the Cool Creek. The allochems are dominated by well-sorted peloids, probably fecal pellets. Some of the beds have well-developed laminations; others are bioturbated.

Heterolithic Facies: Heterolithic units in the Cool Creek are characterized by varieties of flaser bedding. The units are composed of alternating layers of lime mud and quartz-rich grainstones and siltstones. The quartz-rich grainstones frequently show small-scale crossbedding, some of which can be related to both symmetrical and asymmetrical ripple marks. This facies is commonly cut by both subaerial and subaqueous mud cracks. This is the facies most often dolomitized in the Cool Creek Formation.

Cherty Facies: Chert is present at several horizons and may replace, at least in part, any of the facies described above. Some of the cherts contain molds and pseudomorphs of an evaporite that appears to have been gypsum. Scanning electron microscopy (SEM) studies by Ragland and Donovan (1985,1986) have confirmed the presence of very small crystals of anhydrite and celestite in the pseudomorph-bearing cherts. Evidence for the former presence of bedded and nodular evaporites in the Cool Creek is extensive, despite their apparent rarity in outcrops. St. John and Eby (1978) cited evidence for hypersaline conditions and vanished evaporites in the Cool Creek Formation, including: (1) restricted faunas, (2) high-relief stromatolites, (3) syndepositionally broken ooids, and (4) length-slow chalcedony. Thick solution-collapse breccias also indicate the former presence of evaporites in the Cool Creek; those breccias are best exposed in the thickest section along the cliff below the gift shop.

Depositional Environment

Facies and sedimentary structures of the Cool Creek Formation suggest a highly productive shallow-marine carbonate platform environment in an arid or semiarid setting. Most of the facies bear the

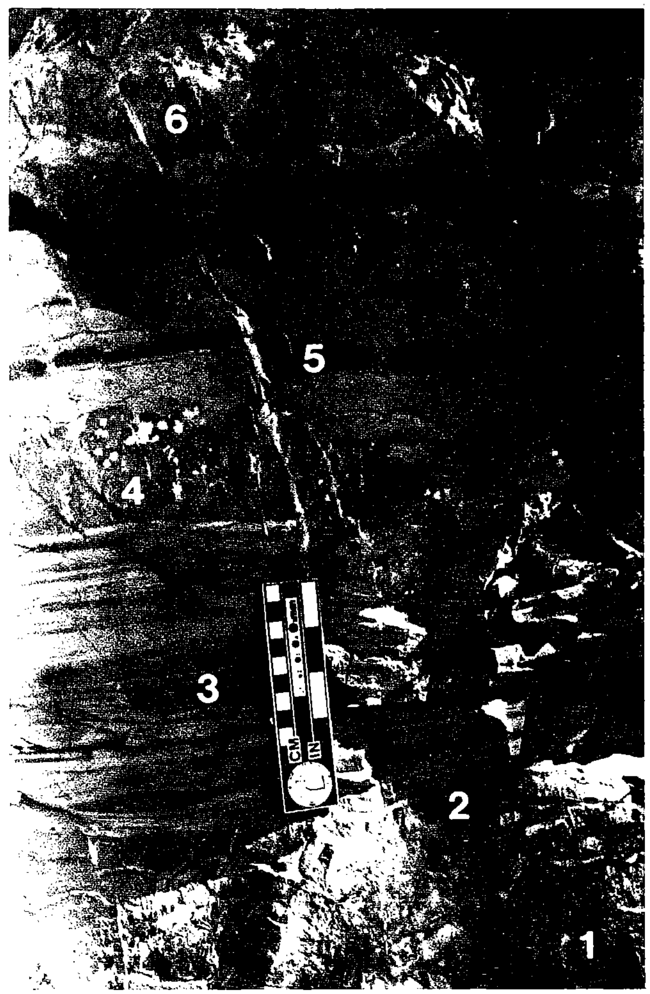


Figure 29. View of a portion of a dominantly subtidal shallowing-upward cycle in the Cool Creek Formation, opposite Turner Falls overlook (stop 4), U.S. Highway 77. The base of the unit is marked by an intraformational conglomerate facies composed of randomly oriented clasts of lime mud, quartz sand, and fragments of encrusting stromatolites (1). Unit 1 is encrusted by a poorly developed algal boundstone facies (2). Overlying the boundstone is a heterolithic facies (3) of micrite, dolomicrite, and quartz silt. The heterolithic facies, in turn, is encrusted by a growth of digitate stromatolites (4). Next is a cherty facies composed of relatively homogeneous micrite containing secondary quartz nodules and chert bands (5). Above the cherty facies is another algal boundstone facies (6).

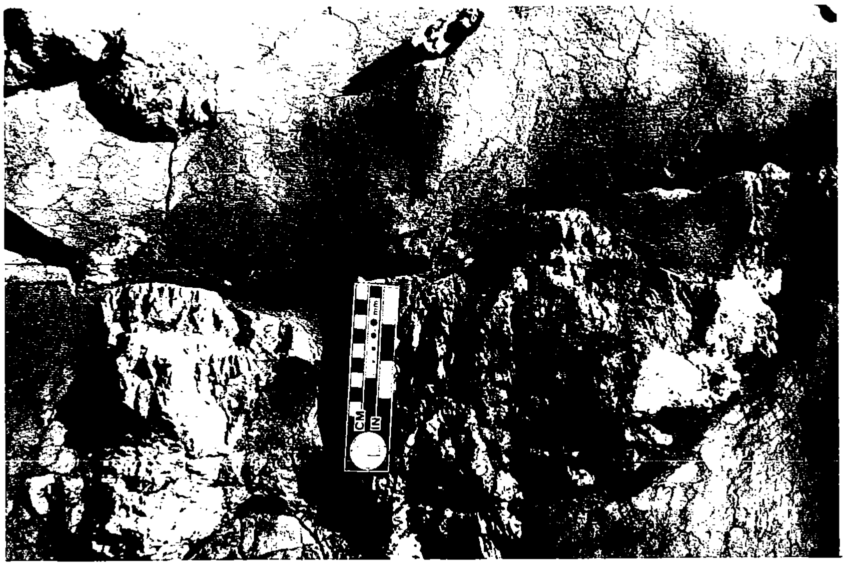


Figure 30. Cherty facies in the Cool Creek Formation, opposite Turner Falls overlook (stop 4), U.S. Highway 77. Chert, occurring in nodular form, selectively has replaced a portion of an algal boundstone facies.

signature of tidal-flat and subtidal sedimentation, and show evidence of periodic supratidal, emergent sabkha-type settings. Evidence for this mode of sedimentation includes evaporite relics and the regular occurrence of thin, stratigraphically persistent dolomite beds. Carbonate packages within the Cool Creek show shallowing-upward cyclicity.

The biota is dominated by blue-green algae, which aid in delineating the regional paleoenvironment. Algal crusts and mats were probably confined to the high intertidal/supratidal zone or restricted bays subject to periodic clastic influx. Digitate-type stromatolitic structures developed primarily in the intertidal zone. 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 growth forms, of which mounds were most common. Thrombolitic structures formed in that part of the subtidal zone where algal mounds were neither subaerially exposed nor subjected to significant clastic influx as frequently as algal growths near the shoreline. Morphologic growth forms intermediate between thrombolites and stromatolites developed in the transition intertidal/subtidal depth zones.

Intraformational conglomerates probably owe their origin to periodic storm events; some of these deposits were subsequently sorted by waves and tidal currents. Alternatively, the conglomerates may record sea-level rise following temporary low stands. The diversity of quartz-rich grainstones and quartz arenites suggests an extensive interplay between storm events, fair-weather waves, and, possibly, tidal influences.

Hydrocarbon Source Rock

Arbuckle Group carbonates are known to be reservoirs in the southern Midcontinent (Gatewood, 1992). However, the hydrocarbon source-rock potential of the Arbuckle Group is open to debate. A panel discussion in Johnson and Cardott (1992a) debated the question "Can carbonates be source rocks for commercial petroleum deposits?" Gatewood (1992) reported that during deposition of the Arbuckle Group carbonates, conditions were good for hydrocarbon source-rock potential.

Johnson and Cardott (1992b) reviewed the literature and summarized the hydrocarbon source-rock potential of Arbuckle Group formations. They concluded that the low TOC (0.03–0.24 wt%) content of Arbuckle carbonates and the limited geochemical data on Arbuckle shales preclude proving or disproving that the Arbuckle Group is a hydrocarbon source rock. Detailed geochemical studies, including oil-source correlations, of the entire Arbuckle sequence are required to verify the source-rock potential of Arbuckle Group carbonates and clastics.

STOP 5
Dougherty Asphalt Quarry

Location

The access road to Lake of the Arbuckles dam and overlook is located east of U.S. Highway 110, ~2 mi (3 km) north of Dougherty. Entrance to Southern Rock Asphalt Co.'s abandoned crushing, screening, and mixing plant is on the north side of the access road. Detailed location: The main pit (U.S. Asphalt No. 2 quarry) is located at the SW¼SW¼NW¼SW¼ sec. 30, T. 1 S., R. 3 E. on the Dougherty Quadrangle map (7.5′ series), Murray County.

CAUTION: Use extreme care when approaching highwalls inside the asphalt pits. Watch for unstable slopes. Obtain permission to enter the quarry from the owner, Gwen Sutton.

Significance

- Dougherty district inactive asphalt quarries.
- Abandoned native asphalt crushing, screening, and mixing plant of Southern Rock Asphalt Co.
- Exhumed reservoir in Viola Group limestone.

Description

Jordan (1964) compiled data on 297 occurrences of petroleum-impregnated rocks, asphaltite deposits, and asphaltic pyrobitumen deposits, located in the southern third of Oklahoma and in northeastern Oklahoma. Petroleum-impregnated rocks include: (1) sandstones and limestones, at or near the surface, that contain asphalt; and (2) rocks in the shallow subsurface (to a depth of 500 ft [152 m]) that contain crude oil. Figure 31 shows the locations of petroleum-impregnated rocks of Oklahoma, including at least 45 sites in the Arbuckle Mountains region.

A number of terms have been used in the literature for asphaltic material (e.g., tar sand, bitumen, heavy oil, oil seep, and asphalt). According to Meyer and de Witt (1990), natural bitumens are semisolid or solid mixtures of hydrocarbons (composed of hydrogen and carbon) and as much as 50% heterocyclic compounds (containing sulfur, oxygen, nitrogen, and trace metals, especially iron, nickel, and vanadium). Natural bitumens are divided into two groups: pyrobitumens (insoluble in carbon disulfide) and soluble natural bitumens (soluble in carbon disulfide). Soluble natural bitumens are divided into three subgroups: mineral wax, natural asphalt, and asphaltite. Natural asphalt, the object of this discussion, is synonymous with the term "tar sand." Meyer and de Witt (1990) defined tar sand as any consolidated or unconsolidated rock that contains natural bitumen (viscosity >10,000 centipoises at reservoir temperature) and heavy oil as having an American Petroleum Institute (API) gravity <20° and viscosity <10,000 centipoises. The organic matter of tar sands is called extra-heavy oil, bitumen, tar, or asphalt, and is the result of petroleum degradation in the reservoir (Tissot and Welte, 1984). In this guidebook, the term "bitumen" will refer to organic matter soluble in organic solvents (e.g., carbon disulfide) and the term "asphalt" will refer to any consolidated or unconsolidated rock that is impregnated with bitumen. Even though the definition of the terms "tar sand" and "asphalt," as used here, are synonymous, the term "tar sand" is not used because the host lithology need not be a sandstone.

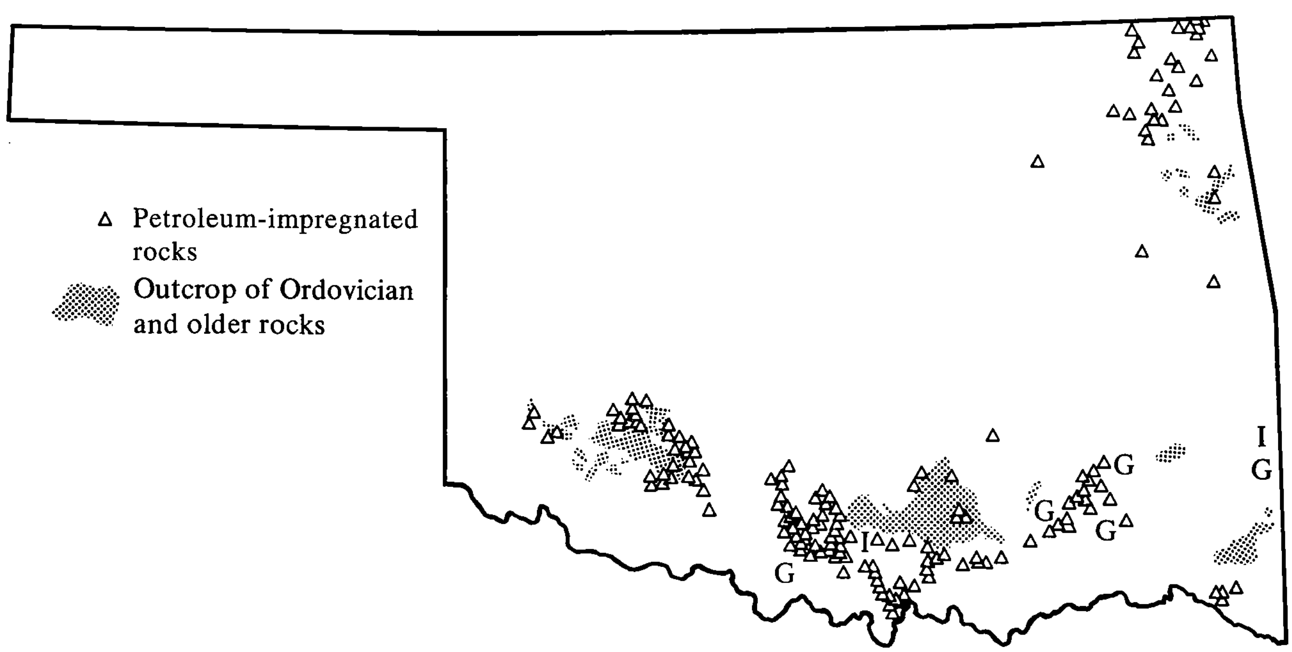


Figure 31. Petroleum-impregnated rocks and asphaltite and asphaltic-pyrobitumen deposits of Oklahoma. G indicates the asphaltite, grahamite; I indicates the asphaltic pyrobitumen, impsonite. Adapted from Jordan (1964) and Hunt (1979).

Figure 32. Southern Rock Asphalt Co. abandoned crushing, screening, and mixing plant at Dougherty district inactive asphalt quarry (stop 5).

The Dougherty (also known as the Brunswick) district asphalt quarries were operated from 1890 to 1960, most recently by the Southern Rock Asphalt Co. Johnson and others (1984) estimated the total production of bitumen-impregnated limestone to be in excess of a million short tons. Bitumen-impregnated rock was quarried from the Dougherty district and Sulphur district (stop 7) and taken by truck to the crushing, screening, and mixing plant near Dougherty. Figure 32 shows the south view of the Dougherty asphalt plant. The blended asphalt product was used as road-paving material.

Six inactive pits and quarries that comprise the Dougherty district are on the southwestern edge of the Mill Creek syncline (Fig. 2). The Reagan fault zone (described as a major left wrench fault or thrust fault) is along the southwestern boundary of the district (trending northwest at the intersection of Highway 110 and the access road). The bitumen is closely associated with numerous faults and joints within the Viola Group limestone (Middle and Upper Ordovician), ~700 ft (210 m) thick. Bitumen content in the Viola limestone varies from 3.0 to 3.5 wt% (Gorman and Flint, 1944; Ham, 1950; Harrison and Burchfield, 1987). Harrison and Burchfield (1987) calculated the total probable in-place bitumen resource of the Dougherty district to be 3.6 million bbl.

The surface geology and an interpretative cross section of the Dougherty district are shown in Figure 33. Refer to stop 2 for a description of the Viola Group. Figure 34 shows the north highwall of the U.S. Asphalt No. 2 quarry; Figure 35 is a close-up view of the asphalt in the talus slope. Gorman and Flint (1944) wrote, "The U.S. Asphalt No. 1 and No. 2 quarries are each about 400 feet [122 meters] in diameter and 15 to 100 feet [5–30 meters] deep. The fault that forms the northern boundary of these quarries also forms the northern boundary of the asphalt deposit. South of this fault the Viola limestone is fairly uniformly impregnated with asphalt, and convenience of quarrying operations rather than asphalt content has been the determining factor in the development of the workings." S. H. Tennant (1980, referenced in Williams, 1985, p. 195) indicated that the dominant porosity in the Viola limestone at the Dougherty district was from fractures caused by faulting. Haas (1981, p. 103) stated: "Extreme brecciation and spaced sheer cleavage observed in the Southern Rock Asphalt quarry marks the wrench crush zone associated with the Reagan Fault."

Bitumen Geochemistry

Published geochemical data on the Dougherty district asphalt is not available. G. E. Michael, C. L. Thompson-Rizer, and R. A. Woods (1993, personal communication) provided the following geochemical data and description for a Dougherty district asphalt sample and a Sulphur district (stop 7) asphalt sample.

Table 2 summarizes the Rock-Eval pyrolysis data of asphalt samples at stops 5 and 7. Total organic carbon (TOC) content is ~6 and ~9 wt%, respectively. The S_1 peaks (amount of extractable bitumen) of ~20 and ~45 mgHC/g Rock, the S_2 peaks (amount of hydrocarbons released during pyrolysis) of ~38 and ~42 mgHC/g Rock, and the production index (PI) of 0.35 and 0.52, respectively, are common for asphalts. The hydrogen index, oxygen index, and kerogen-type indicator are not applicable to asphalt samples.

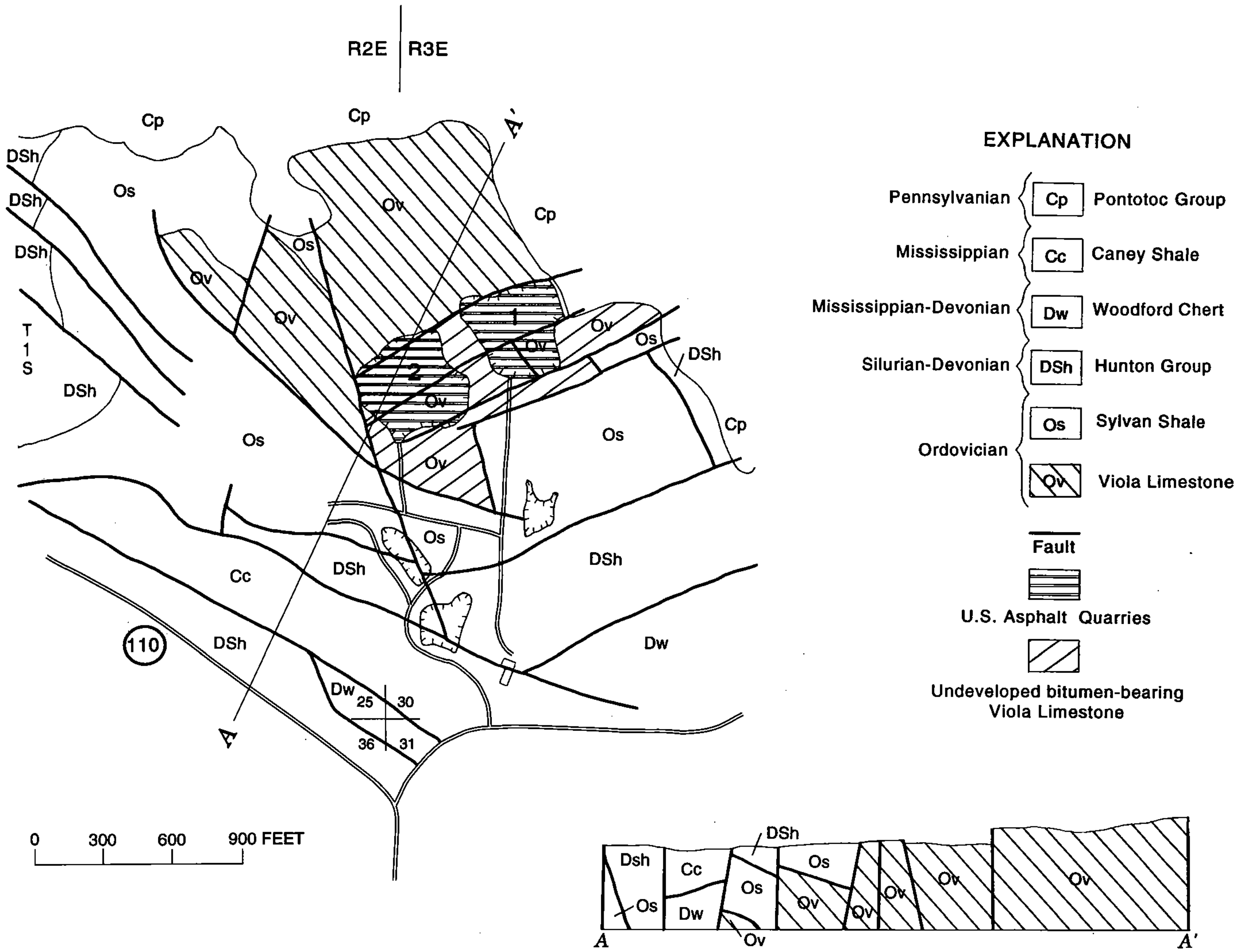


Figure 33. Geologic map and interpretive cross section of the Dougherty district asphalt area. Numbers refer to U.S. Asphalt Co. No. 1 and No. 2 quarries. Modified from Gorman and Flint (1944) and Harrison and Burchfield (1987).

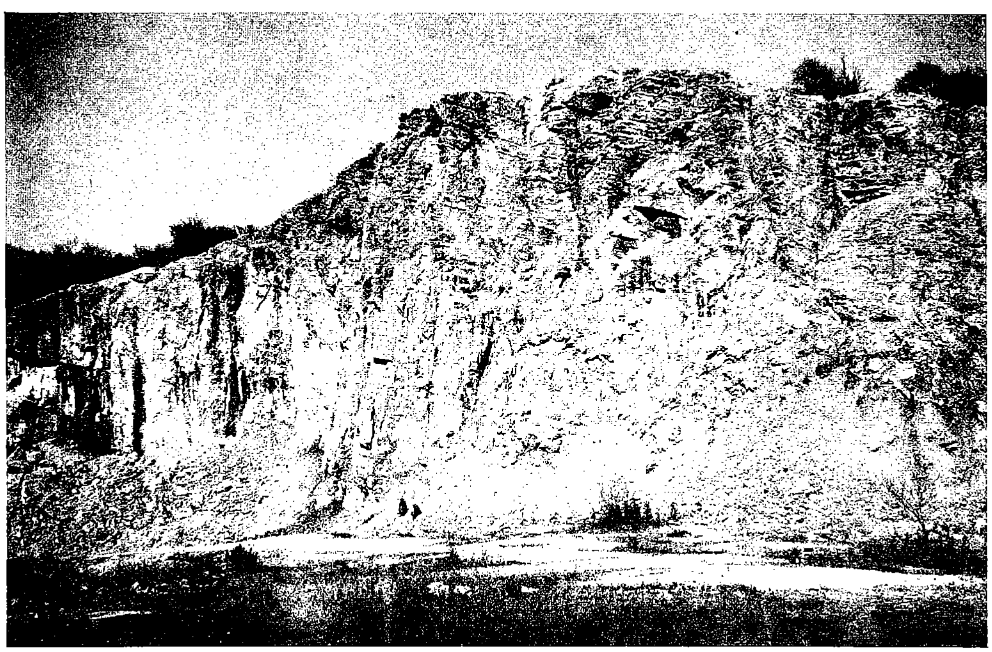


Figure 34. View of north high-wall of the U.S. Asphalt No. 2 quarry (stop 5). Two geologists are sitting on the talus slope.

Figure 35. Close-up view of asphalt-saturated limestone in the talus slope of the U.S. Asphalt No. 2 quarry.

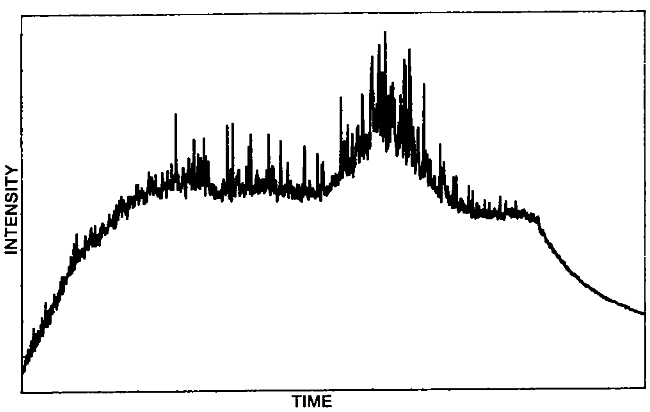


Figure 36. Saturate fraction gas chromatogram of Dougherty district asphalt sample. Sample biodegraded to the extent that no normal paraffins (n-alkanes) remain. From G. E. Michael, C. L. Thompson-Rizer, and R. A. Woods (1993, personal communication).

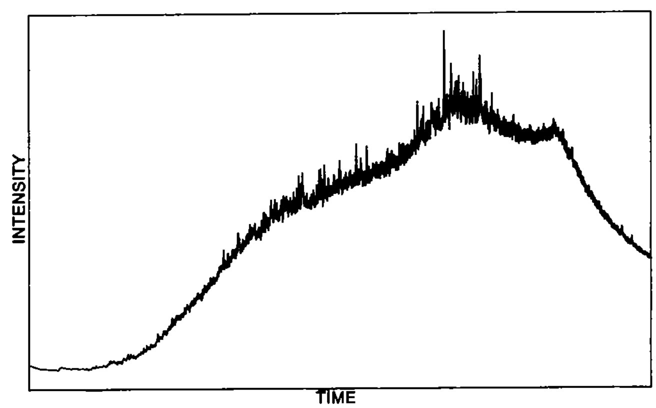


Figure 37. Saturate fraction gas chromatogram of Sulphur district asphalt sample. Sample biodegraded to the extent that no normal paraffins (n-alkanes) remain. From G. E. Michael, C. L. Thompson-Rizer, and R. A. Woods (1993, personal communication).

Both the Dougherty district and Sulphur district asphalt samples are biodegraded to the extent that no normal paraffins (n-alkanes) remain. A few isoprenoids and polycyclic biomarker compounds are the only distinguishable peaks on the saturate fraction gas chromatograms (Figs. 36,37). Removal of nearly all sulfur aromatics (benzothiophenes) and phenanthrenes suggests that both samples have been affected by extensive water washing (Palmer, 1984). In general, there is good correlation between the Dougherty and Sulphur asphalt samples, based on their biomarker distributions and stable carbon isotope values (Tables 4,5; Figs. 38,39). Correlation parameters involving peak E generally are in poor agreement. This is due to the low C_{30} hopane content of the Sulphur sample, which appears to be a result of biodegradation. Biomarkers in both asphalts have been altered to some extent by biodegradation, as evidenced by reduced concentrations of the extended hopanes. The presence of 28,30-bisnorhopane and gammacerane is indicative of, though not absolute evidence for, an anoxic and brackish water (hypersaline) depositional environment for the bitumen source rock (Fu and others, 1992). Relative amounts of the tri- and tetracyclic terpanes, especially as seen in the C_{24} tetracyclic/C_{26} tricyclic ratios, show greater similarity to the Woodford Shale extract described by Jones and Philp (1990) than to the Viola extract described by the same authors. On this basis, the Woodford Shale is the more probable hydrocarbon source rock for the asphalts.

TABLE 4. — EXTRACT AND ISOTOPE DATA[a]

Stop no.	Unit	Total extract (ppm)	Normalized (%)				Stable carbon isotopes	
			SAT[b]	ARO[c]	NSO[d]	Asph.[e]	$\delta^{13}C$ SAT	$\delta^{13}C$ ARO
2	Viola	29,839	16.4	24.1	35.6	23.9	−30.5	−30.1
7	Oil Creek	82,384	18.6	21.2	34.1	26.1	−30.4	−29.8

[a] Data from G. E. Michael, C. L. Thompson-Rizer, and R. A. Woods (1993, personal communication).
[b] Saturated hydrocarbons.
[c] Aromatic hydrocarbons.
[d] Nitrogen-, sulfur-, and oxygen-containing nonhydrocarbons.
[e] Asphaltenes.

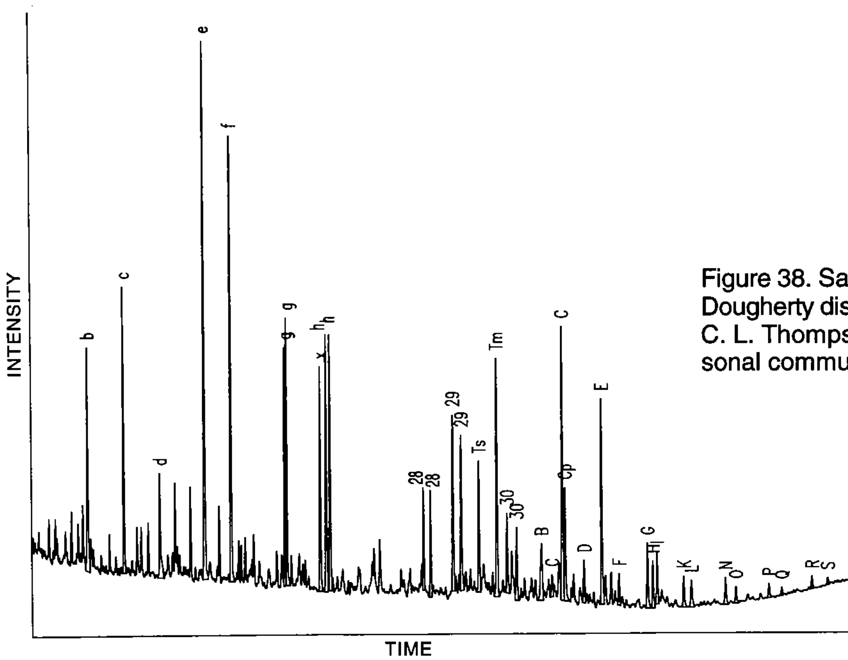


Figure 38. Saturate fraction m/z 191 chromatogram of Dougherty district asphalt sample. From G. E. Michael, C. L. Thompson-Rizer, and R. A. Woods (1993, personal communication).

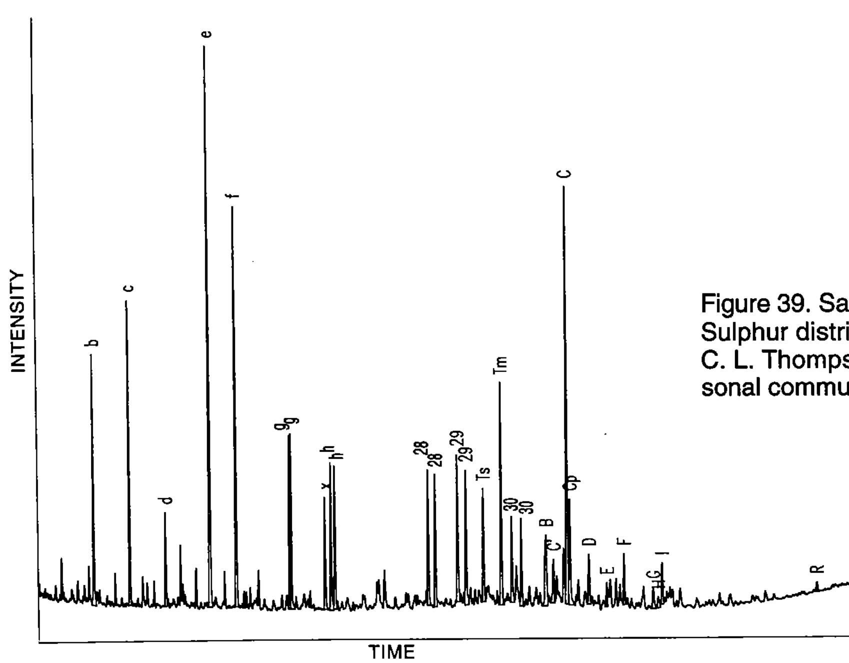


Figure 39. Saturate fraction m/z 191 chromatogram of Sulphur district asphalt sample. From G. E. Michael, C. L. Thompson-Rizer, and R. A. Woods (1993, personal communication).

TABLE 5. — BIOMARKER PARAMETERS[a]

Parameter	Dougherty Asphalt (stop 5)	Sulphur Asphalt (stop 7)
Terpanes		
e/f	1.24	1.47
x/h	0.42	0.38
e/E	2.26	19.68
T_s/T_m	0.54	0.52
C/C_p	2.09	3.39
C/E	1.15	16.88
(C+E)/(C+D+E+F)	0.86	0.78
G/(G+H)	0.58	0.64
K/(K+L)	0.51	0.16
(R+S)/(P+Q)	0.88	1.58
Hopanes/Steranes	0.47	0.16
C'/E	0.13	1.09
C'/C	0.11	0.06
I/E	0.26	0.27
B/E	0.4	4.8
Steranes		
Normalized percent:		
$C_{27}\beta\beta$	35.2	45.3
$C_{28}\beta\beta$	20.8	25.4
$C_{29}\beta\beta$	43.9	29.2
E/(8+11)	1.72	0.39
(1+2)/(8+11)	1.77	5.26
20/22	1.53	0.67
(20+21)/(19+20+21+22)	0.54	0.52
19/(19+22)	0.63	0.57
Triaromatic Steranes		
$C_{20}/(C_{20}+C_{27})$	0.19	0.19
$C_{21}/(C_{21}+C_{28})$	0.10	0.06

[a]Data from G. E. Michael, C. L. Thompson-Rizer, and R. A. Woods (1993, personal communication).

Explanation for Table 5

Peak designation	Identification
Terpanes	
b	C_{20} Tricyclic terpane
c	C_{21} Tricyclic terpane
d	C_{22} Tricyclic terpane
e	C_{23} Tricyclic terpane
f	C_{24} Tricyclic terpane
g	C_{25} Tricyclic terpanes
x	C_{24} Tetracyclic terpane
h	C_{26} Tricyclic terpanes
28	C_{28} Tricyclic terpanes
29	C_{29} Tricyclic terpanes
T_s	18α(H),21β(H)-22,29,30-Trisnorhopane
T_m	17α(H),21β(H)-22,29,30-Trisnorhopane
30	C_{30} Tricyclic terpanes
B	17α(H),21β(H)-28,30-Bisnorhopane
C'	17α(H)-25-Norhopane
C	17α(H),21β(H)-30-Norhopane
C_p	C_{29} Hopane of unknown structure
D	17β(H),21α(H)-30-Normoretane
E	17α(H),21β(H)-Hopane
F	17β(H),21α(H)-Moretane
G	17α(H),21β(H)-30-Homohopane (22S)
H	17α(H),21β(H)-30-Homohopane (22R)
I	Gammacerane
K	17α(H),21β(H)-30,31-Bishomohopane (22S)
L	17α(H),21β(H)-30,31-Bishomohopane (22R)
N	17α(H),21β(H)-30,31,32-Trishomohopane (22S)
O	17α(H),21β(H)-30,31,32-Trishomohopane (22R)
P	17α(H),21β(H)-30,31,32,33-Tetrakishomohopane (22S)
Q	17α(H),21β(H),30,31,32,33-Tetrakishomohopane (22R)
R	17α(H),21β(H)-30,31,32,33,34-Pentakishomohopane (22S)
S	17α(H),21β(H)-30,31,32,33,34-Pentakishomohopane (22R)
Steranes	
1	13β(H),17α(H)-Diacholestane (20S)
2	13β(H),17α(H)-Diacholestane (20R)
8	5α(H)-Cholestane (20S) + 5β(H)-Cholestane (20R)
11	5α(H)-Cholestane (20R)
19	5α(H)-Stigmastane (20S)
20	5α(H),14β(H),17β(H)-Stigmastane (20R)
21	5α(H),14β(H),17β(H)-Stigmastane (20S) + 5β(H)-Stigmastane (20R)
22	5α(H)-Stigmastane (20R)

STOP 6
Hunton Quarry and Woodford Shale Pit

Location

The Hunton quarry and Woodford Shale pit are located 0.5 mi (0.8 km) east of Highway 110 and ~0.2 mi (0.3 km) south of Goddard Youth Camp Road (Fig. 40). Detailed location: The Woodford Shale pit is located at the SE¼SE¼NW¼ sec. 31, T. 1 S., R. 3 E. on the Dougherty Quadrangle map (7.5′ series), Murray County.

CAUTION: Use extreme care when approaching highwalls inside the quarry. Obtain permission to enter the quarry from the owner, James D. Lance of Sulphur.

Significance

- Three-dimensional cross-sectional view of anticline exposed in Hunton quarry.
- Small-scale model of tectonic style that influenced the development of the Arbuckle anticline.
- Fossil collecting site.
- Woodford Shale as hydrocarbon source rock.
- Excellent example of ideal relationship between hydrocarbon source rock (Woodford Shale) and reservoir rock (Hunton Group).

Description

Rock units deformed in the Hunton quarry area range from the Viola Group (Ordovician) to the Woodford Shale (Upper Devonian–Lower Mississippian). The anticline exposed in the quarry is best developed in post-Sylvan (Upper Ordovician) rocks, namely the Haragan/Bois d'Arc Formations (Lower Devonian) of the Hunton Group and the Woodford Shale (Fig. 3). Differences in the size and style of folds between the massive, more competent carbonate beds of the Bois d'Arc Formation and the thinner, less competent, cherty Woodford shales is shown in the quarry. Although not well exposed in the quarry, the Hunton/Woodford contact is an erosional unconformity. Paleokarstic horizons are apparent below the regional pre-

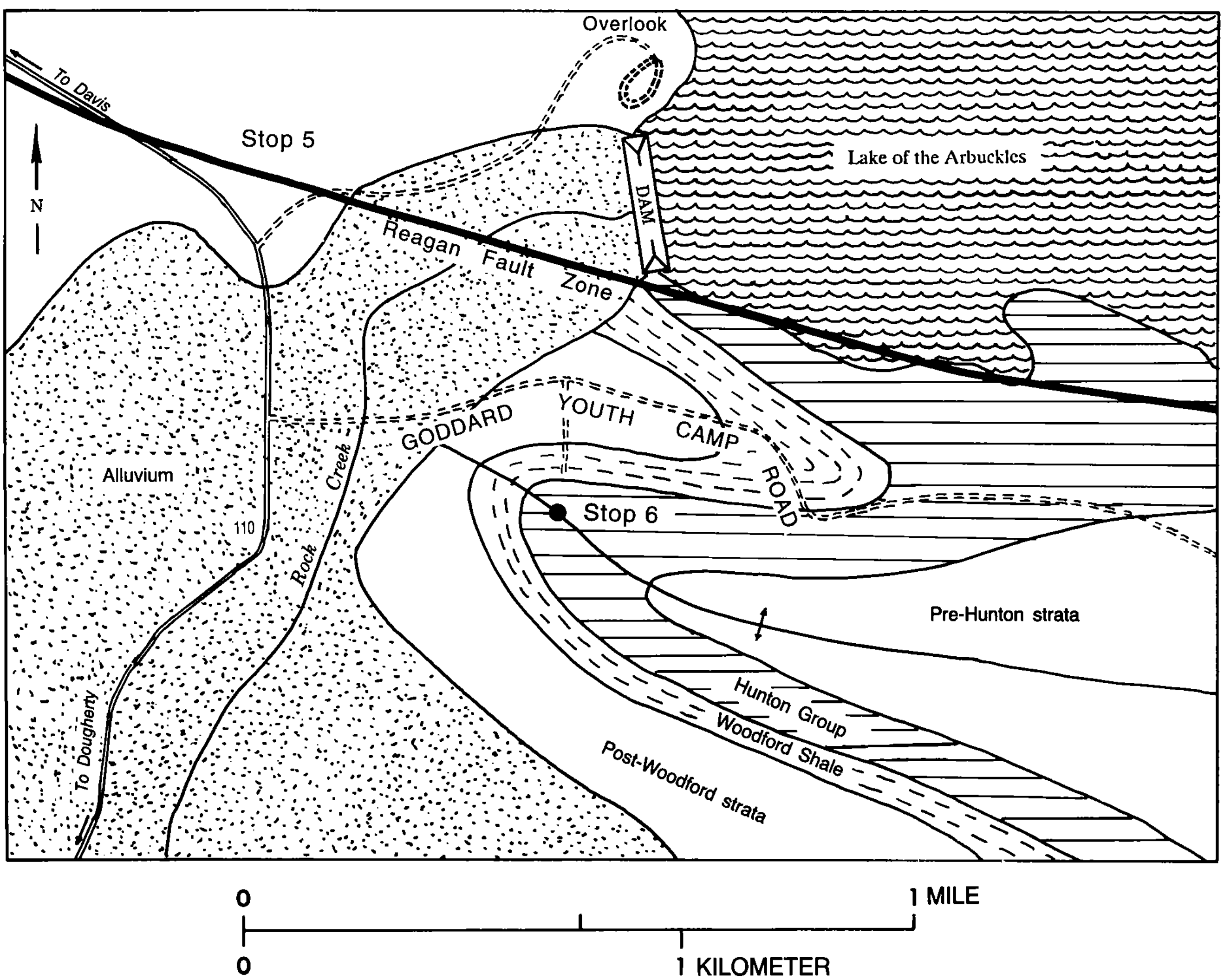


Figure 40. Generalized geologic map of stop 6, showing the axis of a northwest-plunging anticline. The WNW-trending Reagan fault zone cuts across the top of the figure (modified from Johnson and others, 1984).

Woodford unconformity. Shallow subtidal and intertidal facies of the Hunton Group are usually dolomitized and have extensive karst profiles. Hunton reservoirs typically consist of fossiliferous wackestones; intercrystalline and moldic porosity often exceeds 20% (Fritz and Al-Shaieb, 1993).

Faunas of the Haragan and Bois d'Arc Formations of the Hunton Group, collected from the Hunton quarry site, include articulate brachiopods (Amsden, 1958a,b; Amsden and Ventress, 1963), conodonts (Barrick and Klapper, 1992), trilobites (Campbell, 1977), bryozoans, cephalopods, corals, crinoids, gastropods, graptolites, pelecypods, and sponges (Amsden, 1956,1960). Refer to stop 3 for a description of the Woodford Shale. Carbonized compressions of the progymnosperm *Archaeopteris* (organ genus *Callixylon*) may be found on weathered bedding planes of the Woodford Shale, especially in the lower portion.

The Hunton quarry is on the north flank of the Tishomingo anticline (Fig. 2). The Reagan fault zone, the north-bounding fault of the Tishomingo anticline, is located along the south side of the Lake of the Arbuckles (Fig. 40), ~0.3 mi (0.5 km) north of the quarry. The axis of an anticline formed in the Hunton Group limestones, exposed in the Hunton quarry (Hunton Quarry anticline of Burke, 1985), plunges west–northwest at an angle of about 15–20°. A low-angle thrust fault passes through the axis of the fold at the top of the quarry face (Fig. 41). The fault dips ~30° toward the south and has a throw of ~30 ft (9 m) (Johnson and others, 1984). The anticline, thrust fault, and smaller flank folds developed during the Arbuckle orogeny (Late Pennsylvanian).

Limestone blocks of the Hunton Group were extracted from the Hunton quarry for use as riprap in construction of the Lake of the Arbuckles dam in 1964–65. The Woodford Shale has been mined at the quarry and used as base material for local county roads. The present shale surface has been exposed since about 1982 (Fig. 42). Figure 43 is a close-up view of the light-colored weathered shale surface.

Hydrocarbon Source Rock

The hydrocarbon source potential of the Woodford Shale was described in stop 3. The Woodford Shale at stop 6 was deposited on the craton in an epicontinental sea under relatively shallow water (<200 ft [60 m]). The hydrocarbon source potential of the Woodford Shale deposited in the aulacogen (stop 3) is compared with the source potential of the Woodford Shale deposited on the craton (stop 6) in Table 2 and below. The Washita Valley fault zone is the craton/aulacogen bounding fault zone (Fig. 4).

G. E. Michael, C. L. Thompson-Rizer, and R. A. Woods (1993, personal communication) reported the visual kerogen composition of the Woodford Shale at stop 6 to be 80% amorphous type A, 10% amorphous type D, and 10% herbaceous; fluorescence intensity from the herbaceous kerogen was strong. Amorphous type D is mixed oil-prone and gas-prone kerogen (Thompson and Dembicki, 1986). Compared to the Woodford Shale at stop 3, the Woodford Shale at stop 6 has more amorphous type D kerogen; solid bitumen is absent at stop 6.

Table 2 summarizes the Rock-Eval pyrolysis data of the Woodford Shale at stop 6. Total organic carbon

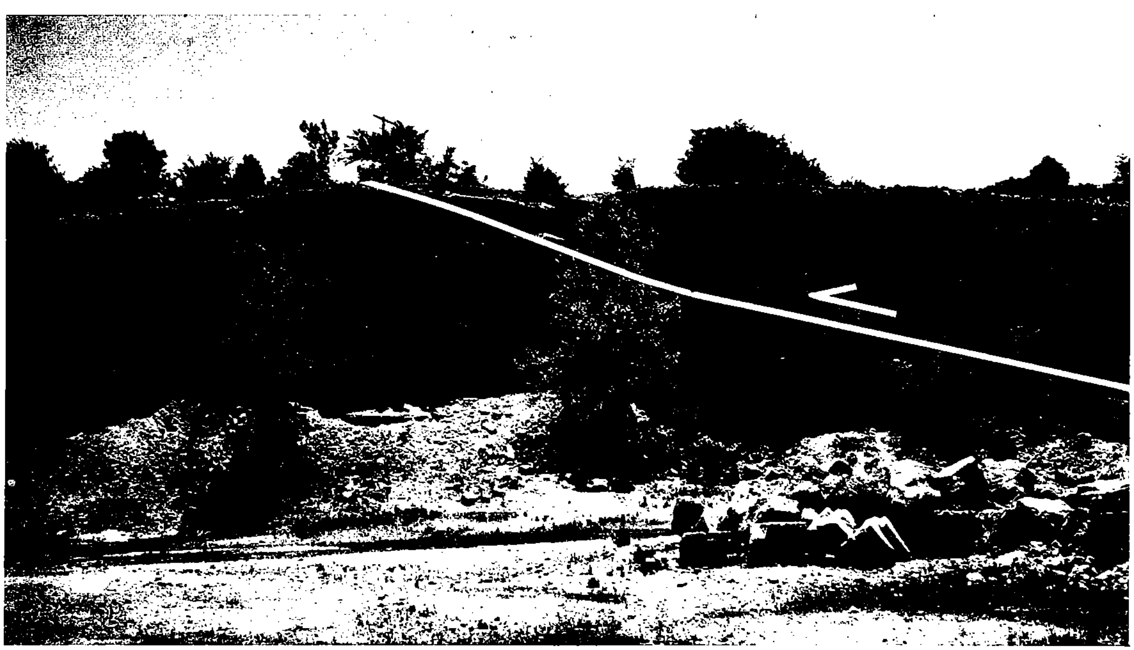


Figure 41. Upper level of Hunton quarry (stop 6), looking southeast along the axis of the anticline. Thrust fault dips ~30° S (right) and cuts across the top of the quarry wall.

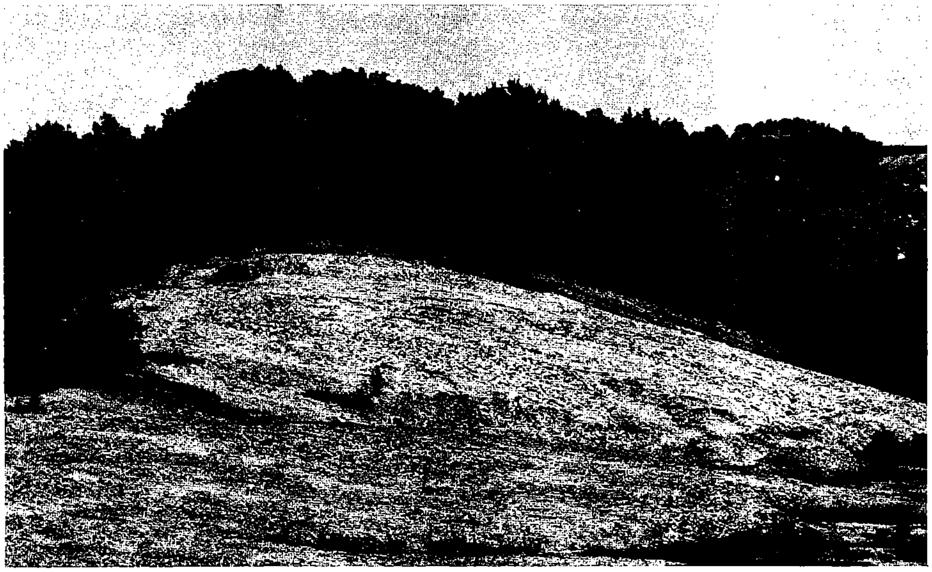


Figure 42. View of Woodford Shale pit (stop 6) looking north from Hunton quarry.

Figure 43. Close-up view of light-colored weathered Woodford Shale surface in Woodford Shale pit (stop 6).

(TOC) content is ~4 to ~9 wt%, considered to indicate very good hydrocarbon source potential. The hydrogen index (HI) has a wide range from 92 to 576 mgHC/g OC; the low value is interpreted to be due to weathering. The oxygen index (OI) has a wide range from 16 to 215 mgCO_2/g OC; the high value is interpreted to be due to weathering. Based on the HI and OI values, unweathered samples of the Woodford Shale contain type II (oil-prone) kerogen (Fig. 22). The kerogen-type indicator value of ~0.4 suggests a weathered sample, while values of ~14 to ~37 suggest that the kerogen is oil prone. The production index of 0.02 indicates that the samples are immature. The T_{max} has a narrow range from 416 to 418°C, indicative of marginal maturity (vitrinite reflectance equivalent of <0.5%). An additional Woodford Shale sample from the Hunton quarry contains 2,760 ppm extractable organic matter (by Soxhlet extraction using 2:1 toluene-isopropanol) (Jane Weber, unpublished data).

The mean random (nonpolarized light, stationary stage; whole-rock pellet) vitrinite reflectance of the Woodford Shale at stop 6 is 0.58% (77 measurements with reflectance range of 0.42–0.76%), indicative of early maturity (i.e., beginning of the oil window).

Hycrude (1986) conducted a hydroretorting assay test on a Woodford Shale sample from the Hunton quarry. Hydroretorting is the heating (>540°C) of shale in a retort under a hydrogen-rich atmosphere at elevated pressures (@1,000 pounds per square inch gauge pressure). The total organic carbon content of the raw shale sample was 9.51 wt%. The raw shale had a hydroretorting assay oil yield of 22.9 gal/ton and Fischer Assay oil yield of 8.4 gal/ton. Samples treated for 120 minutes (20.94 wt% TOC) increased the hydroretorting assay oil yield to 46.8 gal/ton and the Fischer Assay oil yield to 20.3 gal/ton.

Hutchison (1911) described a vein deposit of asphaltic pyrobitumen (impsonite) in the Woodford Shale at the Williams prospect (W on Fig. 5), ~1.5 mi east of stop 6 (Fig. 31). The prospect is probably below water level of the Lake of the Arbuckles. Samples are unavailable to verify the classification as impsonite or reclassify the material as another type of migrabitumen (Murray County impsonite locality of Abraham, 1960).

STOP 7
Sulphur Asphalt Quarry

Location

Stop 7 is located along the north side of Cedar Blue Road ~1.5 mi (2.5 km) west of U.S. Highway 177 and 3 mi (5 km) south of Sulphur. (Obtain permission to enter the quarry from Randy Kirby of Sulphur.) Detailed location: The easternmost pit is located at the NW¼ SE¼SW¼SE¼ sec. 15, T. 1 S., R. 3 E. on the Sulphur South Quadrangle map (7.5′ series), Murray County.

Significance

- Sulphur district inactive asphalt quarries.
- Exhumed reservoir in the Oil Creek Formation sandstone (Simpson Group).

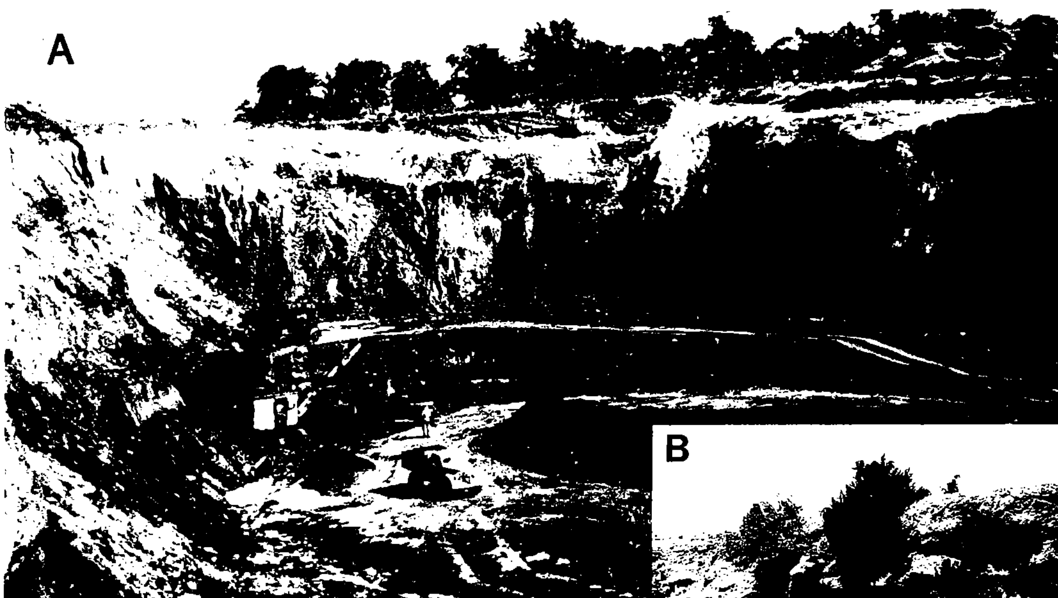
Description

The Sulphur (also known as part of the Buckhorn) district asphalt quarries, last operated by the Southern Rock Asphalt Co., were open from about 1890 to 1962 (Ham and others, 1973) (Fig. 44). Johnson and others (1984) estimated the total production of the Sulphur district to be at least 1.5 million short tons of bitumen-bearing sandstone. The district contains 10 major and several minor asphalt quarries (Fig. 45) primarily in the sandstone member of the Oil Creek Formation (Simpson Group, Middle Ordovician) (Fig. 3). Bitumen stains also occur in most of the other Ordovician to Late Pennsylvanian rock units of the area. Bitumen content varies from 0.4 to 13.0 wt% (Johnson and others, 1984). Harrison and Burchfield (1987) evaluated the asphalt resource of the Sulphur district and indicated that bitumen-impregnated strata occur to a depth of >600 ft (180 m). The total measured and probable in-place bitumen resource of the Sulphur district was determined to be at least 46.4 million bbl. Williams (1985) determined the in-place resource to be as much as 376 million bbl.

The Oil Creek Formation consists of an upper informal limestone member (thinly interlaminated limestone and shale; maximum thickness of 350 ft [106 m]) and a lower informal sandstone member (massive, well-sorted, rounded to subrounded, poorly cemented, very fine- to medium-grained sandstone, sand grain size of 1–4 phi; maximum thickness is 400 ft [122 m]). Clumps of sand grains are partially cemented with carbonate. White silica veins are caused by granulation cataclasis (Williams, 1985) (Fig. 46). The crude sand of the sandstone member is of high purity (as high as 99.57% silica) and is mined as a glass sand in other parts of the Arbuckle Mountains region (Ham, 1945; Ham and others, 1973).

The Sulphur district is within the Mill Creek syncline (Fig. 2); the Mill Creek fault is along the northeastern boundary of the Sulphur district. Williams (1985, p. 186) conducted a detailed structural study of the Sulphur district and stated: "The structure is essentially a northeast–southwest trending anticline, possibly plunging southwest broken by thrusts and extensive high-angle reverse faulting." The map and cross section in Figure 45 illustrate the southeast directed thrusting of the region and northeast trend

A



B

Figure 44. Two photographs of Sulphur district asphalt quarry. (*A*) View of surface mine that reached a depth of ~90 ft (27 m) before being abandoned in the 1960s. (*B*) Modern view of abandoned asphalt quarry. From Johnson and others (1984).

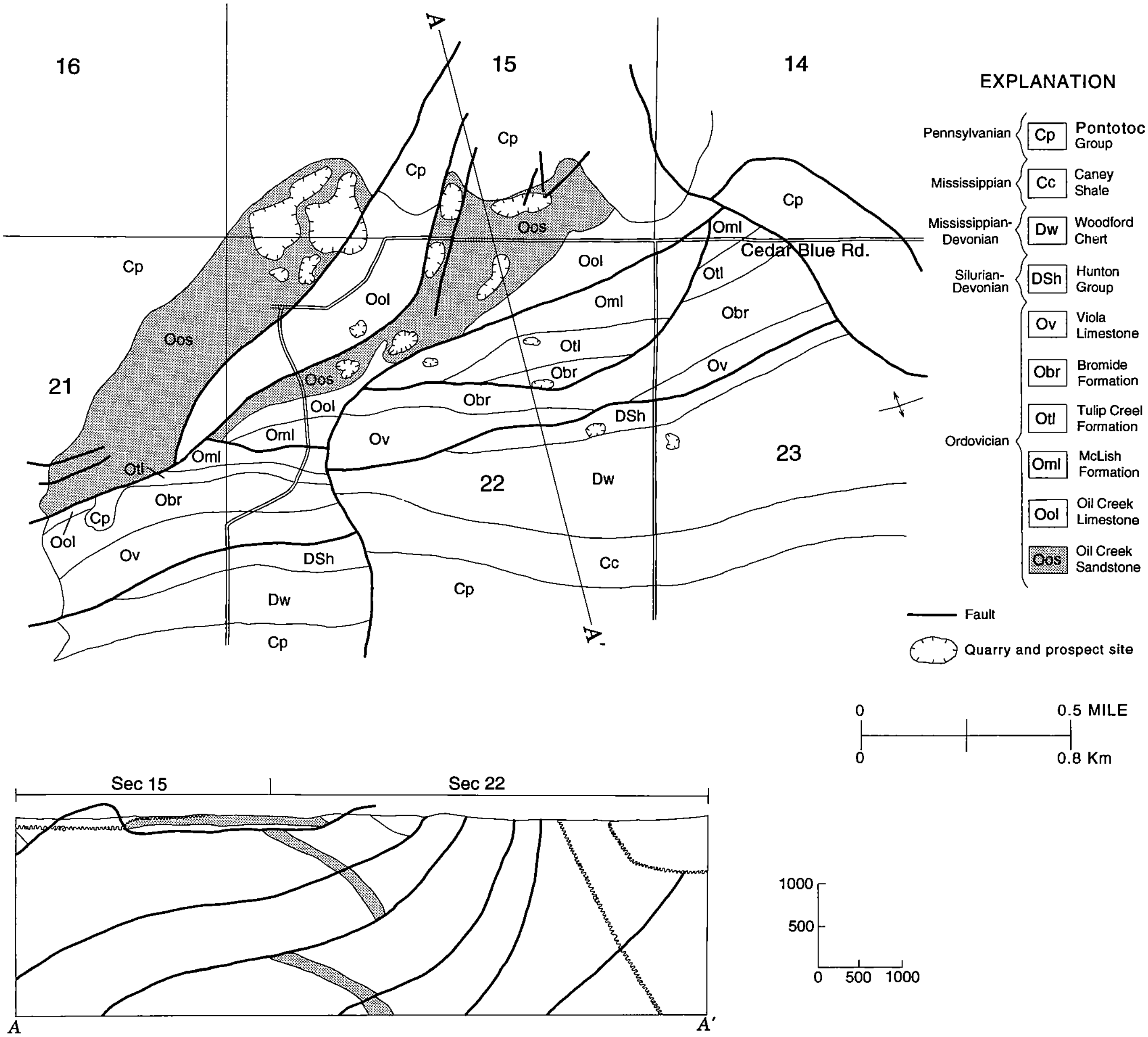


Figure 45. Geologic map and interpretive cross section of Sulphur district asphalt area. Modified from Gorman and others (1944), Johnson and others (1984), Williams (1985).

of the anticline. Williams (1985) presented evidence of right wrenching (clockwise movement) following left wrenching (counterclockwise movement) in the Sulphur district.

Bitumen Geochemistry

The native asphalts of the Sulphur district are classified as extra-heavy oils (API gravity of 0–63°, and average of 4.22°) (Williams, 1985). Lin and others (1989), referring to recent heavy oil movement, described the Sulphur district bitumens as "active seeps" (oil migrating to the surface).

A number of investigators have characterized the geochemistry of the Sulphur district bitumens. Based on gas chromatography and gas chromatography–mass spectrometry, Williams (1985) concluded that Oil Creek sandstone crude oil samples collected northwest of the Sulphur district and Oil Creek sandstone oil-sand bitumen samples from the Sulphur district came from the same source rock or source sequence. The source rock interval was not identified. The oil-sand bitumen was formed from the biodegradation, water-washing, and inorganic oxidation of crude oil. Bitumen-saturated Oil Creek sandstone cobbles within the Late Pennsylvanian-age Vanoss Conglomerate in the Sulphur district provided evi-

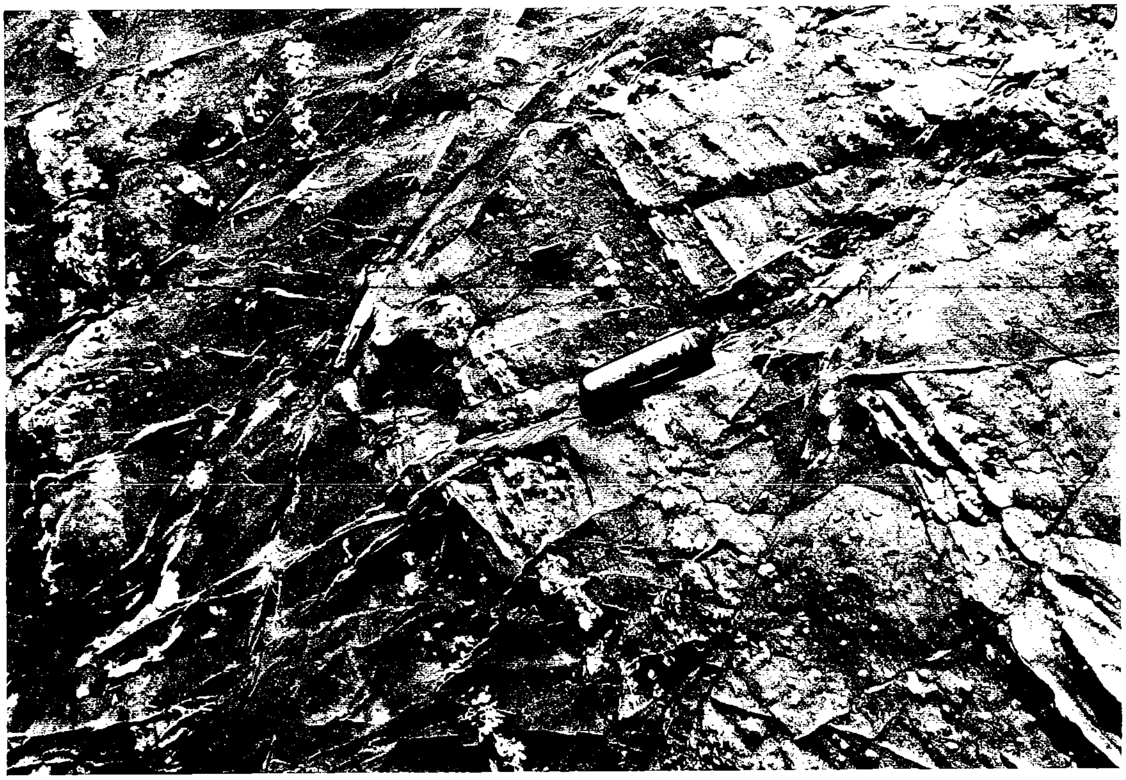


Figure 46. White silica veins in Oil Creek sandstone in easternmost pit of Sulphur district (stop 7).

dence for the sequence, from crude oil emplacement to degradation. Migration of crude oil into an anticlinal structural trap occurred prior to thrusting. Subsequent thrusting brought the reservoir into contact with meteoric waters where the crude oil was degraded.

D. E. Miiller and others (1984, described in Lin and others, 1989, p. 513) noted several biomarkers (n-alkanes, isoprenoids, low molecular weight aromatic hydrocarbons and thiophenes) that had been completely removed from the Sulphur district bitumens; there was partial loss of steranes, C_{30+} hopanes, and 18α-trisnorhopane (T_s on Table 5). Diasteranes, triaromatic steroid hydrocarbons, tricyclic terpanes, C_{24}-tetracyclic terpane, C_{29}-hopane, and 17α-trisnorhopane (T_m on Table 5) were resistant to biodegradation.

In a geochemical study of bitumens from core samples representing three localities in south-central Oklahoma, including the Sulphur district, Weber (1988, p. 10) reported, "The general absence of prominent n-alkanes, isoprenoids, and definable aromatics; the presence of UCM [unresolved complex mixture] humps on both saturate and aromatic scans; and the seemingly enhanced abundance of steranes, hopanes, and tricyclic terpanes together support the conclusion these bitumens have endured moderate to heavy biodegradation."

Lin and others (1989) concluded that the relative order of degradation of hopanes and steranes from the south Woodford asphalt deposit and the Sulphur district bitumens was unpredictable. The Woodford asphalt deposit is located south of the town of Woodford in T. 3 S., R. 1 W.; the Rod Club sandstone (Goddard Formation, Late Mississippian) is the host rock (described by Harrison and Burchfield, 1987). Porphyrin distributions, on the other hand, were not altered by biodegradation and could be used in biomarker correlation studies.

Michael and others (1989) and Jones and Philp (1990) concluded that the tar-sand bitumen from the south Woodford asphalt deposit and Oil Creek Formation oils from the southeastern Anadarko basin were derived from the Woodford Shale. Geochemical data on one asphalt sample from the Sulphur district east pit (locality of stop 7) is provided in Tables 2 and 5 (see description with stop 5). G. E. Michael, C. L. Thompson-Rizer, and R. A. Woods (1993, personal communication) found the Sulphur district bitumen to be geochemically similar to Woodford Shale extracts.

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