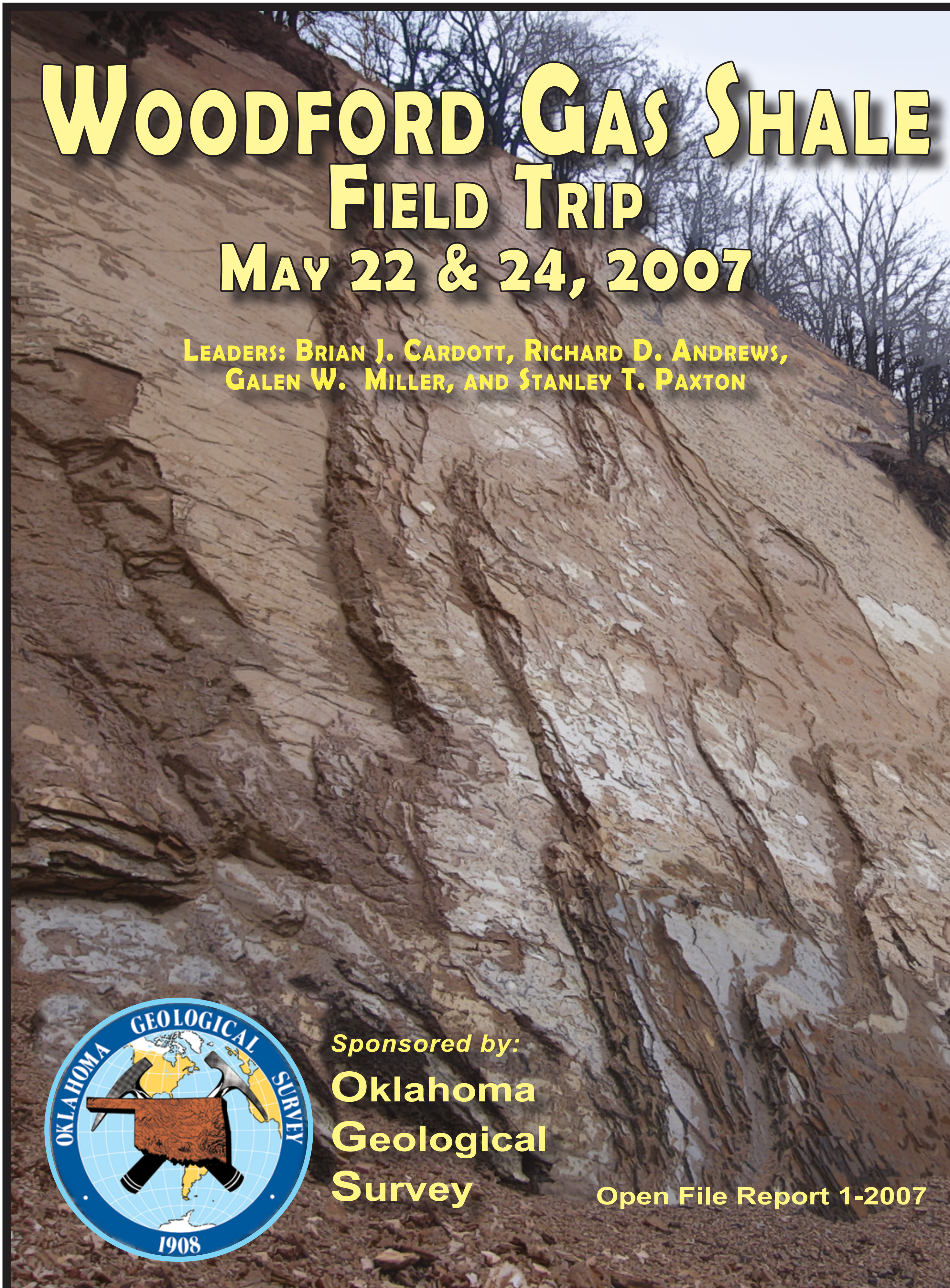

WOODFORD GAS SHALE FIELD TRIP

MAY 22 & 24, 2007

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OKLAHOMA GEOLOGICAL SURVEY
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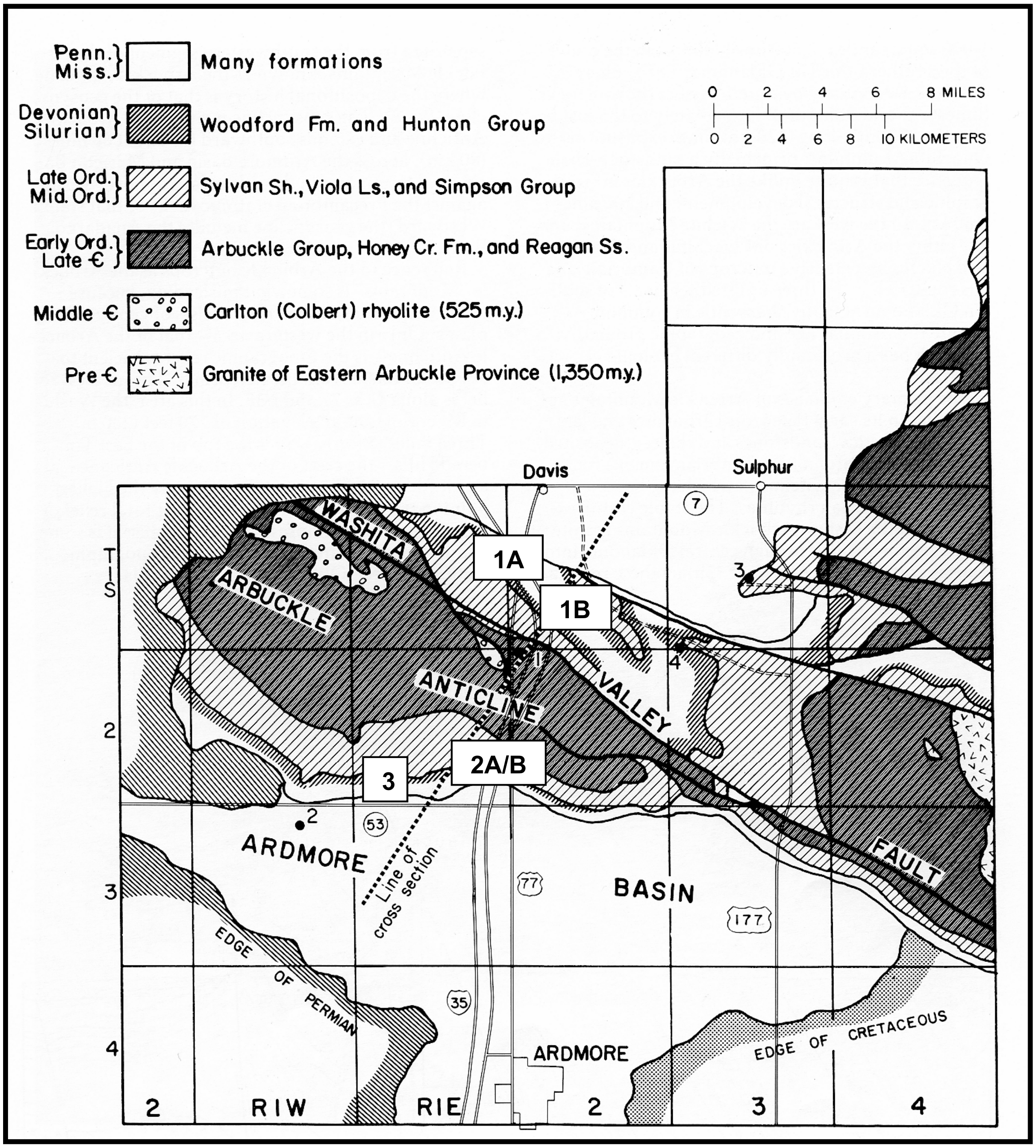
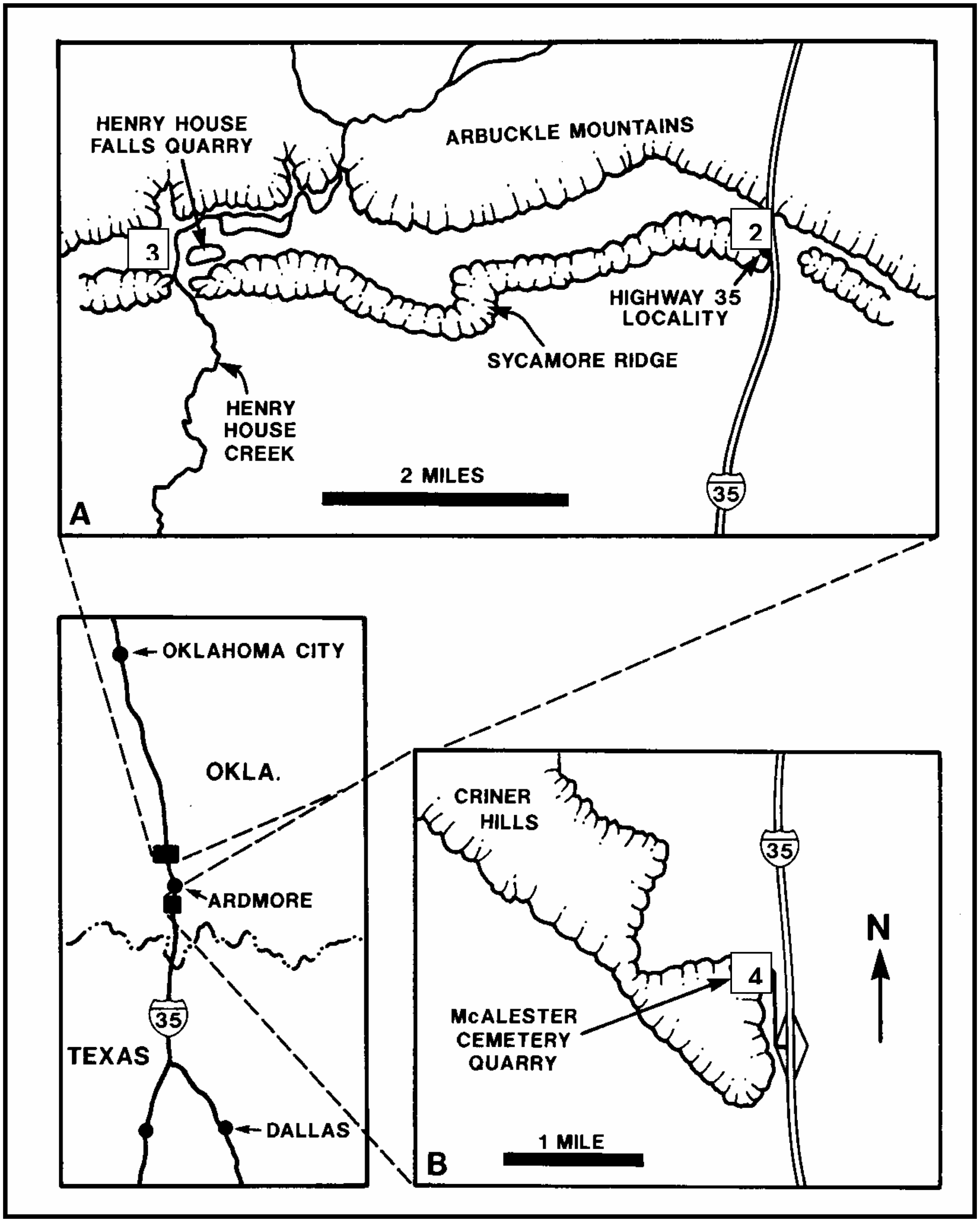
Field Trip Stops



Map 1. Generalized geologic map of Arbuckle Mountains showing location of field trip stops. Modified from Johnson and others (1984, OGS Special Publication 84-1, figure 4, p. 5).



Map 2. Location of (A) Henry House Falls Quarry and I-35 road cut, and (B) McAlester Cemetery Quarry. Modified from Kirkland and others (1992, OGS Circular 93, figure 1, p. 39).

The following overview, as well as description of Stop 2a, are from Oklahoma Geological Survey Special Publication 93-3 by Cardott and Chaplin.

OVERVIEW OF ARBUCKLE MOUNTAINS GEOLOGY

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.

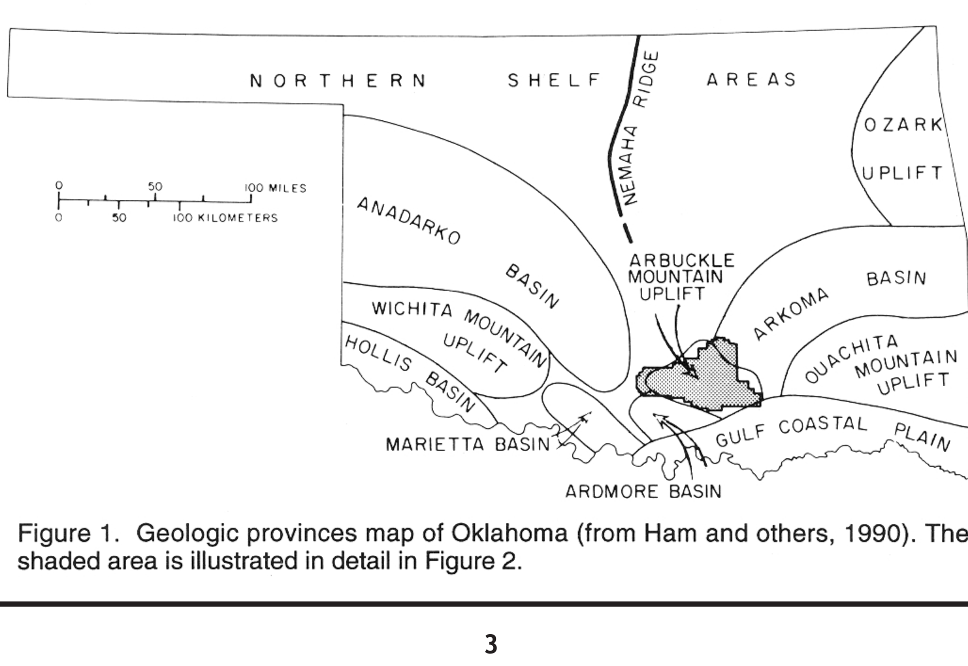


Figure 1. Geologic provinces map of Oklahoma (from Ham and others, 1990). The shaded area is illustrated in detail in Figure 2.

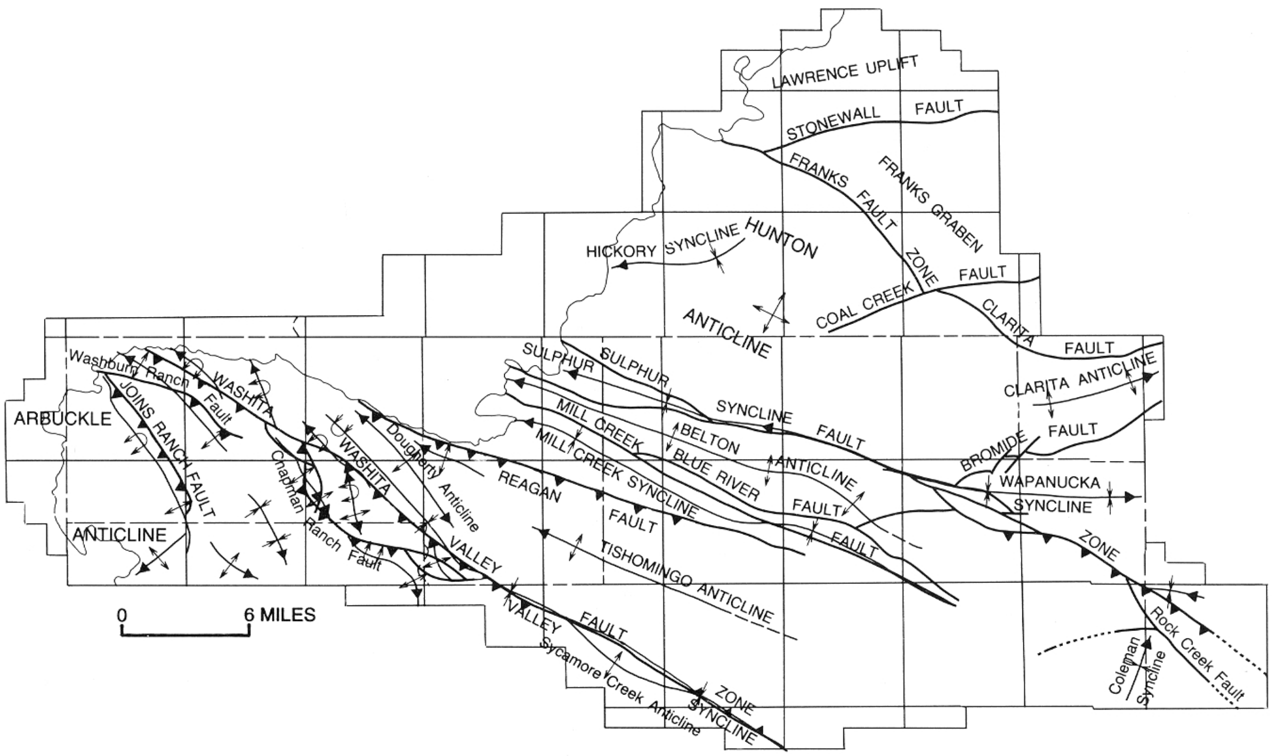


Figure 2. Index map of Arbuckle Mountains showing principal structural features (from Ham and others, 1990). Location of this area is shown (shaded) in Figure 1.

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).

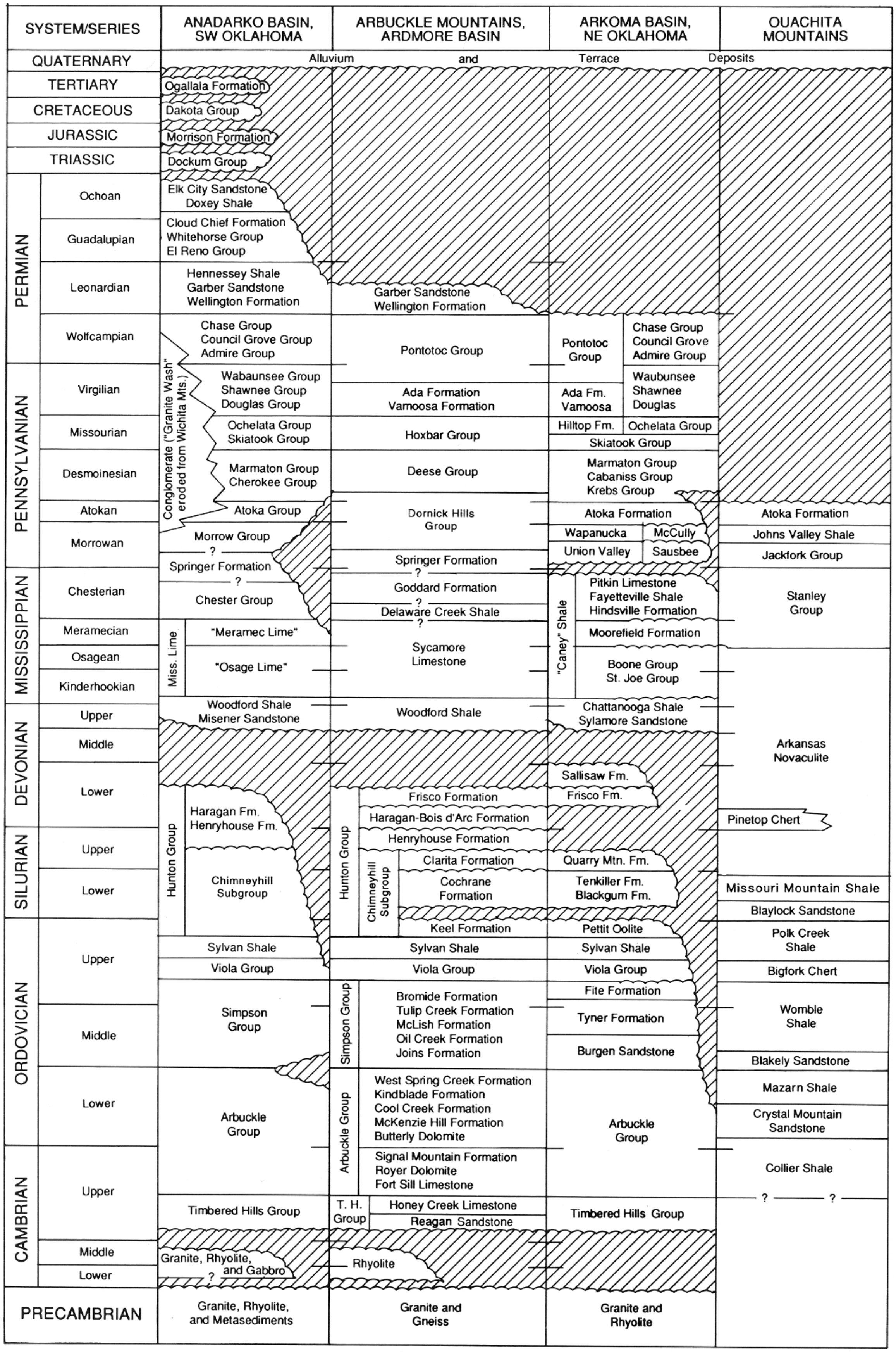


Figure 3. Generalized correlation of rock units in Oklahoma (from Johnson and Cardott, 1992b). Height of boxes is not related to thickness of rock units.

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).

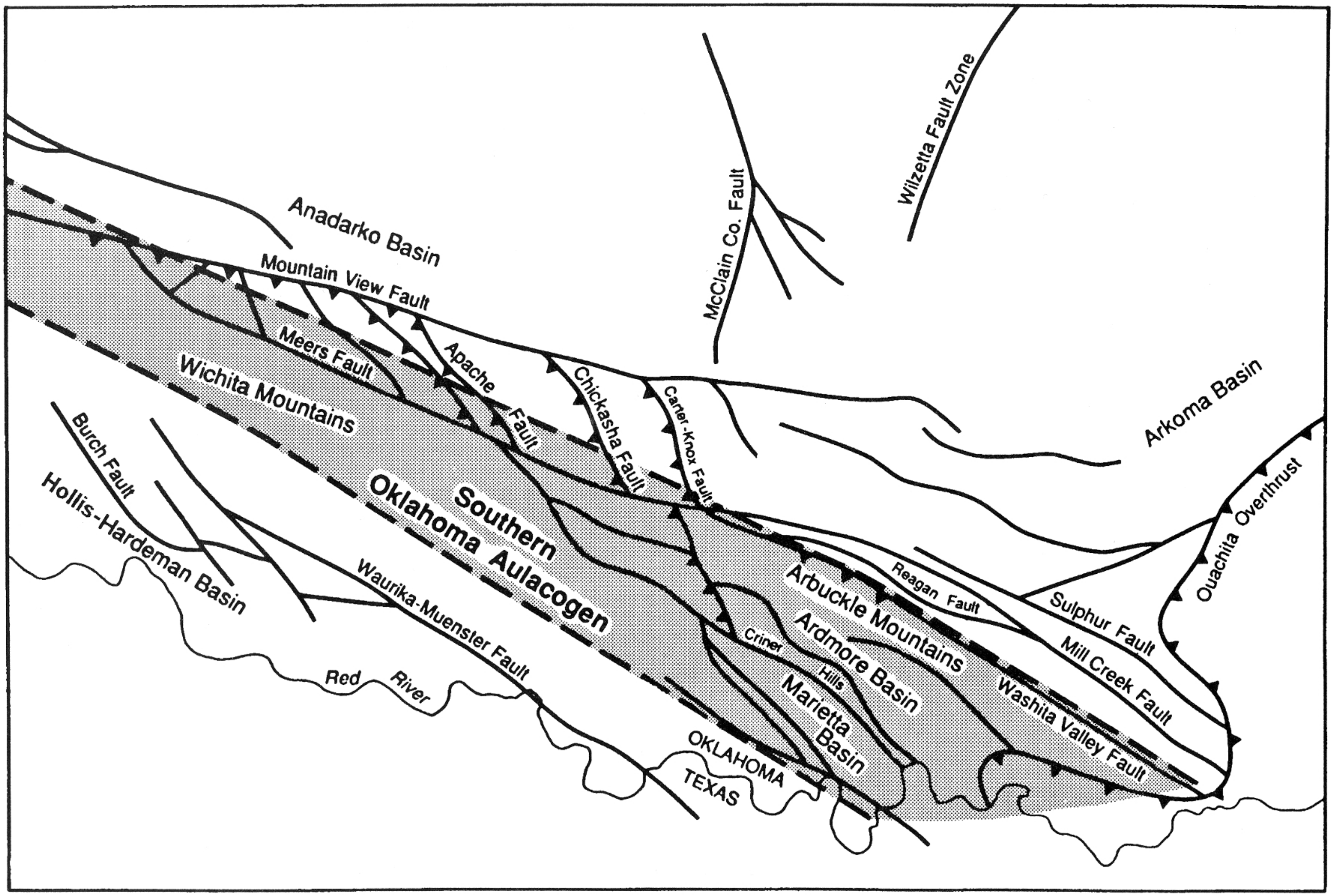


Figure 4. Major faults and structures of southern Oklahoma (adapted from Axtmann, 1983).

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 PENNSYLVANIAN	• 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).

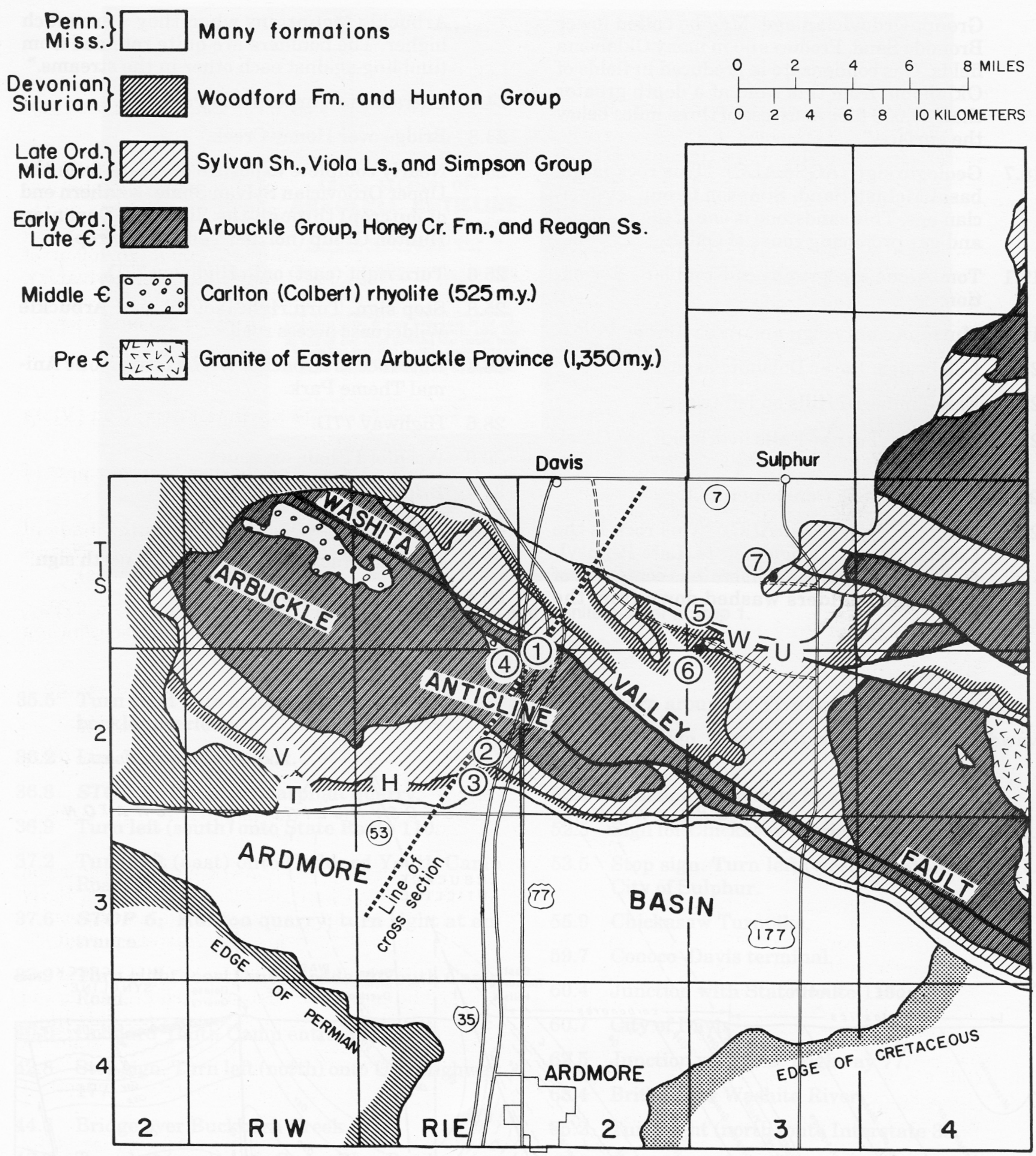


Figure 5. Generalized geologic map of the western Arbuckle Mountains showing location of seven field-trip stops (adapted from Johnson and others, 1984). Cross section is shown in Figure 6. ① = Field trip stops. H = Henry House Falls quarry (Kirkland and others, 1992); T = Woodford Shale type locality (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).

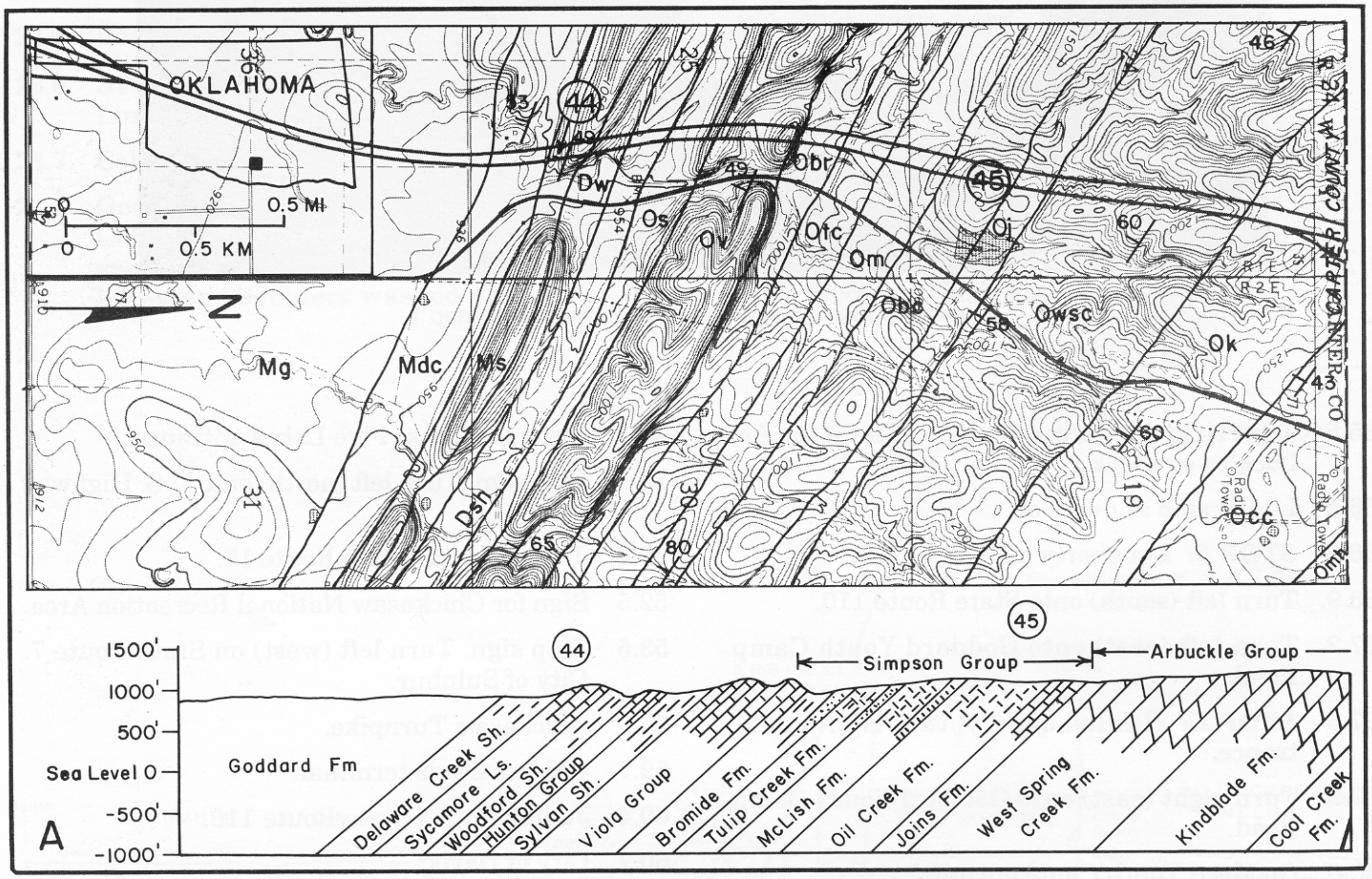


Figure 8 (this and facing page). Geologic map and profile of Arbuckle Mountains along Interstate 35 (from Fay, 1988). *A* is to the south; *C* is to the north. Circled numbers 44–51 are mileposts.

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

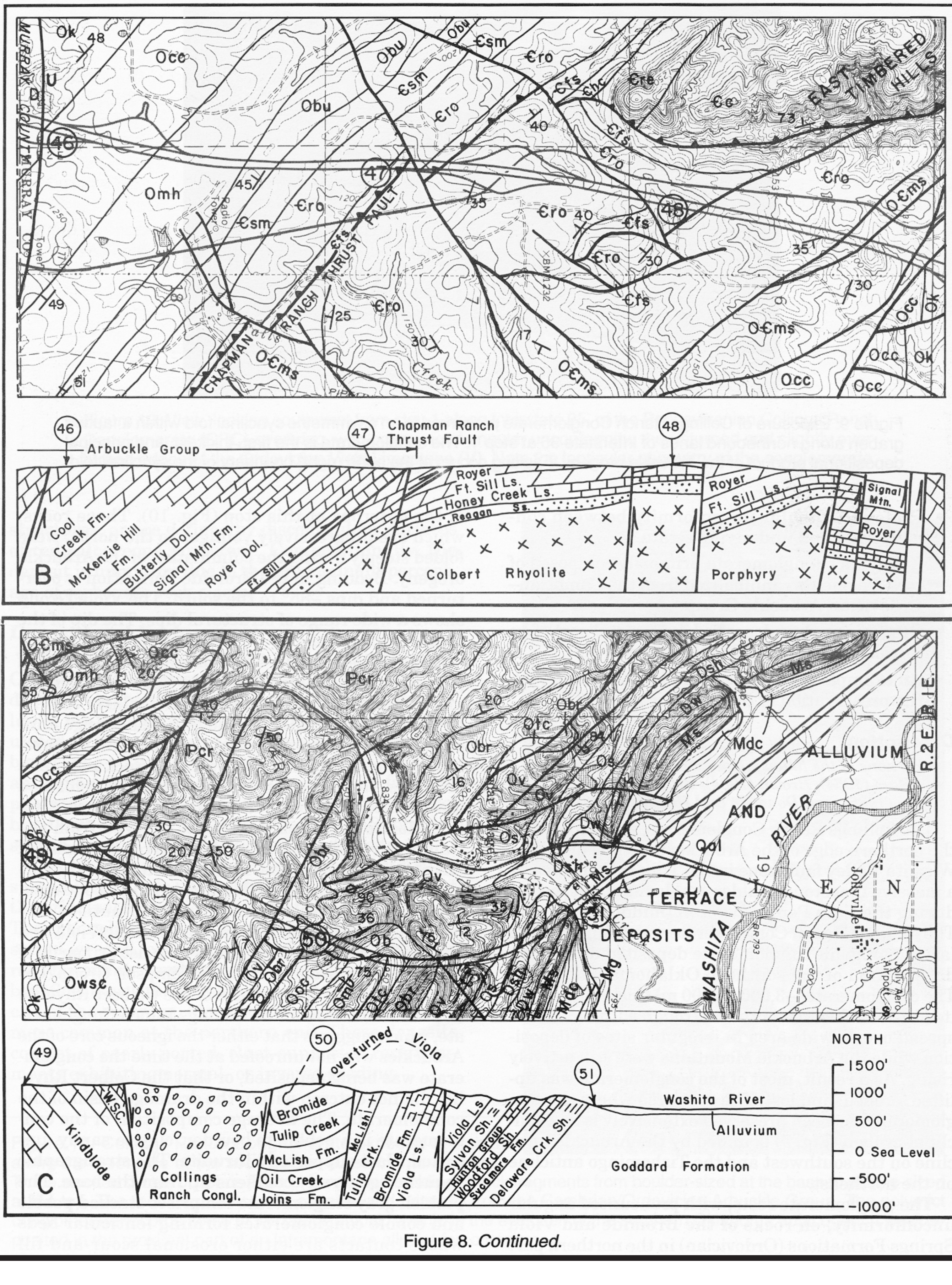


Figure 8. *Continued.*

STOP 1A – SYLVAN SHALE TO CANEY SHALE TRANSITION

By Galen W. Miller, Oklahoma Geological Survey

Objectives and Things to See

- Steeply dipping strata exposed along the south limb of the Washita Valley Syncline.
- Compare and contrast producing and non-producing gas shale lithologies (the Sylvan versus the Woodford and Caney Shales).
- Upper Ordovician - Lower Devonian Hunton Group, shallow to moderately deep shelf carbonate ramp.
- Initiation of deep water sedimentation – the Woodford Shale, Sycamore Formation, and Caney Shale(?) (Upper Devonian - Lower Mississippian).

Description – Good exposures of the Sylvan Shale, Hunton Group, the Sycamore Formation, and the base of the Caney Shale can be seen at this location. Though the Woodford Shale is present, it is poorly exposed and only the very base of the formation can be observed.

At this stop we are within the south limb of the Washita Valley Syncline. Structural orientation of the formations is steeply dipping to the east, and is illustrated well by the Sylvan Shale-Hunton Group contact on the west side of the outcrop (Fig 1).

Very little study has been done on the Upper Ordovician Sylvan Shale. For the most part the unit is fossil-poor, and so, little to no paleontological studies have been done on the shale to determine its sedimentological history or environments of deposition. The Sylvan is very clay-rich and contains very little organic material, making it both a poor source rock for oil and gas (Burruss and Hatch, 1989), and equally a poor petroleum reservoir; however, it does constitute a very good trap rock for both Viola Limestone and Hunton Group reservoirs. Current interpretation is that the Sylvan Shale represents fairly shallow water deposition into the southern Oklahoma aulacogen, and marks an increase in clay-sized terrigenous clastic deposition, rather than an increase in water depth compared to depositional conditions that were occurring during Viola deposition (Brown

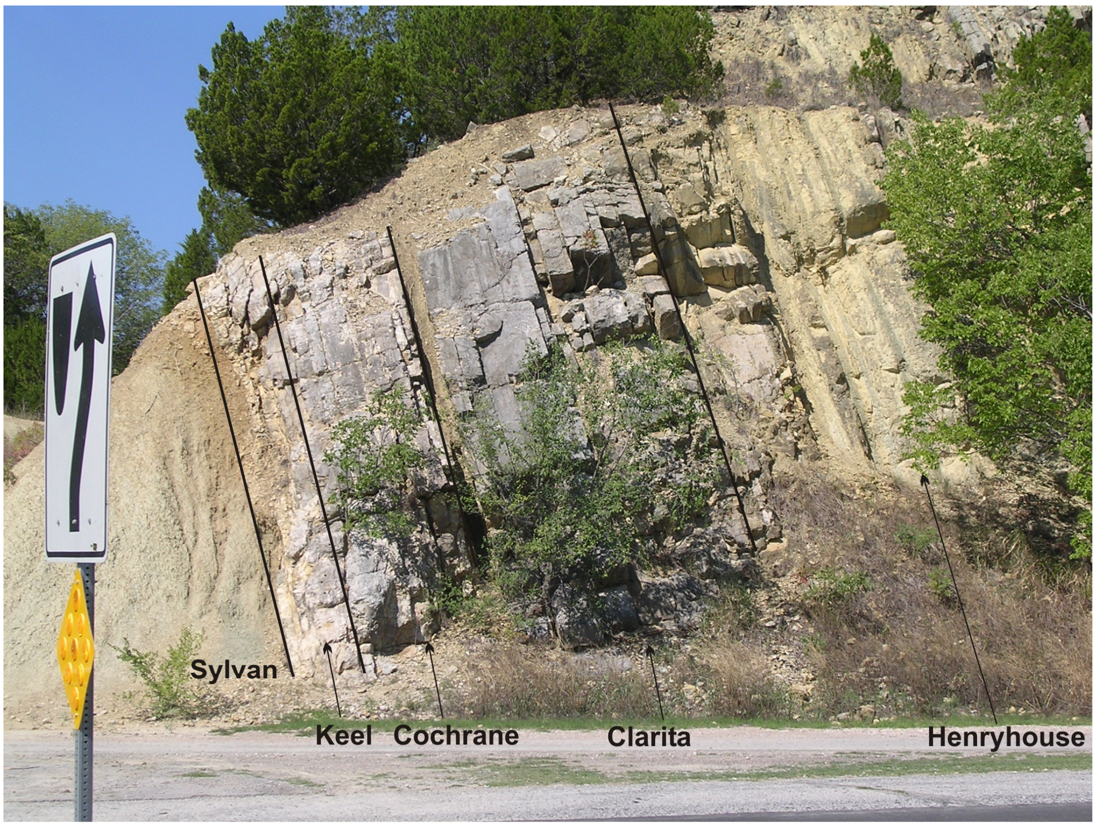


Figure 1.-- Steeply dipping contact between the Sylvan Shale and the Hunton Group. Also illustrated are the different formations exposed in the lower part of the Hunton.

and Grayson, 1985). Once terrigenous influx ended, carbonate production resumed in the southern Oklahoma aulacogen with the deposition of the Hunton Group.

The Hunton Group is composed of a number of thin lithostratigraphic units that were deposited throughout the Late Ordovician and ending in the Early Devonian. Essentially the units of the Hunton represent shallow- to moderately deep-water sedimentation along a carbonate ramp (Stanley, 2001). Most units are very fossiliferous, and many worldrenown Silurian and Devonian fossil localities occur within the Group. Lithologically, the Hunton consists of all manner of carbonate textures and fabrics, including oolitic grainstones, skeletal grainstones, packstones and wackestones, and argillaceous carbonate mudstones (Fig. 2). A number of unconformities occur within the sedimentary package that testifies to deposition along a stable, shallow water shelf that was periodically affected by fluctuating sea level.

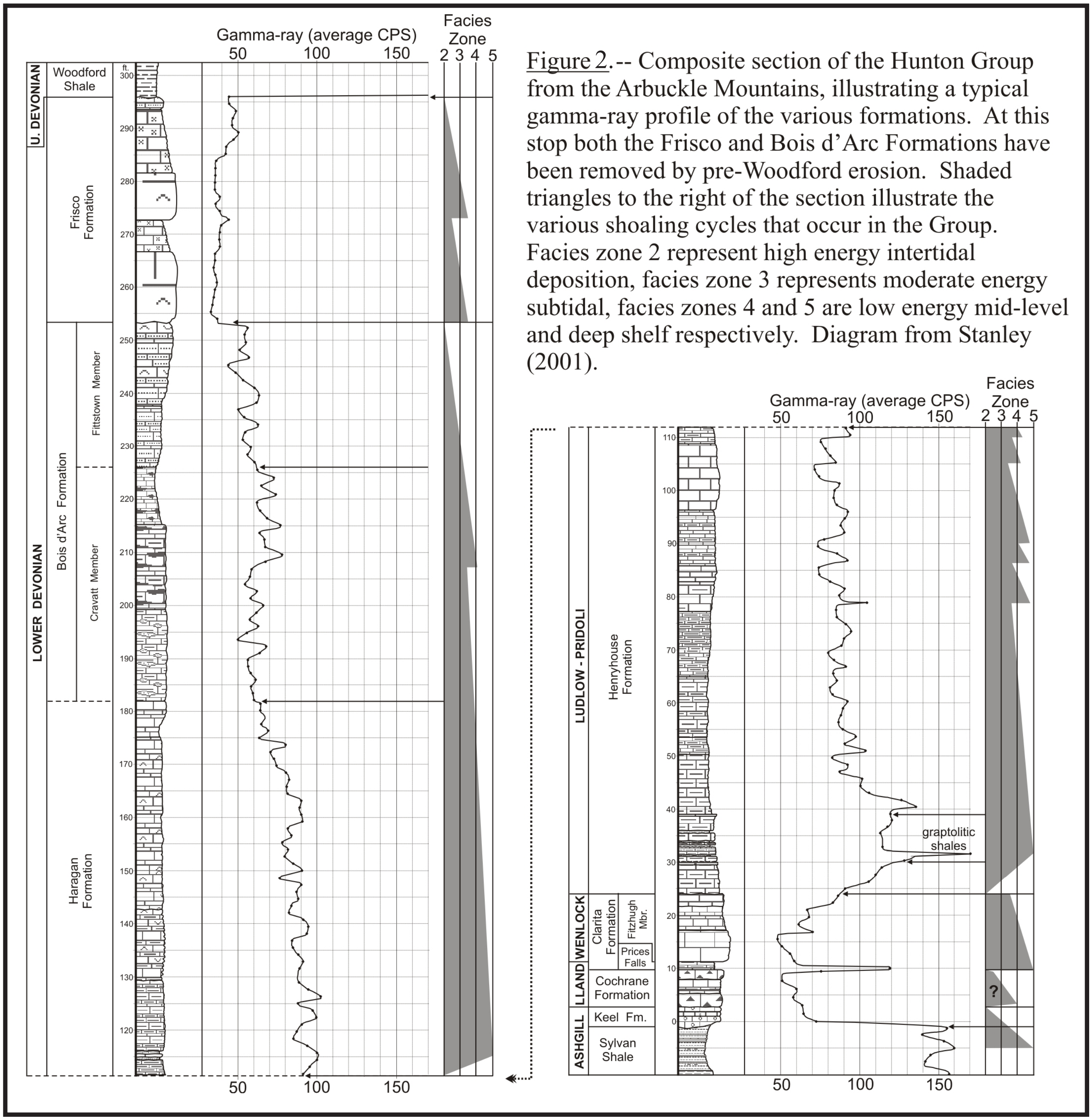


Figure 2.-- Composite section of the Hunton Group from the Arbuckle Mountains, illustrating a typical gamma-ray profile of the various formations. At this stop both the Frisco and Bois d'Arc Formations have been removed by pre-Woodford erosion. Shaded triangles to the right of the section illustrate the various shoaling cycles that occur in the Group. Facies zone 2 represent high energy intertidal deposition, facies zone 3 represents moderate energy subtidal, facies zones 4 and 5 are low energy mid-level and deep shelf respectively. Diagram from Stanley (2001).

The Hunton Group is also a fairly important petroleum reservoir, particularly in the Anadarko Basin. In areas where it has good hydrocarbon potential the Hunton facies tend to consist exclusively of shallow water grainstone textures that underwent secondary porosity and dolomitization (i.e., the Keel, Cochrane, and Henryhouse Formations) (Fig. 1).

After Hunton deposition (latest Early Devonian), the southern Oklahoma aulacogen, as well as most areas across the cratonic shelf in Oklahoma, experienced a major regression that caused extensive erosion of older units. Evidence for this period of erosion, which lasted into the Late Devonian, consists of the absence of about 110-150 feet of Hunton section (Frisco and Bois d'Arc Formations) at this locality (Fig. 2). Instead Upper Devonian Woodford Shale rests on top of Lower Devonian Haragan Formation.

Toward the end of the Middle Devonian or at the beginning of the Late Devonian the aulacogen underwent extensive subsidence, commensurate with deposition of deeper water marine shales of the Woodford Shale (Upper Devonian through Lower Mississippian). The Woodford consists of an organic-rich, fissile black shale with abundant chert nodules and beds; phosphate nodules are common throughout, and sandstone usually occurs at the base of the formation. Given the shales high organic content, the depositional environment of the Woodford was anaerobic deep water conditions. The Woodford Shale represents major source for hydrocarbons in Oklahoma. Although the Woodford is not well exposed at this locality, one can get a better look at it at the next stop.

Deep water deposition and subsidence continued in this area as the Woodford grades into the overlying Sycamore Formation and Caney Shale (Delaware Creek Shale of Fay, 1989). Here, the Sycamore is represented by a dense, slightly argillaceous, unfossiliferous carbonate mudstone, with local shale partings and interbeds (Fig. 3). Due to the lack of fossils and sedimentary structures a precise interpretation of the environment of deposition for the Sycamore is not possible. However, some complex, horizontal trace fossils have been found along bedding planes suggesting that sedimentation rates were slow and possibly occurred under deep water conditions (Brown and Grayson, 1985).

Figure 3. .-- Overturned contact between the Sycamore Limestone and the (?)Caney Shale. In Fay's (1989) Guidebook, he calls the Caney the Delaware Creek Shale.

It is unclear, but at the far east end of the outcrop the base of the Caney Shale may be exposed. Here shale, which may or may not be Caney, is in sharp contact with the Sycamore Formation; in fact the beds in this part of the section are overturned, again owing to severe deformation along the south limb of the Washita Valley Syncline (Fig.

3). The shale looks similar to the Woodford: fairly organic-rich, fissile, with some thin interbeds of sandstone and siltstone; this evidence suggests that it is both a good source rock and a reservoir for hydrocarbons.

STOP 1B – WOODFORD SHALE

By Galen W. Miller, Oklahoma Geological Survey

Objectives and Things to See

- Overturned beds of the Woodford Shale along the south limb of the Washita Valley Syncline.
- General lithostratigraphic characteristics of the Woodford Shale.
- Highly siliceous nature of the basal beds of the Woodford Shale.

Description – Unlike the last stop, this location affords a better look at the Woodford Shale. The road that leads to this site transects the Hunton-Woodford section. Note that the strata are slightly overturned, with the younger Woodford resting on top of the older beds of the Hunton. As with the last stop, the uppermost units of the Hunton Group (Frisco and Bois d'Arc Formations) are missing, again highlighting the post-Hunton erosional event. At this site, just east of the I-35 overpass, the Hunton-Woodford contact is covered by County Road 77D; lower beds of the Henryhouse Formation are exposed on the south side of the road, and the lower parts of the Woodford are exposed on the north.

The Woodford Shale is an organic-rich, fissile black shale that is lithostratigraphically equivalent to the Chattanooga, New Albany, and Ohio Shales found in the Eastern and Midwest United States. As with most of these Devonian-Mississippian black shales, the Woodford was probably deposited in a deep marine environment, under highly anoxic conditions. Compositionally, the Woodford averages 30% clay, 50% radiolarian chert, and 20% organic matter. Total organic carbon varies from 5.4 weight % in the cherts to as much as 13.7 weight % in the black shale (Roberts and Mitterer, 1992). The high organic content of the formation underlines its value as a petroleum source rock.

Examining the lower beds of the Woodford, one notes a large proportion of thin beds of chert interbedded with equally thin intervals of fissile shale, and local sandstone lenses and partings. This is typical of most Woodford exposures in the Arbuckle Mountains, where the lower and upper parts of the formation contain abundant chert, while the middle half is predominantly fissile shale (Fig 4).

Figure 4. -- Overturned, cherty beds of the basal Woodford Shale.

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STOP 2A. WOODFORD SHALE

Brian J. Cardott, Oklahoma Geological Survey

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.

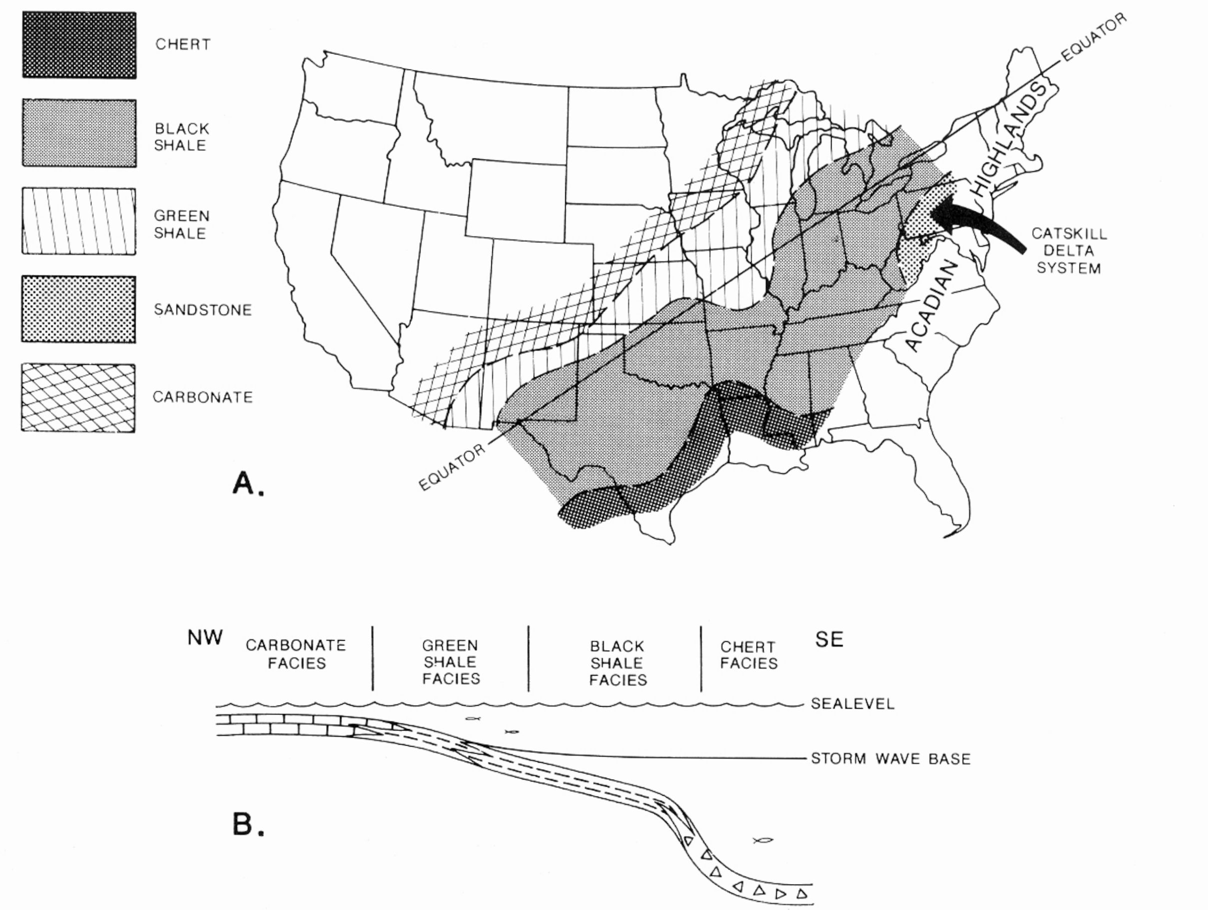

Figure 19. (*A*) Paleogeography and facies distribution in the Late Devonian. (*B*) Northwest–southeast cross section through the Woodford depositional basin showing the relationship of facies to relative water depth (from Kirkland and others, 1992).

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.

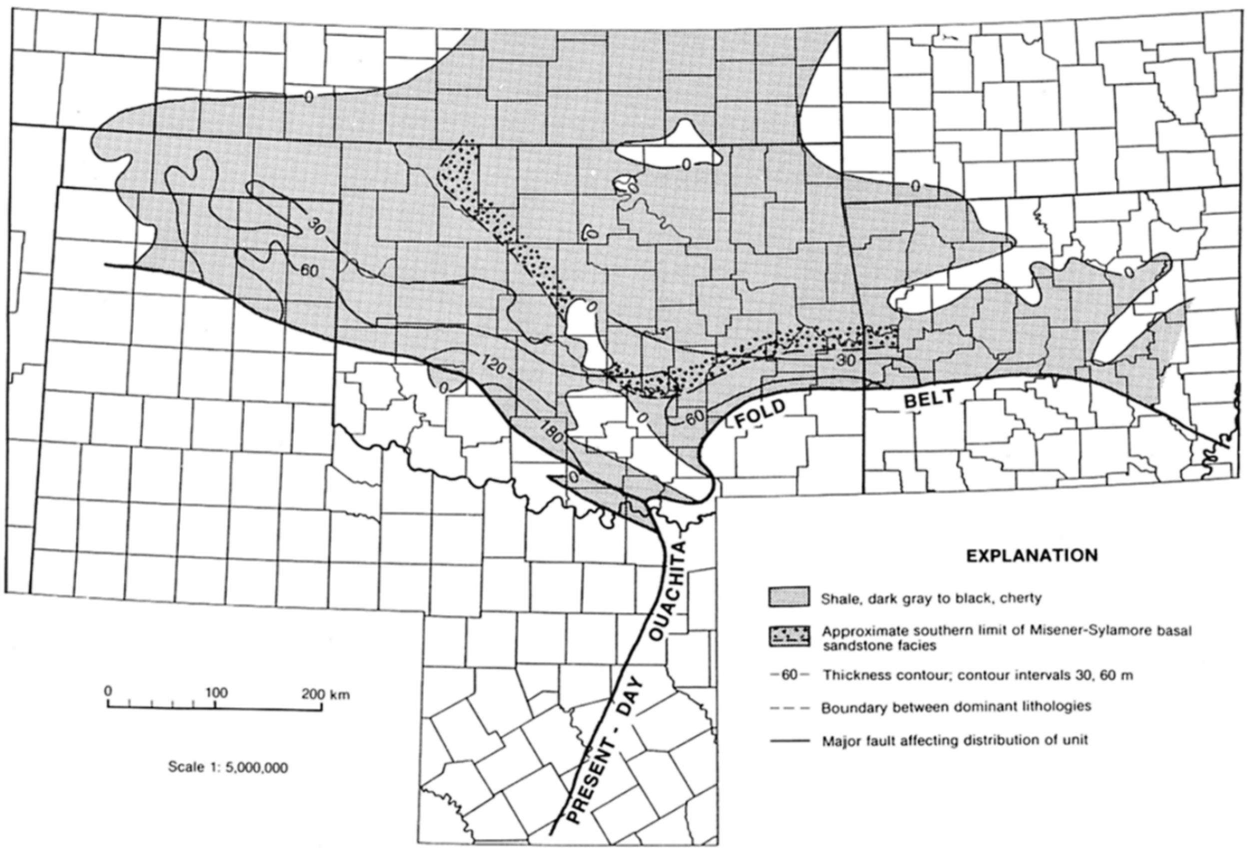

Figure 20. Thickness and dominant lithologies of the Woodford–Chattanooga Shale (from Johnson and others, 1988).

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

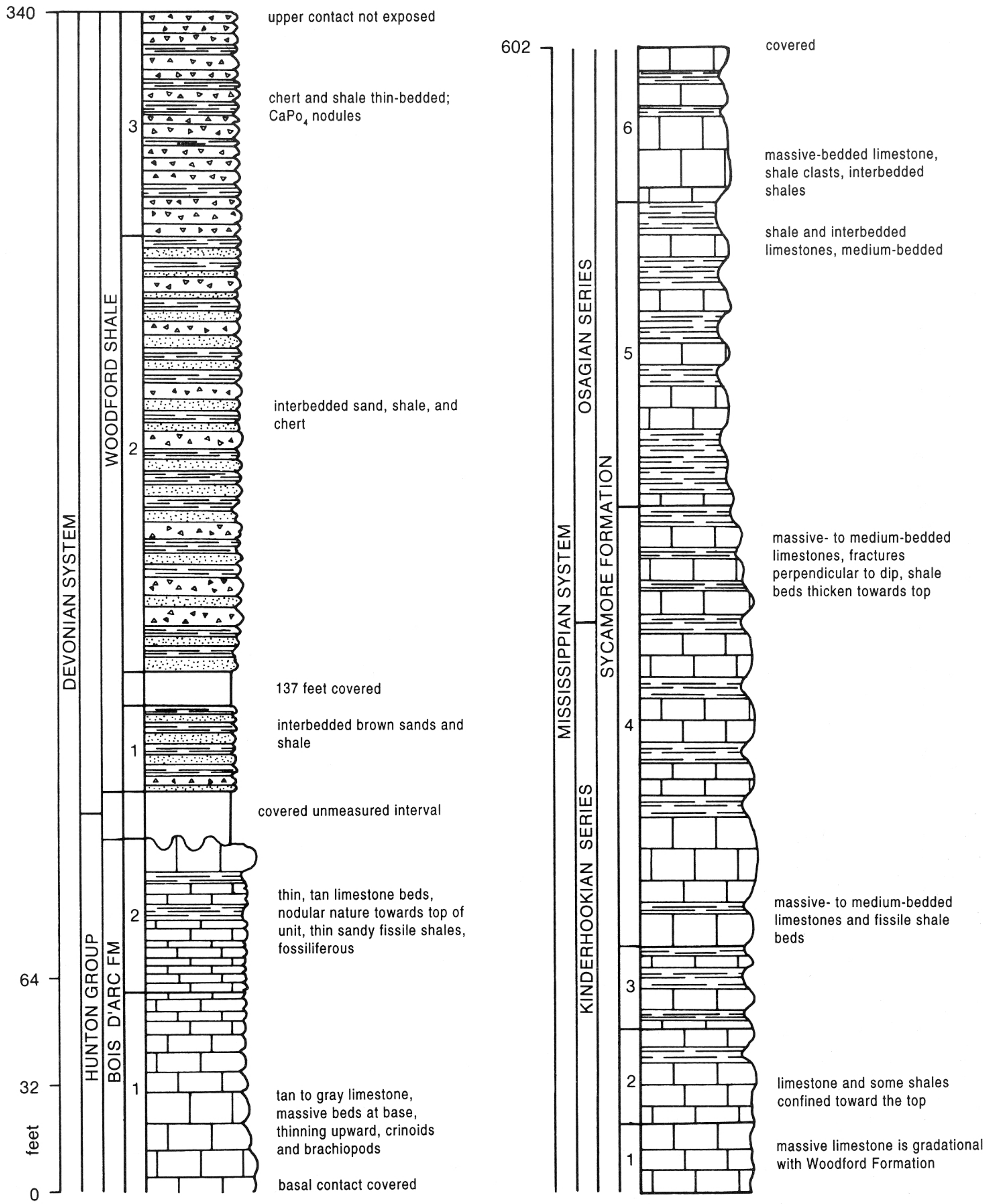

Figure 21. Measured section of the Bois d'Arc, Woodford, and Sycamore Formations at stop 3 (modified from Ellis and Westergaard, 1985).

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.

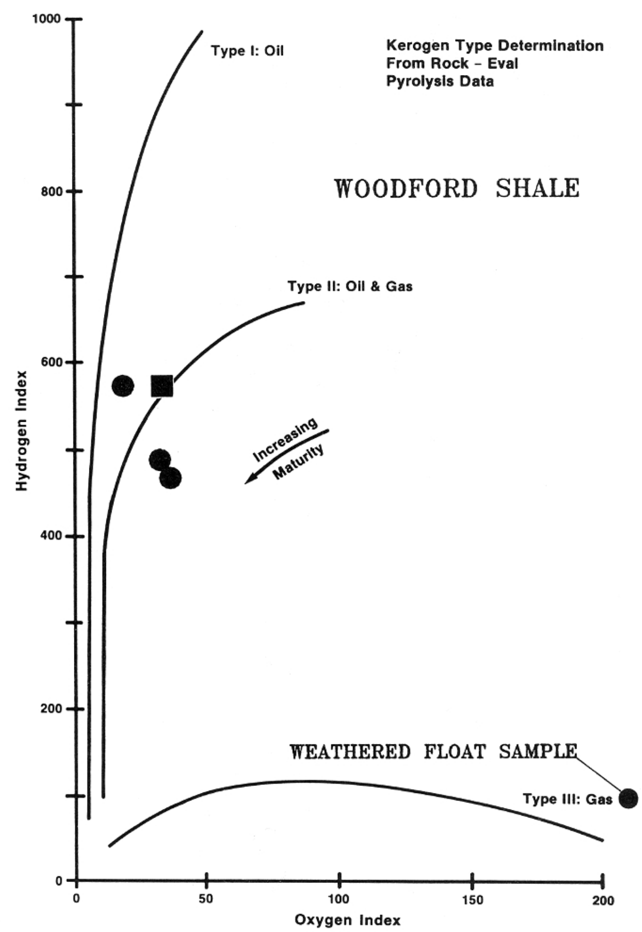

Figure 22. Van Krevelen-type diagram of Rock-Eval pyrolysis data showing the kerogen type of the Woodford Shale at stop 3 (■) and stop 6 (●). Data is in Table 2.

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.

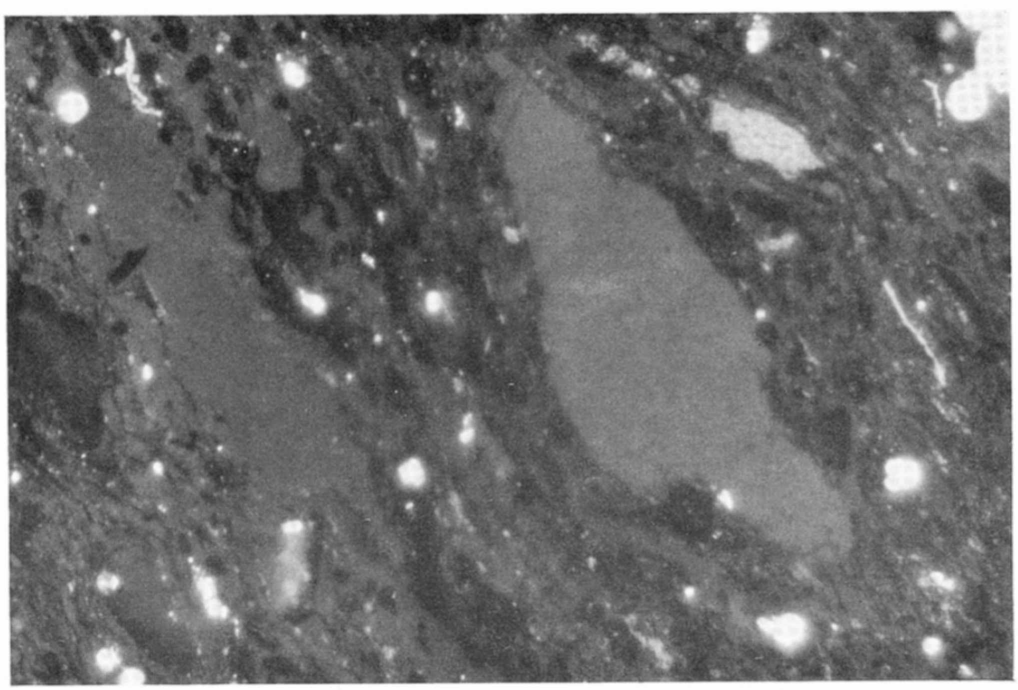

Figure 23. Photomicrograph of low-reflecting bitumen (on left; 0.36% R_o) and vitrinite (0.52% R_o) from Woodford Shale type locality (T on Fig. 5; reflected white light, oil immersion, 200×, field width is 140 μ).

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 2B. THE CANEY SHALE ALONG PHILLIPS CREEK ON THE SOUTH SIDE OF THE ARBUCKLE MOUNTAINS

Richard D. Andrews, Oklahoma Geological Survey

This outcrop is probably one of the best representative sections of the Caney Shale in southern Oklahoma. It consists of 334 ft gray to dark gray fissile shale and interbedded siltstone/carbonate strata (Boardman and Puckette, 2006). Located on the south flank of the Arbuckle Mountains and just off I-35 (Fig. 1) it is easily accessible and well exposed.

This section exposes much of the Delaware Creek Member of the Caney Shale Formation – the middle member as mapped in the Lawrence Uplift area 35 miles northeast (Boardman and Puckette, 2006).. The upper and lower contacts of the Caney are not well exposed; the formation appears to be underlain directly by the Sycamore Limestone and overlain by the Goddard Shale.

Stratigraphy

The Caney Shale is a formal formation name applied to surface and subsurface mapping in south-central and southeastern Oklahoma. The name is also used in the deep Anadarko Basin of southwestern Oklahoma. The Caney appears to be litho-stratigraphically correlative to the Fayetteville Shale in the Ozark Uplift of northeastern Oklahoma and the Barnett Shale of north Texas. Being middle to upper Mississippian in age, these non-conventional reservoirs are all closely time correlative.

In the Lawrence Uplift area, the Caney Formation is comprised of 3 members: the Sand Branch, Delaware Creek, and Ahloso. However, in the Ardmore Basin only the middle member is recognized. These stratigraphic relationships and formation ages are shown in Figure 2.

More importantly, the Caney in the subsurface is distinguished by two distinct lithostratigraphic zones that probably have no affiliation to formal stratigraphic nomenclature. These zones include an upper interval consisting of shale and interbedded siliciclastics (largely siltstone) and subordinate carbonate beds. The lower zone is comprised mostly of fissile shale. Representative wireline log responses (Fig. 3) are shown for a well in the Arkoma Basin. In the Ardmore Basin, the Caney Shale may be several hundred ft thick but thins eastward to about 200–250 ft in the western part of the Arkoma Basin. In eastern Oklahoma and in far western Arkansas, the Caney is less than 100 ft thick.

Rock Characteristics

At this locality and elsewhere, the Caney Shale weathers light gray but is dark gray in freshly broken pieces. Pieces of shale weather with conspicuous fissility, are brittle, and splintery (Fig. 4). Pieces of shale are very sharp to the touch and do not react with HCl. Although (phosphatic?) nodules are routinely found (Fig. 5) they are not abundant when compared to the amount of nodules found in the Woodford. Macro fossils in the Caney are seldom found and fracturing is moderate at best. Vertical fractures generally extend only a few ft (Fig. 6) but may also die-out along bedding surfaces (Fig. 7).

The Caney Shale is believed to be a deep water anoxic facies deposited far from shore. Despite this, regionally persistent siliciclastic beds occur in the upper part of the formation. These beds consist mostly of siltstone with silica and/or carbonate matrix cement. The siliciclastics are usually only a few ft thick but may be much thicker in the subsurface. At this location, they are lenticular in nature (Fig. 8) although their lateral distribution is widespread and stratigraphic position remarkably uniform. Upper and lower contacts with shale are sharp (Fig. 9). The siltstone? beds at this stop react easily with dilute HCl and faint bedding can be observed (Fig. 10). Nevertheless, their environment of deposition and depositional process is an elusive detail to these sediments.

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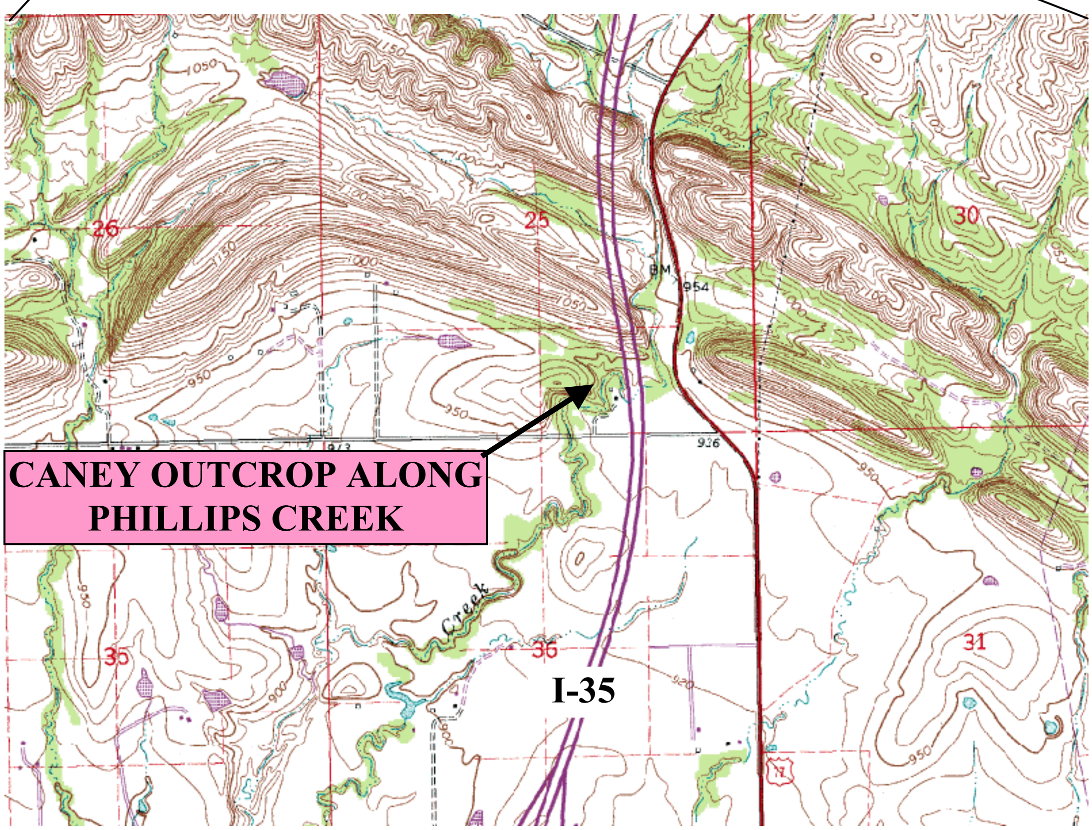
FIGURE 1
Generalized Location Map
of Stop 2B

CANEY SHALE

South side of the Arbuckle Mountains just west of I-35 and ~1.2 miles north of exit #42 (HY 53) along Phillips Creek: SE/4 sec. 25, T2S-R1E, Carter Co., OK



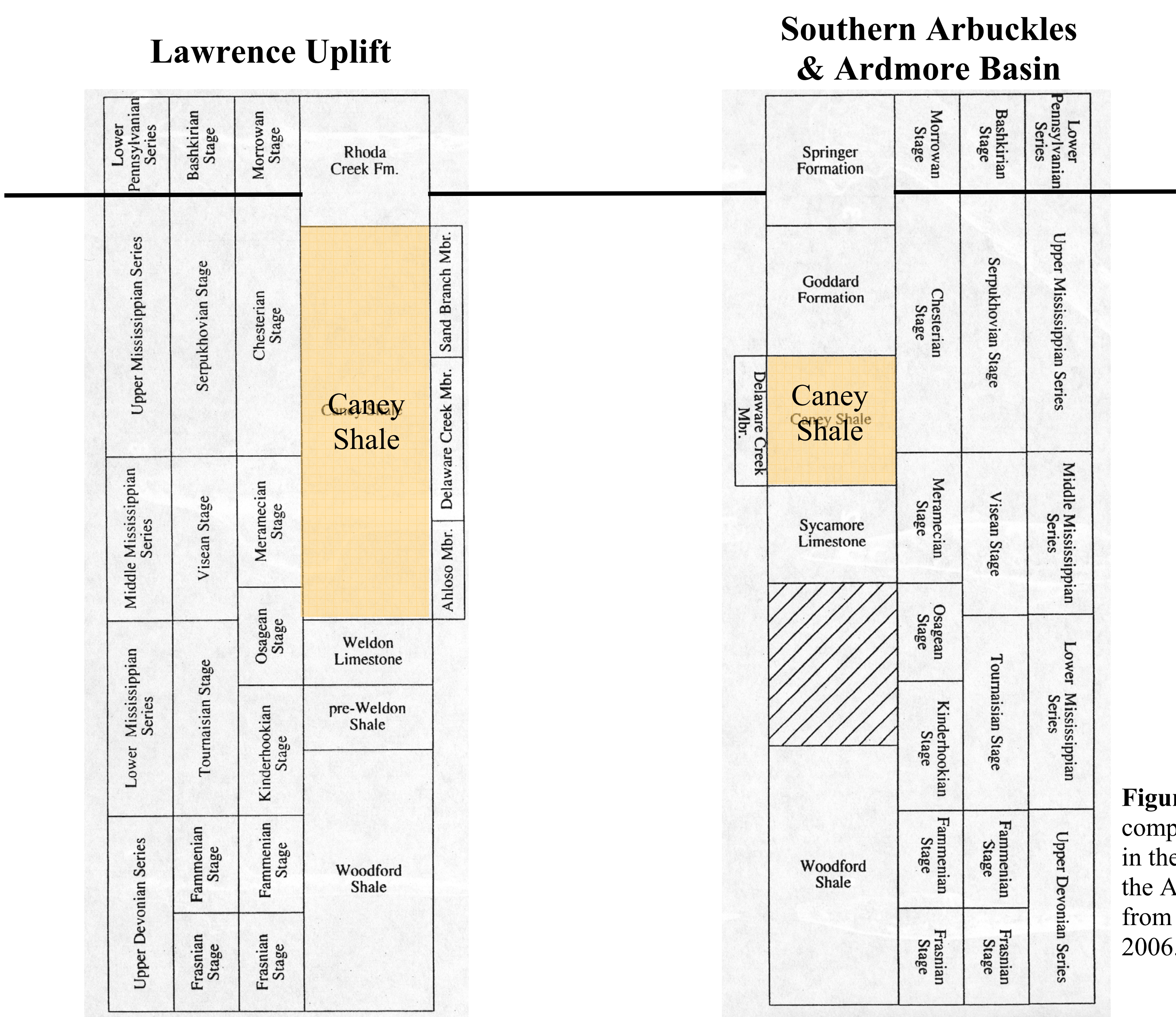


Figure 2. Stratigraphic charts comparing Mississippian strata in the Lawrence Uplift area to the Ardmore Basin. Modified from Boardman and Puckette, 2006.

Citrus Energy Wild Turkey No. 1
NE NE sec. 7, T. 9 N., R. 13 E.

Cum Production: >320 MMCFG through June 2005

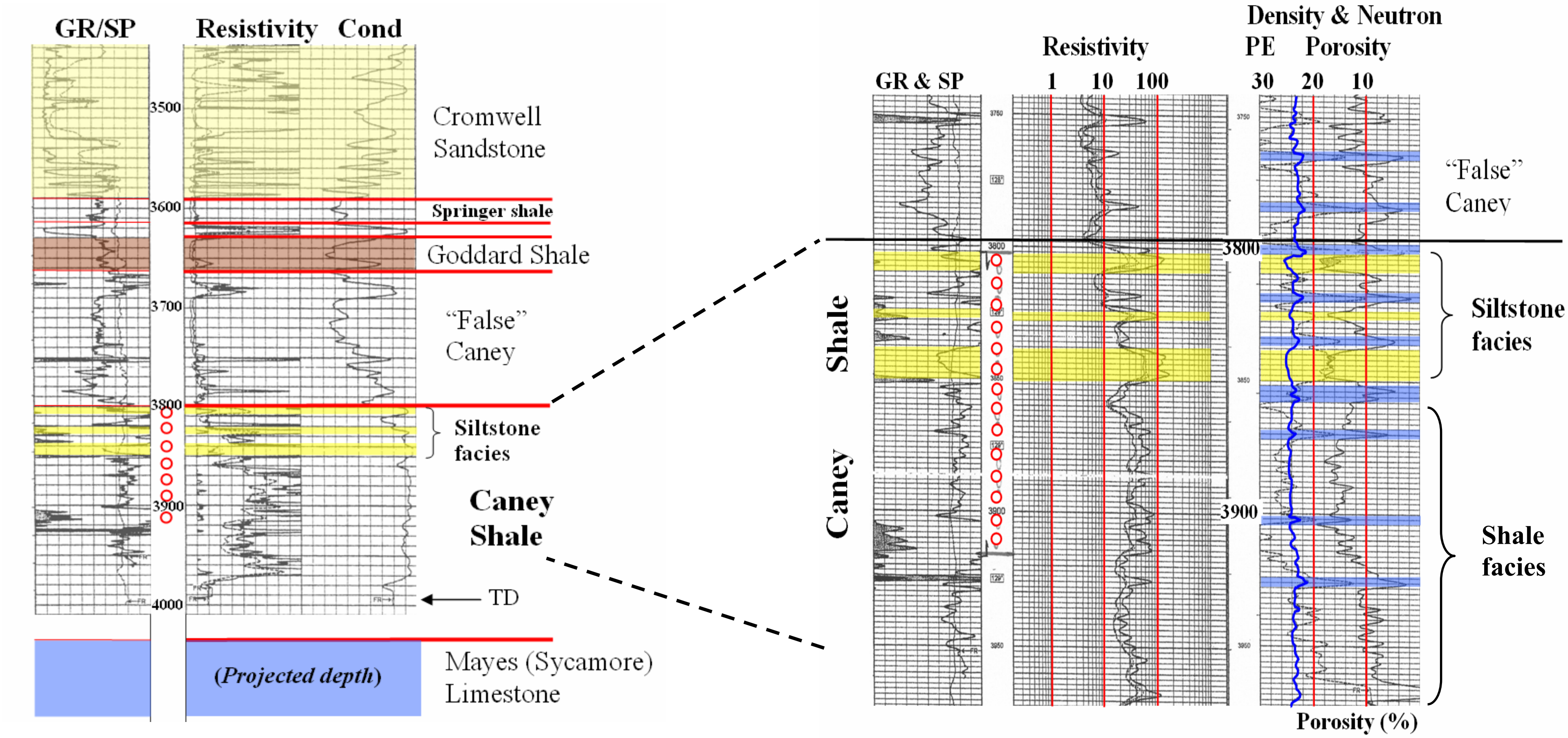


Figure 3, Stop 2B. Well logs of the Citrus Energy No. 1 Wild Turkey well located in the Arkoma Basin of Oklahoma. Characteristic log responses in the Caney Shale include high gamma-ray intensity (GR) and high resistivity. The porosity logs show density-neutron crossover in the siliciclastic (siltstone) beds (colored yellow). Blue beds in the Caney are limestone.

Figure 4, Stop 2B

The Caney Shale characteristically weathers a light gray and is very fissile. Pieces of shale are splintery and very sharp.

Figure 5, Stop 2B

Nodules in the Caney Formation are frequently observed but not abundant. They are usually about an inch in diameter and presumed to be phosphatic in composition. Their distribution in the formation does not seem to have any relationship to the overall gamma-ray intensity as recorded in subsurface well logs.

Figure 6, Stop 2B

Fracturing in the Caney Shale is vertical and widely spaced. Fracture length is relatively short and extends only a few ft before ending against other bedding surfaces.

Figure 7, Stop 2B

Fracturing and small-scale displacements locally die-out along bedding surfaces as shown here (note curvature of fracture above and left of penny)

Figure 8, Stop 2B

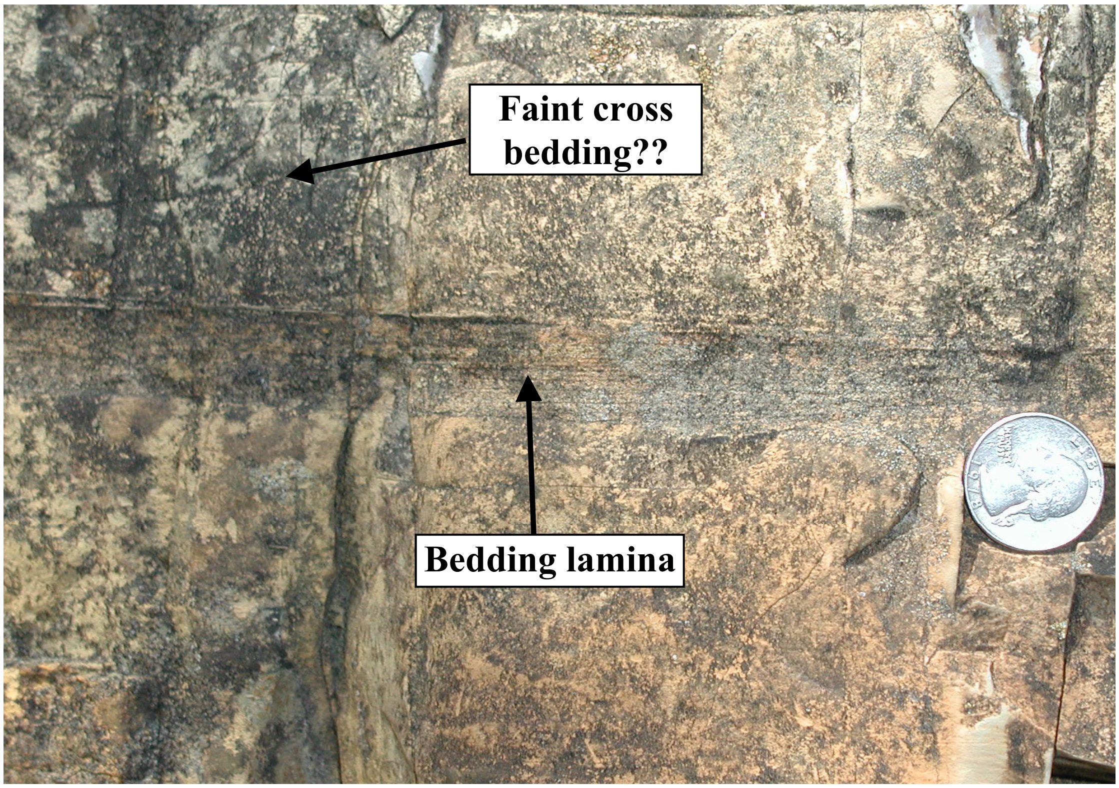
Siliciclastic and carbonate beds occur in the upper part of the Caney Formation. Their lateral distribution is regional in nature and their stratigraphic position is remarkably consistent. Here, a calcareous/dolomitic siltstone? lens is exposed along Phillips Creek. The bed extends across the creek but is discontinuous immediately in front of OGS geologist Neil Suneson. Farther up the hill to the north this same bed is exposed for hundreds of feet.

Figure 9, Stop 2B

The siliciclastic and carbonate beds in the upper part of the Caney Formation often have sharp upper and lower contacts with shale yet no scouring/erosion is observed. Their depositional process and origin is highly speculative.

Figure 10, Stop 2B

Sedimentary structures in the siltstone/carbonate beds are uncommon. Here, faint lamina across the center of the picture can be seen. In the upper left, faint cross bedding is also visible.



Stop 3. Complete section of Woodford Shale adjacent to the Henry House Falls Quarry on the south side of the Arbuckle Mountains.

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Note: This field location is private property. The field site is not accessible to the general public after completion of the May 24, 2007 field trip.

To date, this location may represent one of the best preserved (and complete) sections of the Upper Devonian - Lower Mississippian black shale lithofacies in the world. Past work at this field site focused on exposures on the floor of the Henry House Falls Quarry, located just to the east of Henry House Creek and the north-south ranch road. The lithofacies in the quarry are well described by Kirkland and others (1992). Hass and Huddle (1965) measured the creek section and also described the conodont biostratigraphy (the classic Hass "A" biostratigraphic section). Over (1992) determined the conodont biostratigraphy from the basal part of the section along the creek. Schwartzapfel and Holdsworth (1996) described the occurrence of radiolarians in the highwall exposure located to the south of the quarry.

Krystyniak (2005) was the first to measure the gamma-ray character of the exposure along the west side of Henry House Creek. Magnetic susceptibility of the outcrop and association with gamma-ray response was evaluated by Aufill (2007).

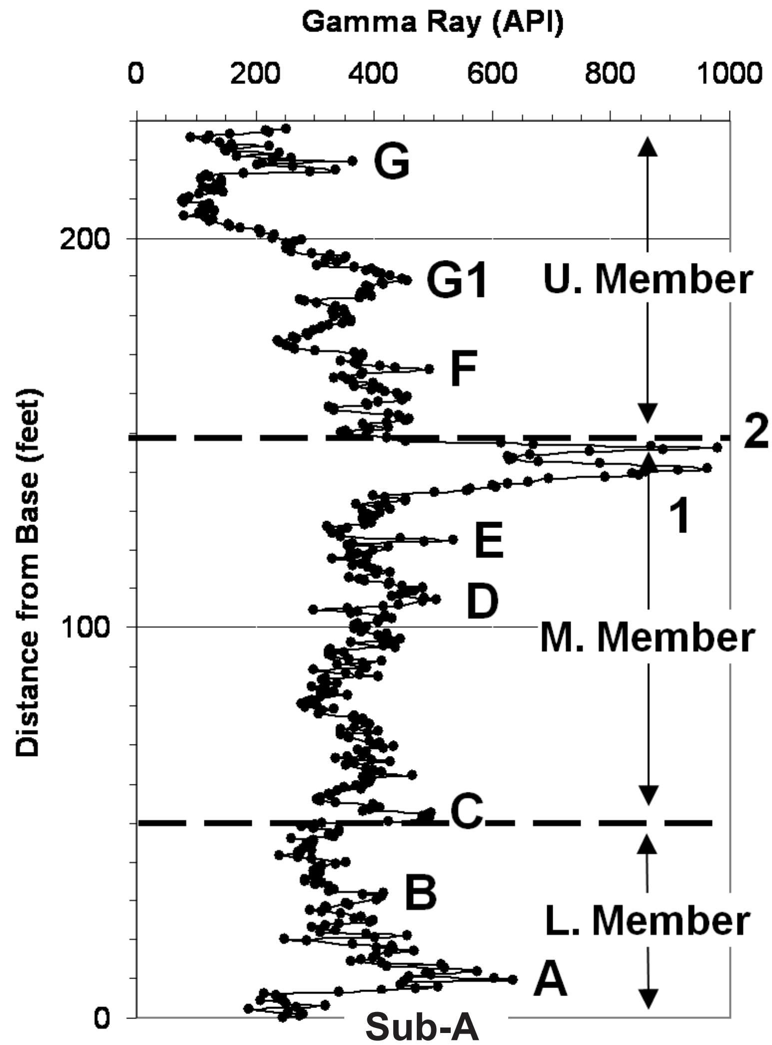

Figure 1 - Spectral gamma-ray profile of the Henry House Creek section. The letters and numbers correspond to sample locations with high gamma-ray response. Note the designation of the informal members or subdivisions of the formation.

For purposes of description, the resistant beds (siliceous and carbonate) at this locality were identified and labeled from the base of the Woodford section to the top of the outcrop using a permanent marker. In turn, the thickness of each resistant bed was measured. The thickness of each intervening fissile interval was also measured. Spectral gamma-ray readings (K, U, and Th) were collected every 15 cm (6 inches) on the outcrop face to yield about 462 sets of measurements from base to top. Samples for laboratory analyses were taken throughout the section based on the character of the gamma-ray response and the variations in lithology.

The Henry House Creek exposure is about 231 feet in vertical thickness. The unit contains three informal members (as defined by Lambert, 1993, for Kansas and northwestern Oklahoma) and up to eleven high-resolution intervals based on gamma-ray response.

The shale lithofacies are organic-rich throughout and either fissile or siliceous (chert-like). All lithofacies are finely laminated and no obvious evidence for bioturbation at this locality has been noted to date. Pyrite occurs throughout the section, though a few thin (cm-thick) intervals are enriched in pyrite, particularly in the fissile (middle) part of the section. The upper part of the section contains an abundance of spherical phosphate nodules. Most of these nodules contain porosity. Large dolomite concretions and/or beds occur at three locations in the section. The dolomite beds near the top of the section are saturated with liquid hydrocarbon. In all cases, the dolomite is very finely crystalline, nonporous, and very dense (see Krystyniak, 2005).

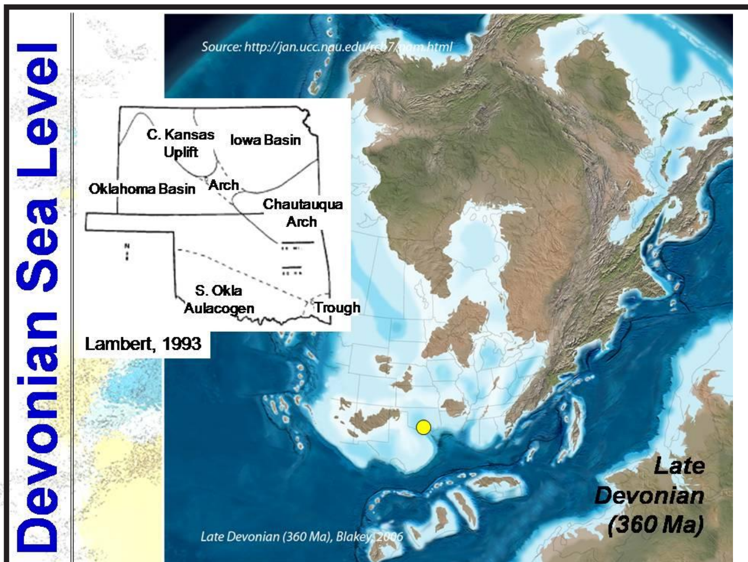

Figure 2 - Reconstruction of late Devonian paleogeography downloaded from the website of Dr. Ron Blakey (University of Northern Arizona). Inset: Lambert, 2005.

On the north end of the exposure, the contact of the Woodford with the underlying Hunton Group carbonates (Bois de Arc Limestone at this locality) is hidden in the tributary creek bed that joins Henry House Creek from the west. The contact may be a subtle angular unconformity on the regional scale. Locally, the contact appears to be a disconformity surface because the dip on the underlying beds is not discernable. In the subsurface, the Hunton Group carbonates contain karst and organized erosional patterns on the unconformity surface that appear to be fluvial in origin. The Hunton Group carbonates produce significant volumes of oil and gas. On a continental scale, this unconformity is referred to as the Acadian Unconformity.

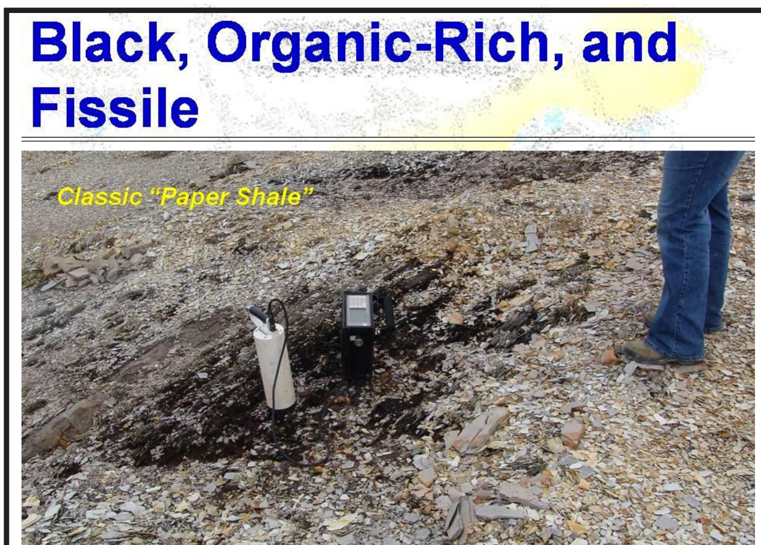

Figure 3 - Paper shale exposed in the quarry floor of Henry House Creek and McAlister Cemetery Quarry.

From base to top, the Henry House Creek outcrop contains about 940 discrete beds. Fissile beds make up about 50% of this total (466 beds). Siliceous beds constitute about 49% of the total beds (460 beds). About 1% of the beds are carbonate, mostly dolomite (12 beds). Fissile beds range from a fraction of an inch to about 5.4 feet in thickness. Siliceous beds range from about 0.125 inches to 4.75 inches in thickness. The mean thickness of the siliceous and fissile beds is 1.3 and 4.5 inches respectively. In terms of gross interval thickness, siliceous beds (which are brittle) make up a progressively greater proportion of the total stratigraphic section from gamma-ray marker E to marker G1.

The basal portion of the section at this location contains alternating intervals of fissile (85%) and siliceous shale (15%). The thickness of the lower informal member is 52 feet (15.8 meters) and extends from gamma-ray marker Sub-A to the base of gamma-ray marker C. The siliceous layers in this lower member contain radiolarians that are visible in some of the hand samples. Some of the siliceous layers contain inclusions of mudrock at the center of the siliceous beds that are a few centimeters in diameter. These mudrock occurrences, isolated within siliceous beds, appear to be portions of the original sediment that were not completely silicified. The mudrock inclusions preserved within the siliceous beds have a slight pinkish color, suggesting the lower part of the Woodford may have been deposited initially as Devonian red mud. Some of the bedding planes in this lower portion of the section also have a smooth feel to the touch that is reminiscent of kaolinite clay.

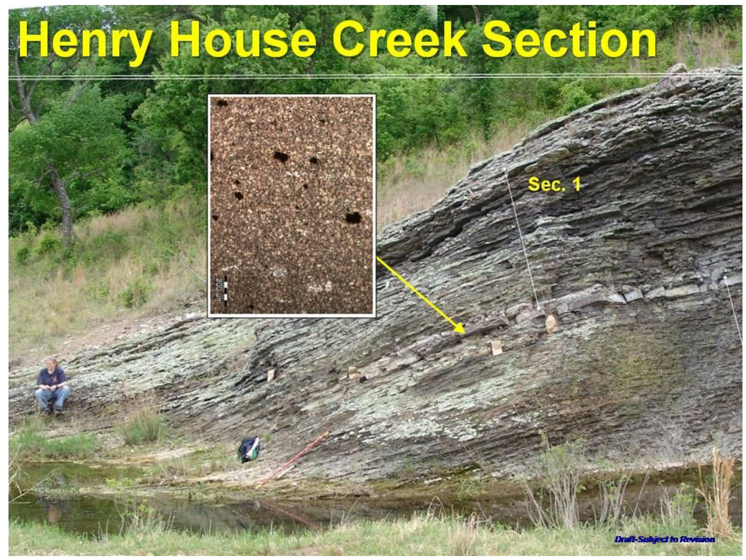

Figure 4 - Hydrocarbon saturated dolomite in the upper member of the Woodford. The inset is a thin section view of the finely-crystalline dolomite groundmass.

The first major gamma-ray kick at the base of the section is located about 10-15 feet above the contact with the underlying Hunton carbonates. The shale interval between the underlying Hunton carbonate and this first major gamma-ray response (A) is relatively K and Th rich according to the spectral data. This K and Th portion of the section is also the interval that appears to contain petrified wood (Callyxylon, see Arnold, 1957). The organic matter type in the lower member of the Woodford is woody-coaly according to Lambert (1993). In total, the observations for the base of the Woodford section along Henry House Creek are suggestive of a relatively rapid transgression of the sea across an erosional surface that was actively accumulating sediment from an adjacent continental land mass. The landmass was populated with plants.

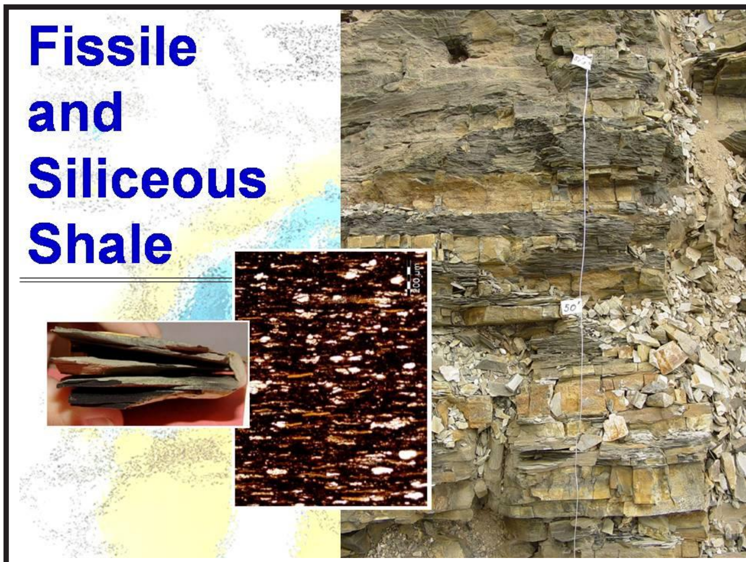

Figure 5 - Fissile and siliceous beds in the Woodford. The TOC is greater in the fissile beds than in the siliceous beds. Fissile and siliceous beds alternate at the scale of centimeters in some locations along the outcrop.

The middle portion of the section is dominantly fissile (92%) with a few, poorly developed and thin siliceous beds. This informal member is 95 feet (29 meters) in thickness. This interval extends from the base of gamma-ray marker C up to the top of gamma-ray marker #2. Strong gamma-ray markers D, E, and marker #1 also occur in this interval. Based on resistance to erosion as exhibited by the small rapids in the stream, the silica content in the shale is beginning to increase between gamma-ray markers E and #1. Gamma-ray marker #1 and #2 contain the greatest concentrations of U in the outcrop (107 and 112 ppm U respectively). In terms of spectral-gamma ray, gamma-ray marker #1 contains a relatively large volume of K and Th in comparison to the immediately underlying units. The K and Th in gamma-ray marker #1 is similar to the abundance of K and Th present in the interval just below gamma-ray marker A, located at the base of the outcrop. Perhaps the increase in K and Th is related to a tectonic uplift in the sediment source area or perhaps the development of a wetter climate (?) in the hinterland. In contrast, gamma-ray marker #2 displays a precipitous drop in K and Th abundance relative to underlying units.

The absence of siliceous beds in the middle member has a direct bearing on the mass wasting of the outcrop. When present, the siliceous beds tend to reinforce the integrity of the outcrop and help to hold the fissile beds in place. In the absence of the siliceous beds, large sub-vertical tension fractures have developed in the outcrop face of the intervals dominated by fissile beds.

The upper portion of the Woodford at this locality (84 feet or 25.5 meters in thickness) contains siliceous beds (55%), fissile beds (44%), and a few dolomite layers (1%). This informal member is defined by the top of gamma-ray marker #2 up through the contact with the overlying lower Mississippian limestone and shale intervals (gamma-ray markers F, G1, and G inclusive). The occurrence and thickness of siliceous beds increases dramatically above gamma-ray marker #2. This change in lithology is one of the most dramatic in the physical appearance of the outcrop. The two strong eastern deflections in the stream drainage that occur in this reach of Henry House Creek are directly related to the abundance of siliceous beds that occur in the upper part of the Woodford Shale. The upper contact of the Woodford can be located near the top of the outcrop (coincident with a vegetation change). Well developed Sycamore Limestone is present in the creek about 150 feet to the south of the last occurrence of a Woodford Shale siliceous bed.

Figure 6 - Typical millimeter-scale laminations in the Woodford of south-central Oklahoma (from Ryan Shale Pit). The fine-scale of lamination is maintained across all lithologies (siliceous, fissile, and dolomite).

Three distinct beds of dense dolomite occur up the upper member. These beds increase in thickness up-section. The dolomite is finely laminated and saturated with hydrocarbon. The dolomite weathers to a characteristic dull white color. The upper most dolomite occurs just below the position in the outcrop where the phosphate nodules become most abundant.
Spherical phosphate nodules are locally abundant in the lower upper half of this informal member, just above the dolomite beds. Based on compaction of layers both in and around the phosphate nodules, growth of the nodules appears to have occurred shallow in burial. In some cases, the bedding surfaces that bound the nodule-rich intervals are curved and wavy, appearing to exhibit evidence for wave energy. On the other hand, the layering also exhibits characteristics of “pinch and swell” and may suggest that relief on the nodules near the sediment-water interface was locally significant enough to influence sedimentation around the nodules. The phosphate nodules are not noticeably enriched in U.

The spectral character of the gamma-ray is diminished in both K and Th from marker #1 to the top of the outcrop. In contrast, the abundance of U in the upper part of the section stays relatively constant up through marker G1. The mutual relations of the spectral response may suggest that sedimentation rate remained relatively constant (as gauged by the U) while terrestrial sediment provenance (as recorded by K and Th) either changed or became more distant. A logical explanation would be that marine flooding of the craton in this interval of time may have sequestered sediment further back toward the hinterland. An alternative explanation is that the K and Th have been diluted by the addition of progressively greater volumes of silica (from radiolarians that now form a significant volume of the siliceous shale).

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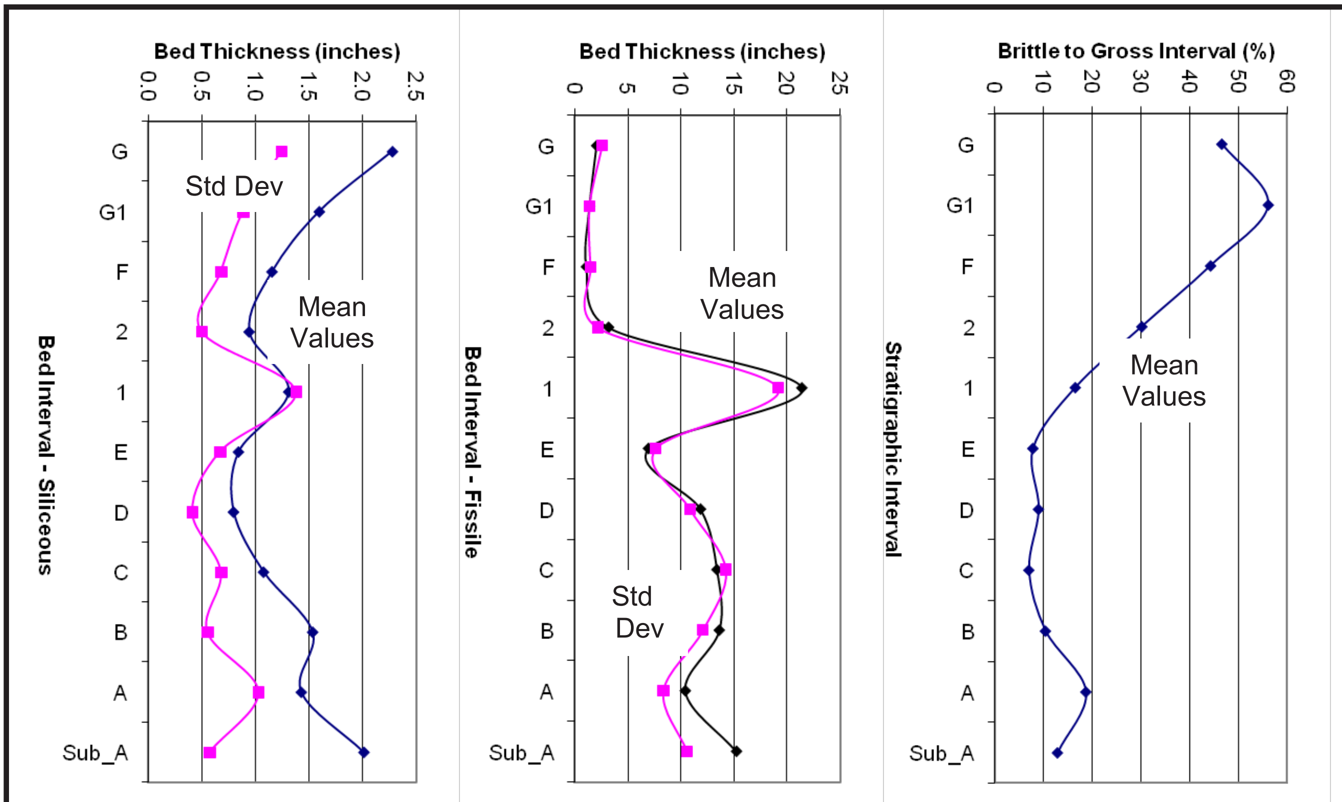

Figure 7 - Bed thickness for both siliceous (left) and fissile intervals (middle) in the Woodford Shale at Henry House Creek. The ratio of brittle (siliceous) to gross interval is shown on the right.

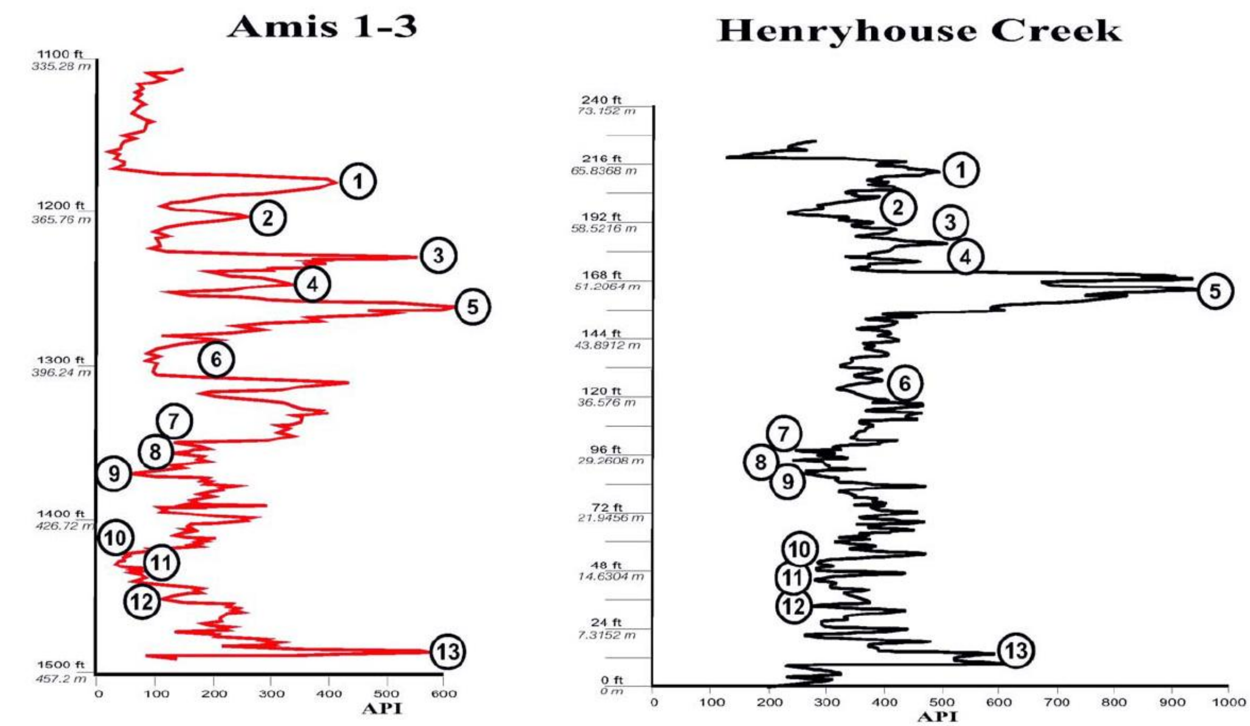

Figure 10 - Comparison of a gamma-ray well log from the subsurface of Murray County to the synthetic profile compiled for the Woodford Shale at Henry House Creek. Some of the major peaks that serve as correlation points are indicated.

Stop 4. Woodford Shale exposed in McAlister Cemetery Quarry in the Criner Hills.

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This quarry is a source of road aggregate for the Carter County and the City of Ardmore. The Woodford exposed in the heart of this quarry is similar in gross physical appearance to the shale exposed in the floor of the Henry House Creek Quarry. However, upon closer inspection, the details of the Woodford exposed throughout this quarry are quite different than observed along the west side of Henry House Creek.

The Woodford Shale lithofacies exposed in the McAlister Cemetery Quarry were described by Kirkland and others (1992). Schwartzapfel and Holdsworth (1996) described the radiolarian biostratigraphy for this locality. The conodont biostratigraphy is summarized in Over (2002).

Kirkland and others (1992) report that a complete Woodford section is present in the quarry (365 feet or 111 meters). The Woodford Shale contact at the base of the quarry is with the underlying Hunton Group carbonates (Haragan Limestone). The limestone blocks at the base of the section (south side of quarry) appear to be in place, though excavation has beveled out the Woodford Shale and the contact is not directly visible. The base of the Woodford at this locality *appears* to be dominated by fissile shale to the exclusion of siliceous shale. In contrast, the base of the Woodford along Henry House Creek has 15% siliceous shale.

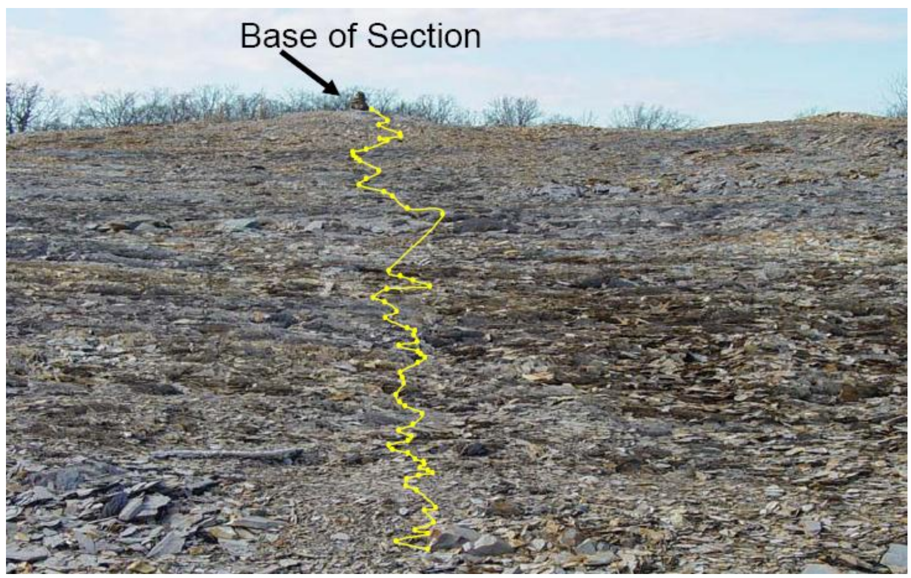

Figure 1 - Gamma-ray profile for the quarry floor at McAlister Cemetery Quarry. The base of the section (as labeled in the distance) is near the contact with the underlying Hunton Group carbonates (Haragan Limestone). This portion of the quarry floor represents the middle member of the Woodford and is dominantly fissile shale.

Krystyniak (2005) was the first to collect spectral gamma-ray data at this location. Krystyniak's gamma-ray profile was compiled with data from the quarry floor. The character of the gamma-ray profile appears similar to the profile through the fissile middle member at Henry House Creek. Krystyniak's work does not include gamma-ray measurements from the base of the section or from the siliceous beds in the highwall. Spectral gamma-ray data collection from the lower and upper part the Woodford at this location is in progress by Paxton and others. Work to date suggests that the strong gamma-ray double peak noted at Henry House Creek is present here in the McAlister Cemetery Quarry.

Aside from the characteristic gamma-ray signature, this quarry contains two significant features not observed in our last stop at Henry House Creek: (1) an upper member that is very siliceous with extremely abundant and well developed nodules and concretions and the (2) occurrence of bitumen concentrations along fractures.

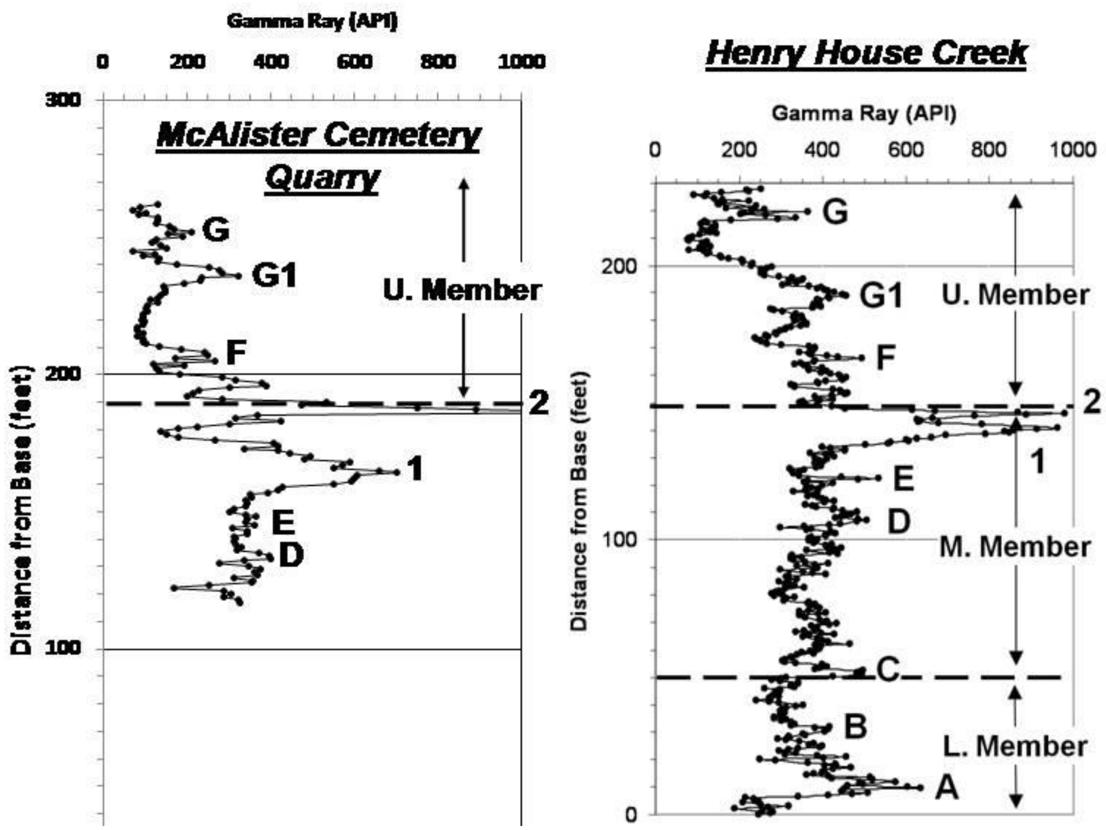

Figure 2 - Comparison of gamma-ray profiles from McAlister Cemetery Quarry (left) and Henry House Creek. The style of correlation between the two locations (letters and numbers as tie points) is based on simple pattern matching and the occurrence of large abundances of potassium and thorium in Peak 1 at both locations relative to Peak 2. (Note: The individual signatures for potassium and thorium are not provided in the figure above.)

The quarry highwall contains abundant siliceous shale, phosphate nodules, dolomite, and some chert. From a lithostratigraphic point of view, the siliceous upper unit appears to be a lateral stratigraphic equivalent to the upper member at Henry House Creek. In contrast to Henry House Creek, however, the degree of primary silicification (assumed from documented occurrence of radiolarians) and the abundance of phosphate nodules suggest that this portion of the ancient seafloor was overlain by a water column with extremely high biologic activity (high primary productivity).

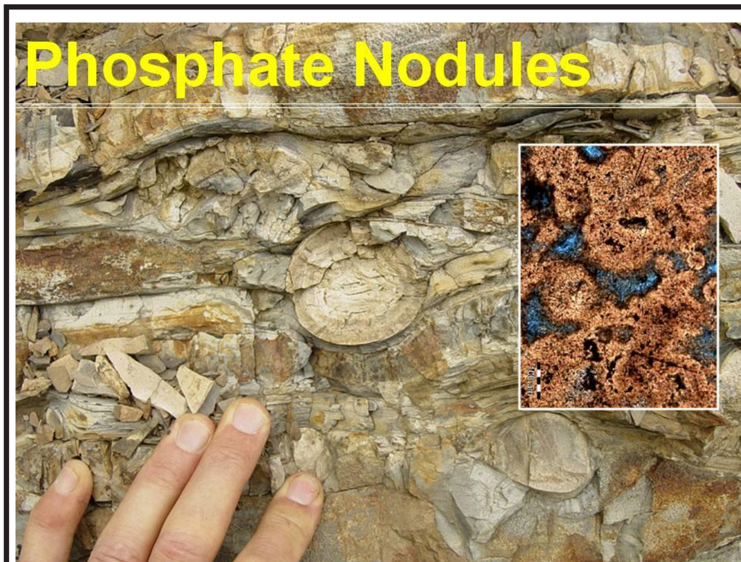

Figure 3 - Concentric phosphate nodule in the upper Woodford. Note contortion of laminations around the nodule. Thin-section inset demonstrates that the nodules contain abundant porosity (blue dye indicating pore spaces).

Based on density of siliceous hand samples, the shale contains abundant microporosity (for housing natural gas). The phosphate nodules are also highly microporous (based on thin sections). The white coloration is this portion of the Woodford Shale is attributed to “bleaching” during the Pleistocene (according to

Kirkland and others, 1992). However, their analysis also indicates that the TOC of this interval is high despite the bleaching. Consequently, the white coloration may be a by-product of oxidized hydrocarbon.

Figure 4 - Siliceous shale in the upper member of the Woodford Shale. Nodules (arrows) at this location are very abundant and quite large.

The bitumen (degraded liquid hydrocarbon) occurs in the fracture system of the upper part of the middle member. Bitumen in this geographic vicinity has been described by Lewan (1987). According to Lewan (1987), the Woodford Shale in this location is in a pre-oil generative state. Consequently, bitumen recognized in fractures of source rock may not be related to primary migration but instead to secondary migration of hydrocarbon. In the case of secondary migration, the oil in the fractures today would have migrated into the fracture system of the shale from deeper and more thermally mature hydrocarbon source rock. Consequently, the bitumen in the fractures is a consequence of secondary migration and not primary migration. However, careful examination of the bitumen occurrence in the fractures of the Woodford in this location is suggestive of primary migration. The tapering of the fractures and the rhythmic co-occurrence of bitumen with the fractures over several vertical feet may provide direct evidence for very local primary migration of hydrocarbon. From a lithostratigraphic point of view, this hydrocarbon occurrence is about twenty feet below the strong double gamma-ray peaks (gamma-ray markers #1 and #2) observed both here and along Henry House Creek.

The McAlister Cemetery Quarry is about 20 miles from the Henry House Creek Woodford Shale exposure. Comparison of the two localities provides evidence for significant lateral facies changes in the Woodford Shale. Supporting evidences includes 1) the absence of siliceous shale at the base of the Woodford in this quarry relative to Henry House Creek and 2) the abundance of siliceous shale and phosphate nodules in the upper member of the Woodford here at McAlister Cemetery Quarry versus that observed at Henry House Creek. These data suggest that the internal properties of gas shale within predefined lithostratigraphic units can change significantly over relatively short distances. Significant changes in shale properties will have a major impact on gas shale resource assessments and exploration/production strategies.

As a point of interest, the folded portion of the upper siliceous member exposed in the highwall of the McAlister Cemetery Quarry is similar in appearance to the chert-rich Miocene Monterey Formation of coastal California (image of the Monterey and G.K. Gilbert for scale included below).

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Krystyniak, A.M, 2005, Outcrop-based gamma-ray characterization of the Woodford Shale of south-central Oklahoma, Unpublished MS thesis, Oklahoma State University, Stillwater, Oklahoma, 145 p.

Lewan, M.D., 1987, Petrographic study of primary petroleum migration in the Woodford Shale and related rock units, in: Migration of Hydrocarbons in Sedimentary Basins, Collection 45, Doligez, B, ed., 2nd IFP Exploration Research Conference, Carcans, France, June 15-19, p.113-130.

Over, D.J., 2002, The Frasnian/Famennian boundary in central and eastern United States: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 181, p. 153-169.

Schwartzapfel, J.A. and B.K. Holdsworth, 1996, Upper Devonian and Mississippian radiolarian zonation and biostratigraphy of the Woodford, Sycamore, Caney, and Goddard formations, Oklahoma: Cushman Foundation for Foraminiferal Research #33, Dept. of Invertebrate Paleontology, Museum of Comparative Zoology (1996), Cambridge, MA, 275 p.

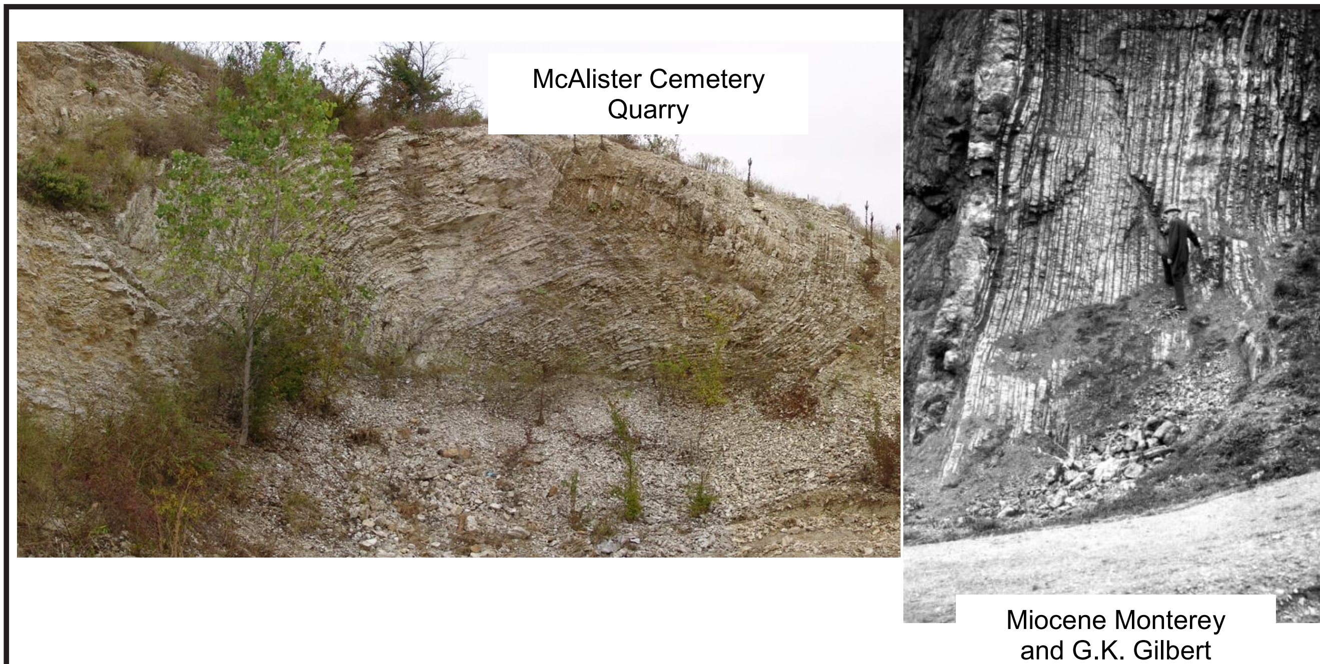

Figure 5 - Folding and faulting of shale in the Woodford exposure, McAlister Cemetery Quarry (left). The photo on the right side shows an image of G.K. Gilbert on an exposure of vertical Monterey Formation chert, California.

Figure 6 - Bitumen accumulation along a fracture network in the McAlister Cemetery Quarry, south-central Oklahoma.

Figure 7 - Alischa Krystyniak measuring the spectral gamma-ray character of the Woodford Shale at McAlister Cemetery Quarry, 2003

Figure 8 - Mike Aufill adjacent to a respectably-sized concretion at the McAlister Cemetery Quarry, 2004. The concretion is composed of calcite that, in turn, encases nodules of phosphate.