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GUIDEBOOK FOR ARBUCKLE MOUNTAIN FIELD TRIP, SOUTHERN OKLAHOMA

DURING UNITAR CONFERENCE ON DEVELOPMENT OF SHALLOW OIL AND GAS RESOURCES

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Cover

Photographs on the cover represent views at each of the four stops made during the field trip. *Upper left:* "Tombstone topography," resulting from differential erosion of resistant and nonresistant limestones at Stop 1. *Center left:* Tar sands exposed along South Woodford Anticline at Stop 2. *Lower left:* Abandoned tar-sand quarry south of Sulphur at Stop 3, showing Pennsylvanian conglomerate (top half) deposited with angular unconformity upon Ordovician tar sands (lower half of rock exposure). *Lower right:* Quarry face at Stop 4 showing gently dipping limestone layers cut by thrust fault that dips 30° from upper left part of quarry to lower right.

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GEOLOGY OF OKLAHOMA—A SUMMARY

Oklahoma is a region of complex geology where a mobile belt of Paleozoic geosynclines and uplifts on the south abuts against the margin of the North American craton to the north. The State contains many classic areas where fundamental concepts of sedimentation, stratigraphy, structural geology, historical geology, and petroleum exploration have been formulated through the years. In the southern Oklahoma mountain belts, there are exposed a great variety of igneous and sedimentary rock units seen at few other places in the Midcontinent area.

Major geologic provinces of Oklahoma (fig. 1) include (1) the cratonic and relatively stable northern shelf areas, including the Ozark Uplift; (2) the Ouachita Geosyncline (now a mountain belt) and associated Arkoma Basin in the southeast; and (3) the Southern Oklahoma Geosyncline, comprising the Anadarko, Ardmore, Marietta, and Hollis Basins as well as the Arbuckle and Wichita Mountains Uplifts. The three principal fold belts, the Ouachitas, Arbuckles, and Wichitas, all originated from a series of Pennsylvanian orogenies (about 300 million years ago) in the two Paleozoic geosynclines.

Most of the outcropping rocks in Oklahoma are of sedimentary origin, and most of these sediments are of Paleozoic age (fig. 2, map). The thickness of Paleozoic sediments ranges from 2,000 to 10,000 feet (600 to 3,000 m) in cratonic shelf areas of the north and is 30,000 to 40,000 feet (9,000 to to 12,000 m) in deep basins of the south (fig. 2, cross sections). Sedimentary rocks overlie a basement of Precambrian to Middle Cambrian igneous rocks, Precambrian metamorphic rocks, and mildly metamorphosed Precambrian sediments. Limestone and dolomite make up most of the Upper Cambrian to Lower Mississippian strata and attest the early and middle Paleozoic crustal stability in most of Oklahoma prior to the Pennsylvanian episodes of mountain building. Thick units of shale and sandstone predominate in the Upper Mississippian and Pennsylvanian sequence. Permian sediments are characterized by red shale and sandstone with interbedded gypsum and salt. Triassic, Jurassic, Cretaceous, and Tertiary deposits are mostly thin units of conglomerate, sandstone, and shale.

Oklahoma's three mountain regions have been the subject of much study. The Ouachita Mountains in the southeast make up an arcuate fold belt that consists mostly of Mississippian and Early Pennsylvanian sandstones, locally about 30,000 feet (9,000 m) thick, deposited in a geosyncline or great trough. In the destruction of the geosyncline by mountain-building forces during Pennsylvanian time, these strata were folded into broad anticlines and synclines and were thrust northward as much as 50 miles (80 km) along a series of major thrust faults. Resistant sandstone formations form long, sinuous mountain ridges that tower 1,000 to 1,500 feet (300 to 450 m) above adjacent valleys formed in easily eroded shales.

The Arbuckle Mountains in south-central Oklaho-

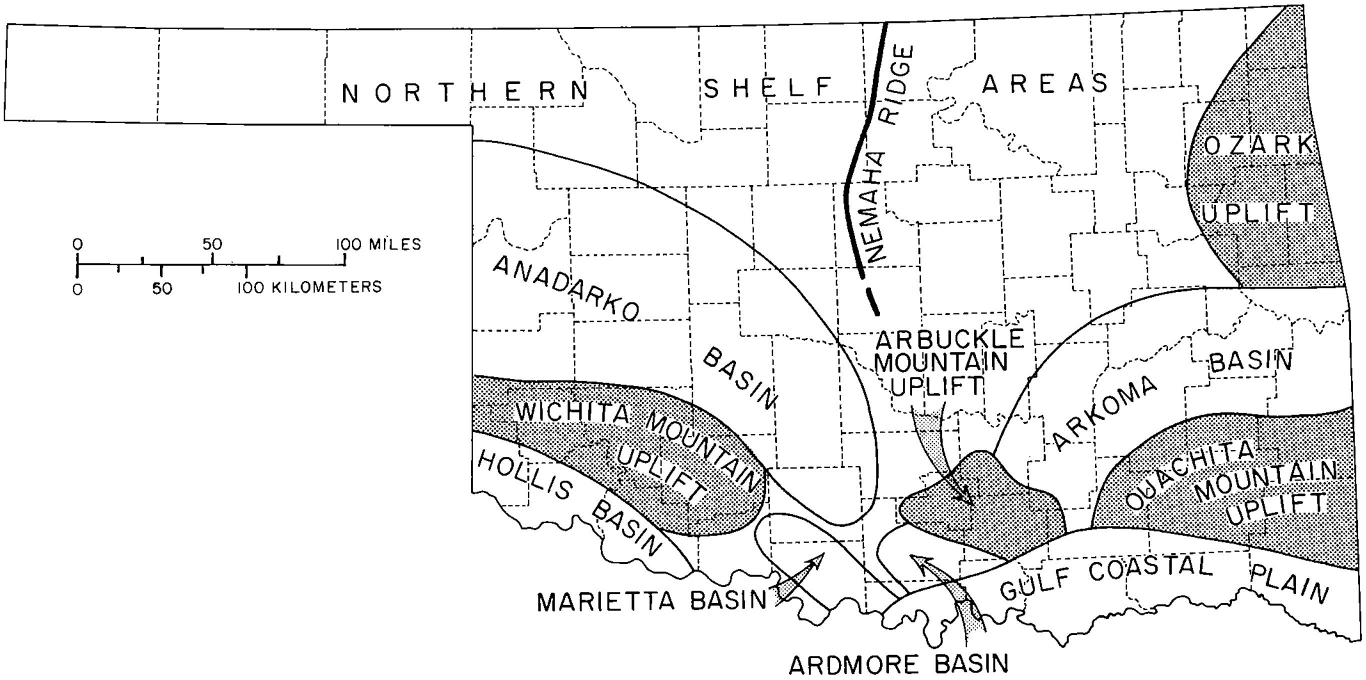

Figure 1. Major geologic provinces of Oklahoma.

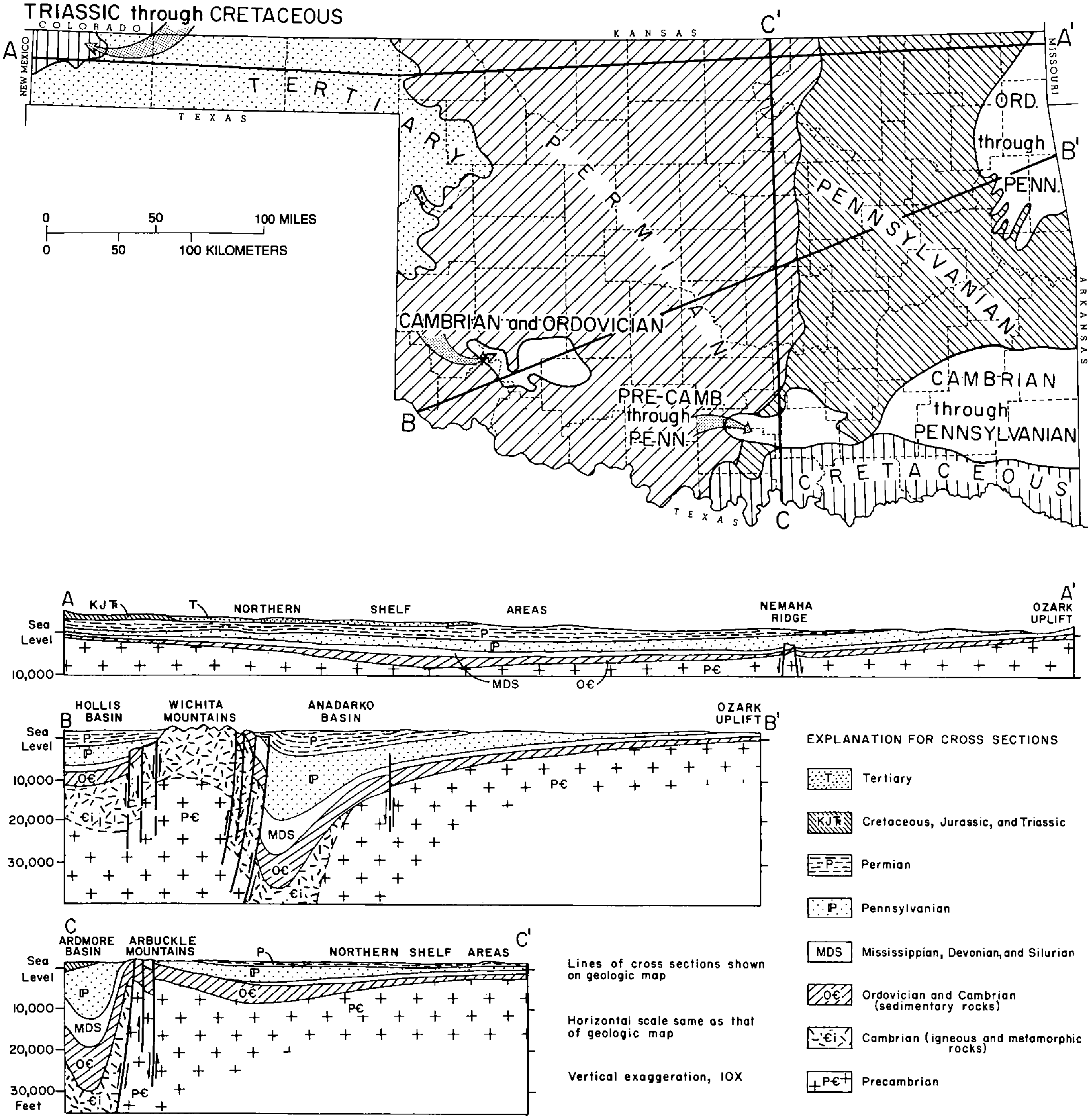

Figure 2. Generalized geologic map and cross sections of Oklahoma.

ma make up an area of low to moderate hills containing 15,000 feet (4,500 m) of folded and faulted sedimentary rocks ranging in age from Cambrian to Pennsylvanian. About 80 percent of these sedimentary rocks are limestones and dolomites, and the remainder are shales and sandstones. Rocks in this part of the Southern Oklahoma Geosyncline were thrust upward and were folded and faulted during several mountain-building episodes in the Pennsylvanian Period. The sedimentary cover was eroded from the underlying Precambrian granites and gneisses in a 150-square-mile (380-km^2) area in the southeastern part of the Arbuckle Mountains, making this the largest exposure of Precambrian rocks in the State.

In the Wichita Mountains of southwestern Oklahoma, granite, rhyolite, and gabbro are the dominant outcropping rocks. These igneous rocks are of Middle and possibly Early Cambrian age and are flanked by scattered outcrops of Cambrian and Ordovician limestones and dolomites like those of the Arbuckle Mountains. The Wichita fault blocks were thrust upward and slightly northward during several Pennsylvanian uplifts, at which time the cover of pre-Pennsylvanian sediments was eroded. The igneous rocks now form hills and mountains that rise 500 to 1,000 feet (150 to 300 m) above a surrounding plain of Permian red beds.

Outcropping Paleozoic rocks outside the mountain regions are essentially horizontal, with dips of 10 to 50 feet per mile (3 to 15 m per 1.6 km) being most common. They typically form gently rolling hills and plains, although the thick shale units form broad, flat plains and valleys. In places, resistant sandstones and limestones cap cuestas and hills 100 to 500 feet (30 to 150 m) high. Badlands, sinkholes, and caves are common in the gypsum-hill regions of western Oklahoma, and deeply dissected cavernous limestones and cherts are typical of the Ozark Uplift. Surface rocks dip to the west across northeastern and central Oklahoma and dip toward the axes of sedimentary basins in other parts of the State.

Cretaceous strata of the Gulf Coastal Plain in the southeast generally consist of loose sands, gravels, limestones, and clays that dip gently southward toward the Gulf of Mexico. The sediments are only slightly dissected by streams, and they commonly form gently rolling hills and plains.

Tertiary deposits in the west are loose sands, gravels, and clays deposited by ancient streams and rivers draining the Rocky Mountains. They now constitute a featureless flat upland surface, which is part of the High Plains.

Our knowledge of Oklahoma geology has come about largely through intensive investigations of the State's petroleum and nonpetroleum mineral resources and through the cooperative exchange of information by all agencies and companies interested in construction and earth materials. The drilling of more than 500,000 wells in search of oil and gas (a Statewide average of 7 wells per square mile!) has provided basic data in all geologic provinces. Although Oklahoma is well known as an oil state, its nonpetroleum resources (limestone, clay, coal, gypsum, salt, etc.) represent a vast mineral reserve needed for future industrial development and construction.

GENERAL GEOLOGY OF FIELD-TRIP REGION

The focal point of the field trip is the Arbuckle Mountains, but we will travel through the Central Redbed Plains on the way to the Arbuckles, and also will make one stop in the Ardmore Basin south of the mountains (fig. 3). The trip traverses nearly the same path shown on the south half of cross section *C- C'* (fig. 2), commencing on the Permian "redbeds" and thence to the Arbuckle Mountains and the Ardmore Basin. The three regions are described separately in the order in which they will be traversed.

Central Redbed Plains

The Central Redbed Plains consist of red Permian shales and sandstones that form gently rolling hills and broad, flat plains. Outcropping strata dip gently westward 10 to 50 feet per mile (3 to 15 m per 1.6 km) toward the Anadarko Basin (see midpoint of cross section *B- B'*, fig. 2) and are exposed in long, parallel north-south belts with east-facing escarpments capped by the more resistant sandstones.

Our drive to the Arbuckles is roughly parallel to the strike of these beds, and thus only 500 to 1,000 feet (150 to 300 m) of Early Permian rocks in the Wellington Formation, Garber Sandstone, and Hennessey Shale (ascending order) will be traversed during our 60-mile (96-km) trip across the red beds. Both the Wellington and Hennessey Formations are chiefly red-brown shale, although they contain several red-brown and brown sandstone beds 5 to 30 feet (1.5 to 9 m) thick. The Garber Sandstone is mainly red-brown sandstone with some interbedded red-brown shale.

Early Permian sediments of the Central Redbed Plains were derived from eastern Oklahoma, which at that time was above sea level. These sediments were interbedded alluvial, deltaic, and shallow-marine deposits laid down near the shore of the large inland sea that covered western Oklahoma and extended northward from west Texas to Nebraska and the Dakotas. The red color so common in these rocks results from a stain of red iron oxides (chiefly hematite) that coats the sand and clay particles making up the rocks.

Arbuckle Mountains

The following description of the geology and significance of the Arbuckle Mountains is slightly modified from Oklahoma Geological Survey Guidebook 17, *Regional Geology of the Arbuckle Mountains, Oklahoma,* by William E. Ham, published in 1969.

The geological province known as the Arbuckle Mountains consists of a huge inlier of folded and faulted Paleozoic and Precambrian rocks. It is covered on the east, north, and west by gently westward-dipping Pennsylvanian and Permian strata and on the south by gently southward-dipping Cretaceous sediments of the Gulf Coastal Plain (fig. 4).

This inlier is a roughly triangular area of nearly

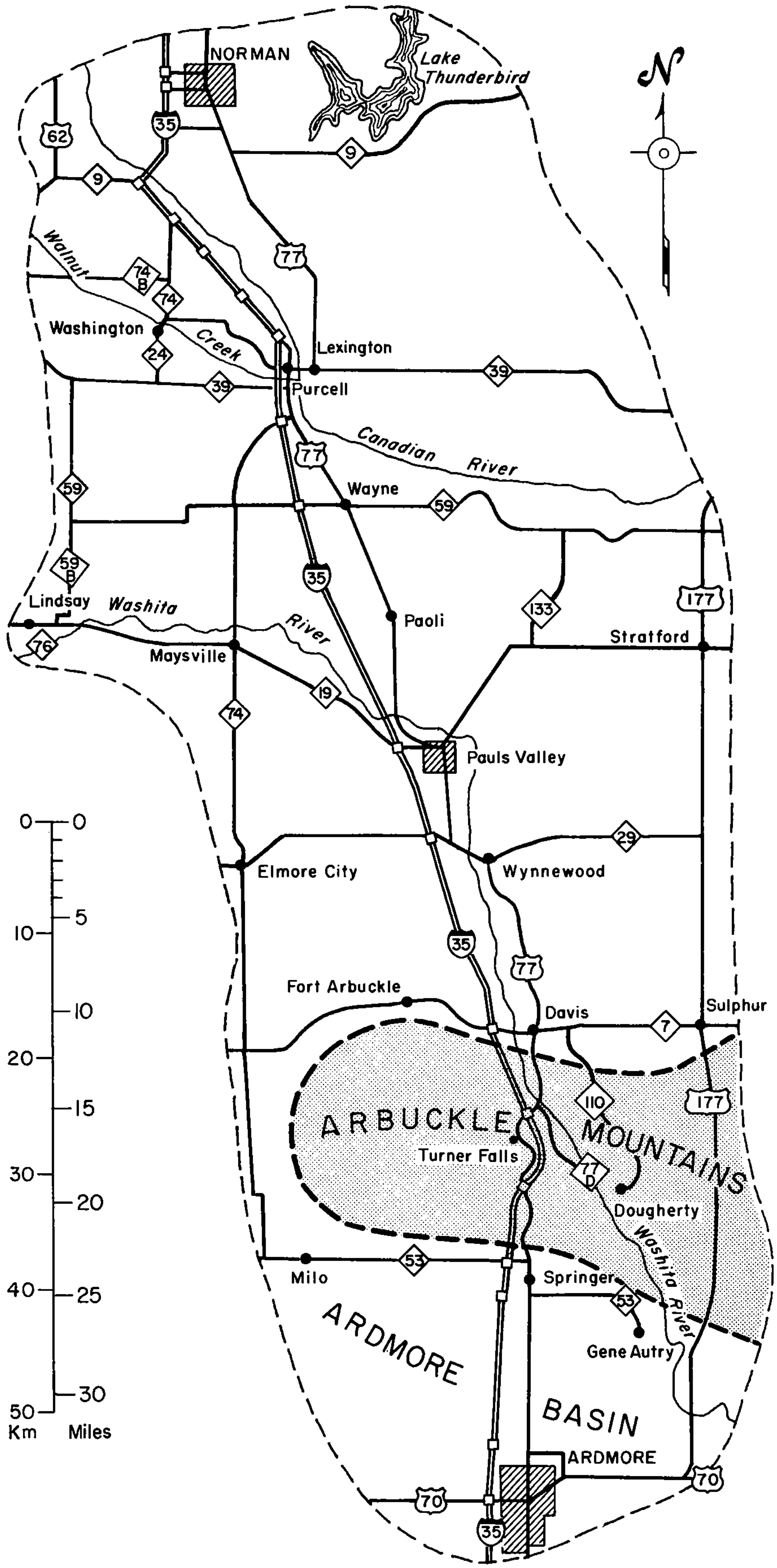

Figure 3. Road map along field-trip route.

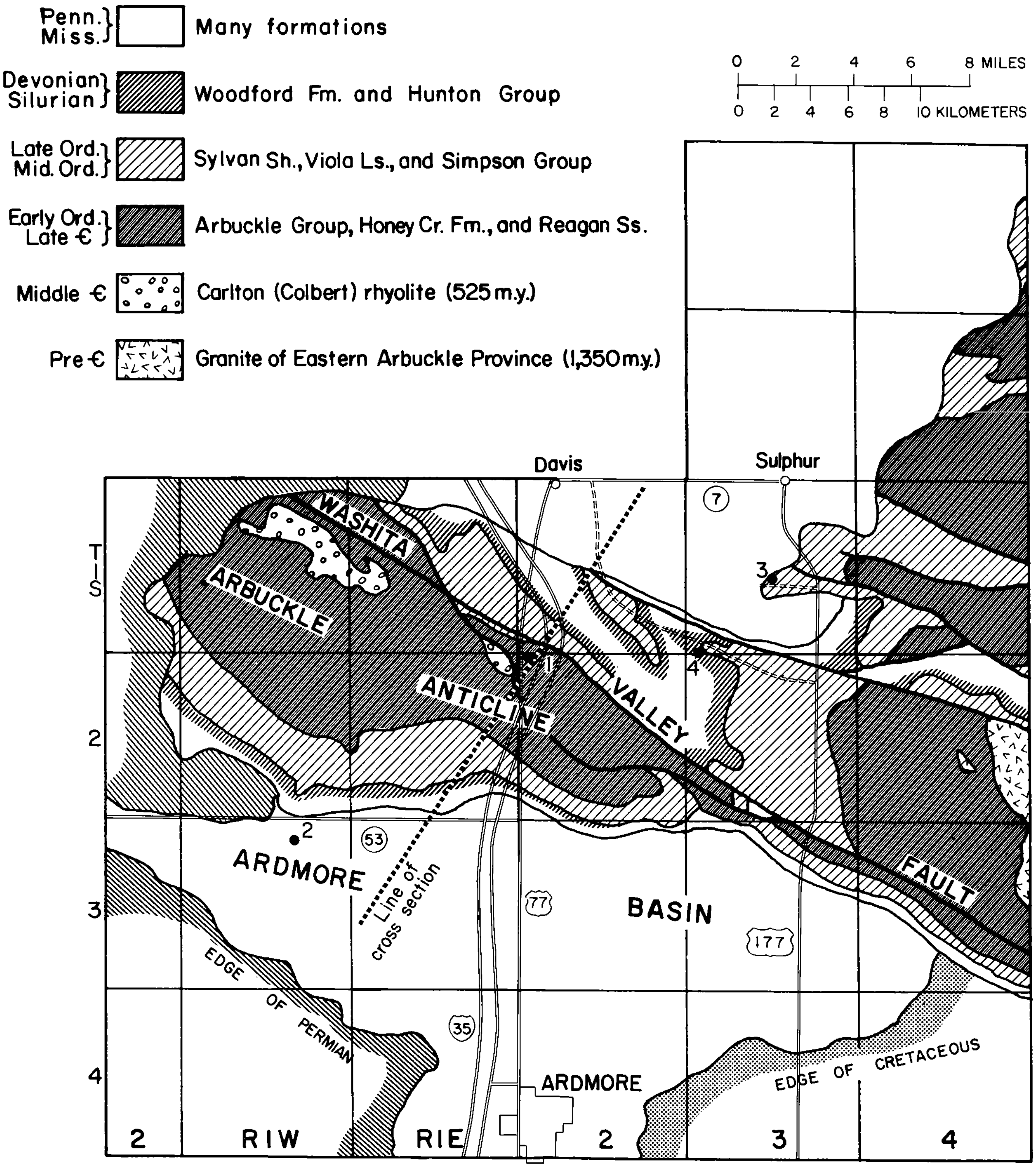

Figure 4. Generalized geologic map of Arbuckle Mountains (modified from Ham, 1969), showing location of four field-trip stops. Cross section is shown in figure 5.

1,000 square miles (2,500 km²), almost in the center of the southern third of Oklahoma. The geology is characterized mostly by outcrops of carbonate rocks (limestone and dolomite). Immediately to the east begins the 200-mile-long (320-km-long) exposure of the Ouachita Mountains, principally a sandstone-shale sequence that is quite unlike the Arbuckles in stratigraphic and structural development; and 100 miles (160 km) to the west are the Wichita Mountains, unlike either the Arbuckles or Ouachitas and characterized chiefly by extensive outcrops of Cambrian igneous rocks. Thus the three uplifted segments of southern Oklahoma actually share little in common, despite their similar age and geographic proximity, and each has a profoundly different geologic emphasis.

The primary emphasis of Arbuckle Mountains geology lies in its early Paleozoic carbonates and late Paleozoic clastics (sandstones and shales), deposited partly upon a craton of Precambrian igneous rocks and partly in a geosyncline in which the basement rocks are Cambrian rhyolites. The stable craton extends from the eastern Arbuckle Mountains granite outcrops northward through central Oklahoma into Kansas and beyond. At a fault contact these rocks are separated from the southwestern segment of the Arbuckle Mountains, known as the Arbuckle Anticline, where the depositional history is that of the geosyncline (fig. 5). The geosyncline includes the Arbuckle Anticline and extends southward for about 50 miles (80 km), across the Ardmore Basin and Marietta Basin, and terminates in the subsurface of north Texas against the Precambrian cratonic rocks of that state. Westward, the geosyncline includes the Anadarko Basin.

Reference to the Arbuckle outcrops as the Arbuckle "Mountains" is somewhat misleading, because about 80 percent of the area consists of gently rolling plains. Only in the western area—that of the Arbuckle Anticline—is the topographic relief sufficient to evoke comment from the newcomer. The greatest relief is along U.S. 77 and I-35. In this area, the Washita River flows at an elevation of 770 feet (230 m). Three miles (5 km) away is the top of the East Timbered Hills—the crest of the Arbuckle Anticline—at an altitude of 1,377 feet (420 m), nearly the highest point in the Arbuckle Mountains. This total relief of 607 feet (185 m) is impressive only because it is some 6 times greater than that of any other topographic feature between Oklahoma City and Dallas.

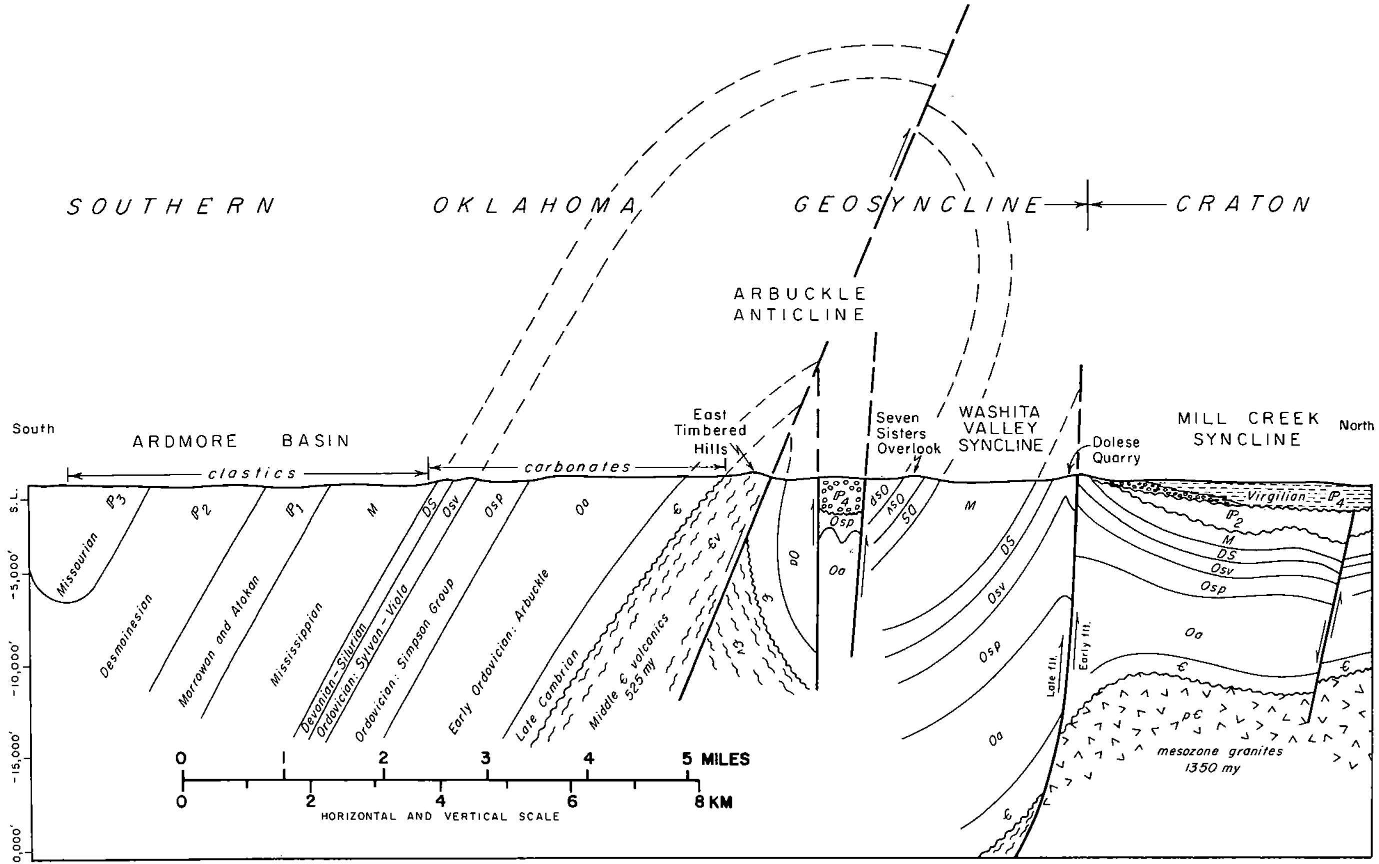

Figure 5. Structural cross section of Arbuckle Mountains in vicinity of Interstate 35 (modified from Ham, 1969). Location of cross section shown in figure 4.

Figure 6. Mosaic of aerial photographs showing routes of U.S. 77 and Interstate 35 across the northwest-trending Arbuckle anticline.

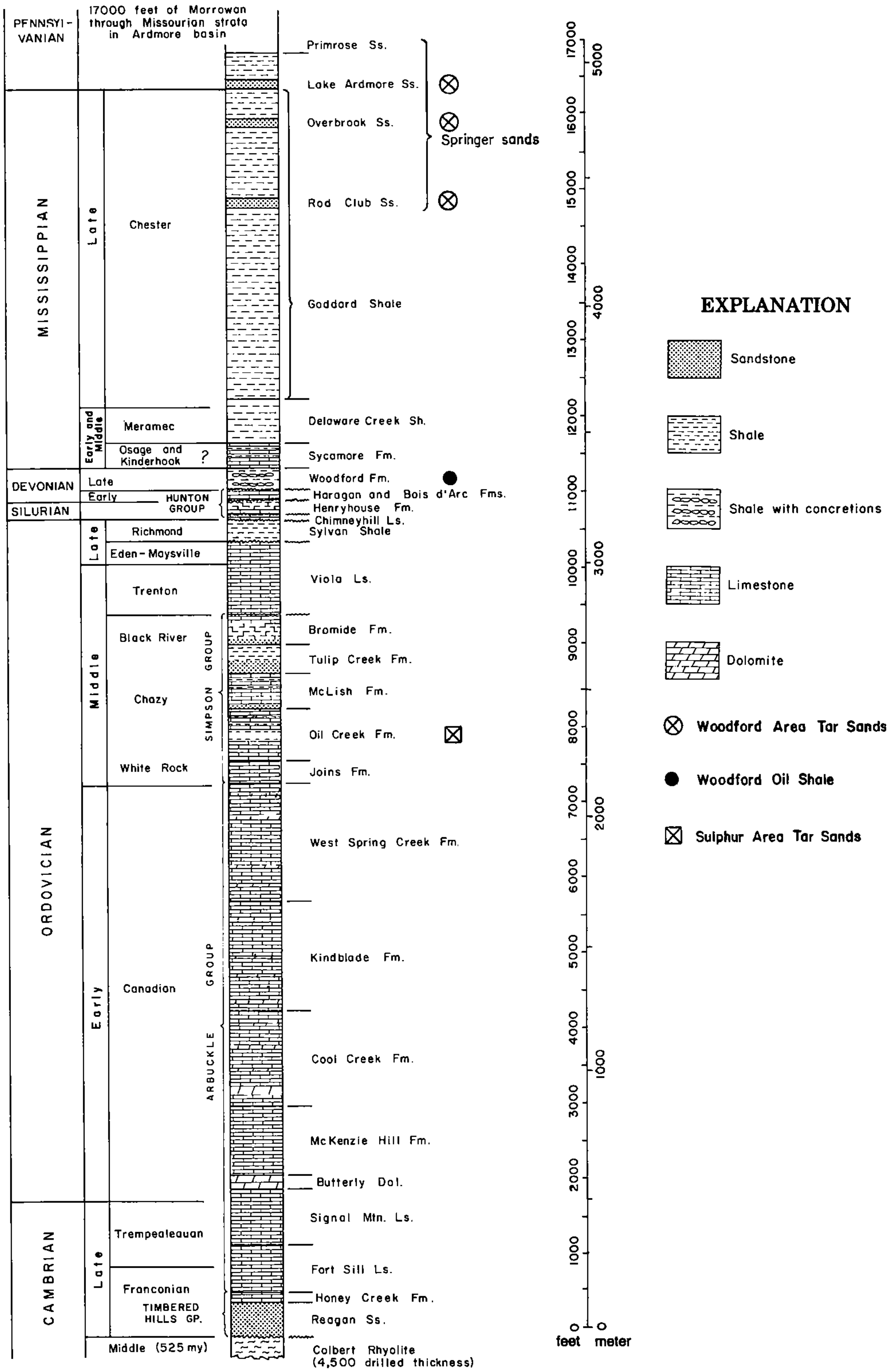

Figure 7. Stratigraphic section of rocks exposed along Interstate 35 (modified from Ham, 1969).

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 (fig. 6). Structurally it is a faulted anticline, overturned to the north (fig. 5). Within the faulted area is a graben containing remnants of the Pennsylvanian-aged Collings Ranch Conglomerate. The conglomerate is faulted and warped into a synclinal fold, indicating that deformation continued during and after deposition of the Collings Ranch Conglomerate. The cross section (fig. 5) shows the general thicknesses of geologic units and the attitudes of strata along the field-trip route.

Whether plains or hill country, the Arbuckle Mountains region is of irresistible interest to geologists, and particularly to petroleum geologists. The 11,000 feet (3,300 m) of fossiliferous Late Cambrian through Devonian strata (fig. 7) constitute the best outcrops and greatest area of exposure of this sequence in all the Midcontinent region. Stratigraphic names taken from the Arbuckles, such as Arbuckle, Simpson, Viola, Sylvan, Hunton, and Woodford, have been widely applied in the subsurface as far away as west Texas, Illinois, and Nebraska. And these widespread rock units are among the most prolific oil- and gas-producing formations throughout the Midcontinent. Therefore, petroleum geologists have conducted extensive field investigations of the excellent exposures here in the Arbuckle Mountains. The 150-square-mile (380-km^2) exposure of Precambrian granites and gneisses in the eastern Arbuckle Mountains is the largest and best outcrop of such rocks in the central United States between the Llano area of Texas and the Black Hills of South Dakota. Finally, as much as 20,000 feet (6,000 m) of Mississippian and Pennsylvanian clastics are present in the region, partly in synclinal grabens of the Arbuckle Mountains and to a much greater extent in the adjoining Ardmore Basin. Fusulinids from thin Pennsylvanian limestones in this sequence are widely used as standards of reference for dating the age of these rocks.

The processes of strong uplift and deep erosion that have produced the Arbuckle Mountains of today have also resulted in the surface exposure of rocks that normally are deeply buried. Among the rocks are many that are commercially valuable, such as (1) limestones from thick and widely distributed outcrops of the Arbuckle and Viola Formations that are extensively quarried as a source of crushed stone, (2) high-purity silica sand from the Simpson Group for glass making and other industrial use, (3) cement-making raw materials from the Viola Limestone and Sylvan Shale, (4) high-purity dolomite from the Arbuckle Group, and (5) building and monumental stone from Precambrian granite.

Ardmore Basin

The Ardmore Basin, located just south of the Arbuckle Mountains, is a downwarped remnant of the Southern Oklahoma Geosyncline containing about 35,000 feet (10,700 m) of Late Cambrian through Late Pennsylvanian (Missourian) sedimentary rocks. It has a northwest trend with an average width of 15 miles (24 km) and a length of about 50 miles (80 km). The general structure is synclinal, but a number of large anticlines are present within the basin. Dips of outcropping strata are steep, particularly along the margins of the basin, with angles of 45° to 90° being common.

Pre-Mississippian strata, present only in subsurface, are similar to those of the Arbuckle region. The Ardmore Basin continued to subside during the Mississippian and Pennsylvanian Periods, receiving some 20,000 feet (6,000 m) of thick shales interbedded with thin sandstones, limestones, and conglomerates. The basin then was tightly folded in the Pennsylvanian orogenies that culminated in uplift of the Arbuckle Mountains.

Outcropping shales in the Ardmore Basin are typically dark gray, gray, and brown and range in thickness from 100 feet (30 m) to several thousand feet. The interbedded sandstones, limestones, and conglomerates are typically 10 to 50 feet (3 to 15 m) thick, and being more resistant than shales they form conspicuous subparallel ridges standing as high as 100 feet (30 m) above adjacent lowlands. Some of the sandstones and conglomerates have been impregnated with oil generated from the interbedded shales, and these sandstones and conglomerates are potential targets for shallow or deep drilling in the Ardmore Basin.

TAR-SAND DEPOSITS IN FIELD-TRIP REGION

Tar sands and heavy-oil deposits have been known in Oklahoma since the late 1800's, and these deposits, or certain aspects of particular deposits, have been described in a number of early publications (Eldridge, 1901; Taff, 1904; Hutchison, 1911; Snider, 1913, 1914; Tomlinson, 1928; Shelley, 1929; Wolfard, 1929; Woodruff, 1934). Jordan (1964) used the H. P. Goodrich File (unpublished) to compile data on 298 occurrences of petroleum-impregnated outcrops and asphaltite deposits as well as several shallow (less than 500 feet or 150 m) oil fields. The Goodrich data are on file at the Oklahoma Geological Survey and constitute a fairly comprehensive summary of surface and shallow occurrences of petroleum and petroleum-related material in the State.

Most of the reported tar-sand occurrences are in the Wichita Mountain, Ardmore–Marietta Basin, and Arbuckle Mountain areas of Oklahoma. Solid bitumens (material soluble in organic solvents) such as grahamite and asphaltite are known only from the Ouachita Mountain region. The bitumen-bearing rocks in Oklahoma are mainly sandstones, although one of the major deposits, at Dougherty, occurs in Ordovician limestone. The geologic age of the deposits in southern Oklahoma varies from Middle Ordovician to Early Cretaceous.

The Arbuckle Mountain region contains a total of 45 tar-sand deposits, which vary from small outcrops and prospect pits to the large quarries that were actively worked until 1960. The following production data (table 1) for the Sulphur and Dougherty quarries (the two largest quarries in the region) are on file at the Oklahoma Department of Mines.

The Arbuckle Mountain region also has both shallow heavy-oil (less than 25° API) and conventional crude-oil production. In 1982, the crude-oil production for Carter and Murray Counties amounted to 17.2 million barrels, and the cumulative production for those two counties is approximately 750 million barrels. Oil seeps and bitumen-impregnated outcrops contributed to the discovery of some of the major fields in the area.

The Oklahoma Geological Survey has, for the last few years, conducted studies to evaluate the heavy-oil and tar-sand potential of the State (Harrison and Roberts, 1979; Harrison and others, 1979; Harrison, 1980; Harrison and others, 1981). The major objectives of this program are to provide information on heavy-oil and tar-sand deposits upon which more detailed exploration and development efforts might be based. The present and projected energy situation in the United States is heavily oriented toward fossil fuels, and it is obvious that extraction technology directed toward enhanced oil recovery, oil shales, and tar sands will become increasingly important. If resource-appraisal studies are maintained at reasonable levels, then perhaps such technology can be implemented as it is developed, and significant delays in producing these "unconventional" resources can be avoided.

FIELD-TRIP STOPS

Stop 1: General Description of Arbuckle Mountains Geology

Limestone beds of the Kindblade and West Spring Creek Formations in the Arbuckle Group are well exposed in road cuts adjacent to the scenic turnout along Interstate 35. These rock units are mainly gray and tan limestones that are fine to medium grained; locally they are oolitic, pelletal, and algal. The limestones typically are thin to thick bedded, and locally they are interbedded with sandstone and highly shaly limestone beds that are 1 to 3 feet (0.3 to 1 m) thick.

Although the limestones were deposited horizontally in a shallow sea that had covered almost all of the Midcontinent region during Arbuckle time (some 500 million years ago), these rocks were later folded and faulted, and they now dip steeply to the north (fig. 8) on the north flank of the major Arbuckle Anticline (Ham, 1969). The major episodes of uplift, folding, and faulting occurred in Late Pennsylvanian time (about 300 million years ago). As the Arbuckle Mountains were being uplifted, thick deposits of conglomerate were laid down within and around the mountain system. Some of the conglomerate layers were faulted down and preserved in grabens at several places within the Arbuckle Mountain area, with one of the best examples being exposed in the road cuts at Stop 1 (figs. 8, 9). At this site the Collings Ranch Conglomerate consists mainly of pebbles and cobbles of limestone eroded from nearby hills and mountains that were exposed in Late Pennsylvanian time. It is possible that the graben formed just before or during deposition of the conglomerate, or that it formed at a later time while a thick sheet of conglomerate mantled the area: regardless of the precise time of graben development, the conglomerate is now preserved only within the down-dropped fault block,

Table 1.—Latest available production data for Sulphur and Dougherty asphalt quarries

Operator	Quarry	Year	Production (short tons)
Southern Rock Asphalt	Sulphur	1954	38,743
U.S. Asphalt	Sulphur	1955	21,502
		1956	77,315
		1957	44,438
		1958	60,026
		1959	no record
U.S. Asphalt	Dougherty	1960	9,275

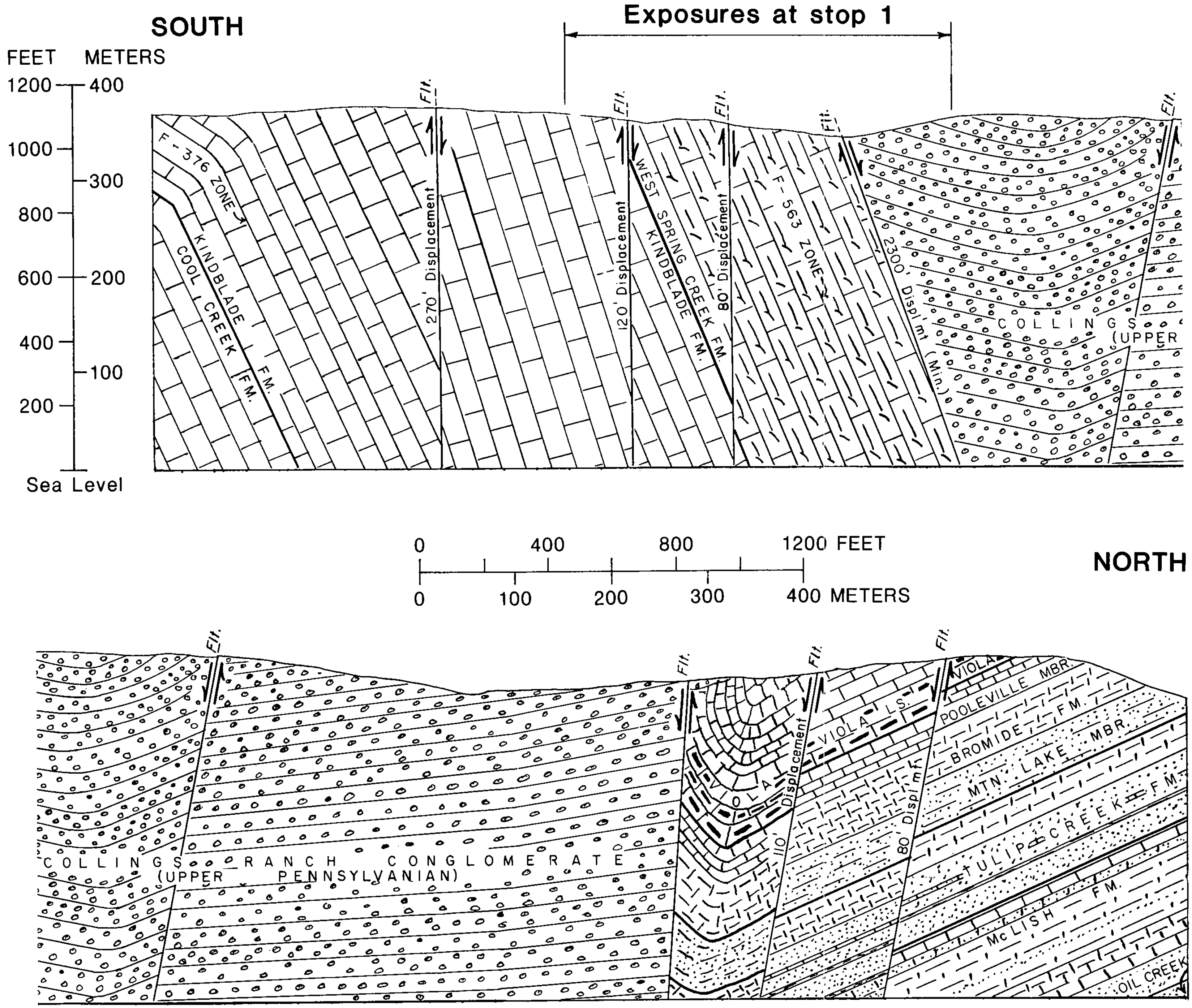

Figure 8. Schematic north-south cross section along part of Interstate 35, showing outcropping rock units and structural geology at Stop 1 (modified from Fay, 1969).

Figure 9. Collings Ranch Conglomerate preserved in graben at Stop 1.

whereas it has been eroded from adjacent areas where it was at a higher elevation.

Another noteworthy feature at Stop 1 is the exposure of a thick zone of randomly oriented boulders or blocks of rock (a "megabreccia") within an otherwise uniformly dipping sequence of upper Kindblade limestones (fig. 10). It had been assumed earlier that this megabreccia was totally a result of faulting during Pennsylvanian uplift of the region, but recent work by Tapp (1978) indicates that the brecciation results mainly from partial dissolution of limestone or other soluble rocks along joints and fractures during Pennsylvanian time, and that the large blocks of rock fell into the cavern system that was created. As dissolution took place, insoluble clays were deposited around the collapsed blocks. Layering in these clays is nearly 90° to layering in the adjacent Kindblade Formation, and as the clay layers themselves are folded it indicates that the clays were deposited during folding of the Kindblade Formation (Tapp, 1978). It is also likely that some further disorientation of the blocks took place as a result of Late Pennsylvanian fault movements.

From this point southward through the mountains, virtually all rock exposed is limestone or dolomite. Differential weathering and erosion of alternating hard and soft limestone layers have produced a unique "tombstone topography" in parts of the mountains (fig. 11). The resistance of some massive limestone units and the steep natural slope of these limestone ridges required cutting of Oklahoma's deepest road cuts in building I-35 through the Arbuckles.

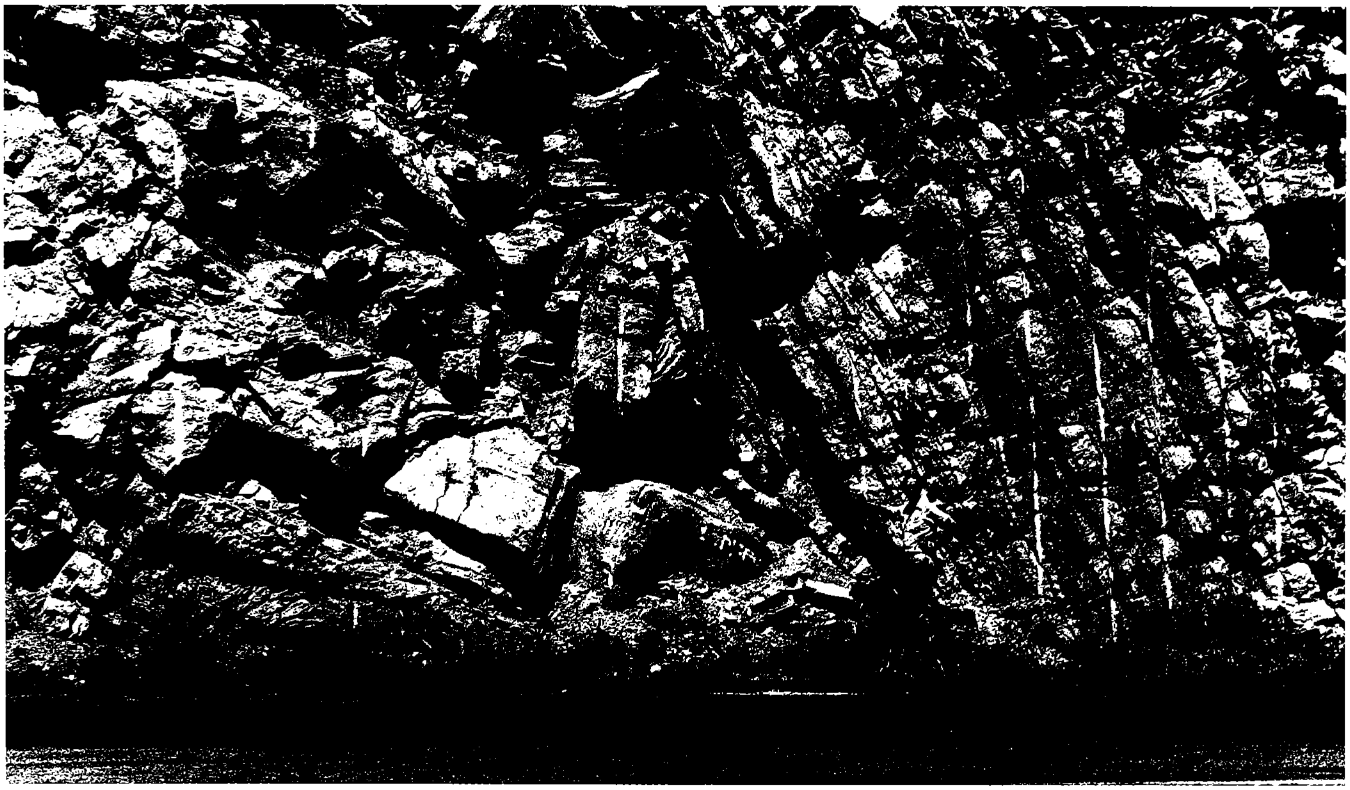

Figure 10. Megabreccia consisting of randomly oriented boulders or blocks of Kindblade limestone at Stop 1.

Figure 11. "Tombstone topography" of Arbuckle Group limestones as seen on south flank of Arbuckle anticline.

Stop 2: Tar Sands of South Woodford Area

The tar-sand area in the northeast part of T. 3 S., R. 1 W., and east-central part of T. 3 S., R. 1 E., has been mined, to a limited extent, and is somewhat unusual in that the deposit exists in vertical strata. Photographs (Hutchison, 1911; Snider, 1913) of the Woodford Asphalt Pit (when it was being actively worked) show the quarry being developed essentially down bedding planes and permit an estimate of the depth to which the deposit was worked (76 feet or 23 m) at that time. Other specific sites were not exploited as fully as was the Woodford pit, and the potential of this general area was relatively unknown prior to this study.

Geology and Tar-Sand Occurrences—Figure 12 is a geologic map of the South Woodford deposit and shows the locations of quarry sites and tar-sand outcrops. The tar-sand deposits are controlled by the geologic feature known locally as the South Woodford Anticline. The stratigraphic positions of the formations that crop out in this area are shown in figure 7. Fay (unpublished), in his recent compilation for the COSUNA (Correlation of Stratigraphic Units of North America) project, developed cooperatively by the U.S. Geological Survey and the American Association of Petroleum Geologists, has placed the Otterville, Primrose, and Lake Ardmore Formations in the Morrowan (Lower Pennsylvanian) and considers the Overbrook and Rod Club sandstones as members of the Goddard Formation, the latter being of Chesterian (Late Mississippian) age.

Site 1 in figure 12 shows the location of several shallow (165 to 480 feet or 50 to 145 m deep) wells that produce heavy oil from vertical Pennsylvanian (probably Otterville) sandstone. The bitumen-impregnated outcrop in this area most likely resulted from surface degradation of heavy oil that migrated from relatively shallow depths. Sites 2 through 7 are either quarries or prospect pits that vary in size from about 100 square feet (9 m^2) to the Woodford Asphalt Pit (site 4 in fig. 12), which is presently about 2,500 square feet (225 m^2; fig. 13). Except for the Woodford pit, the maximum depth to which the quarries were worked cannot be determined inasmuch as they have collapsed and, for the most part, have been partially back-filled. The average bitumen content for these quarries is about 11 percent (wt.). Site 8 is an outcrop of Primrose sandstone, which contains 6.5 to 8.5 percent bitumen.

Several active oil seeps exist along the axis of the South Woodford Anticline in the Rod Club sandstone. The tar-like material which is ascending along bedding planes builds up layers several inches thick and affects areas up to several hundred square feet in size.

Lithologically, the sandstones that crop out in this area are similar and usually consist of brown to tan, fine to very fine sand with abundant clay laminations and stringers (fig. 14).

Table 2.—Reservoir characteristics of selected sandstone cores from South Woodford deposit (see fig. 12 for locations)

Core	Depth (feet)	Porosity (%)	Permeability (md)	Saturation (%) Oil	Water
OGS Fitzgerald 1	14.8	27.5	—	90	1
	66.3	27.6	—	91	1
	148.2	26.6	—	77	1
OGS Fitzgerald 3	7.7	30.9	—	82	1
	51.8	28.8	—	81	1
	106.2	23.9	—	73	1
OGS Fitzgerald 4	9.3	26.7	—	67	1
	77.4	27.9	—	90	1
	168.3	27.5	—	89	1

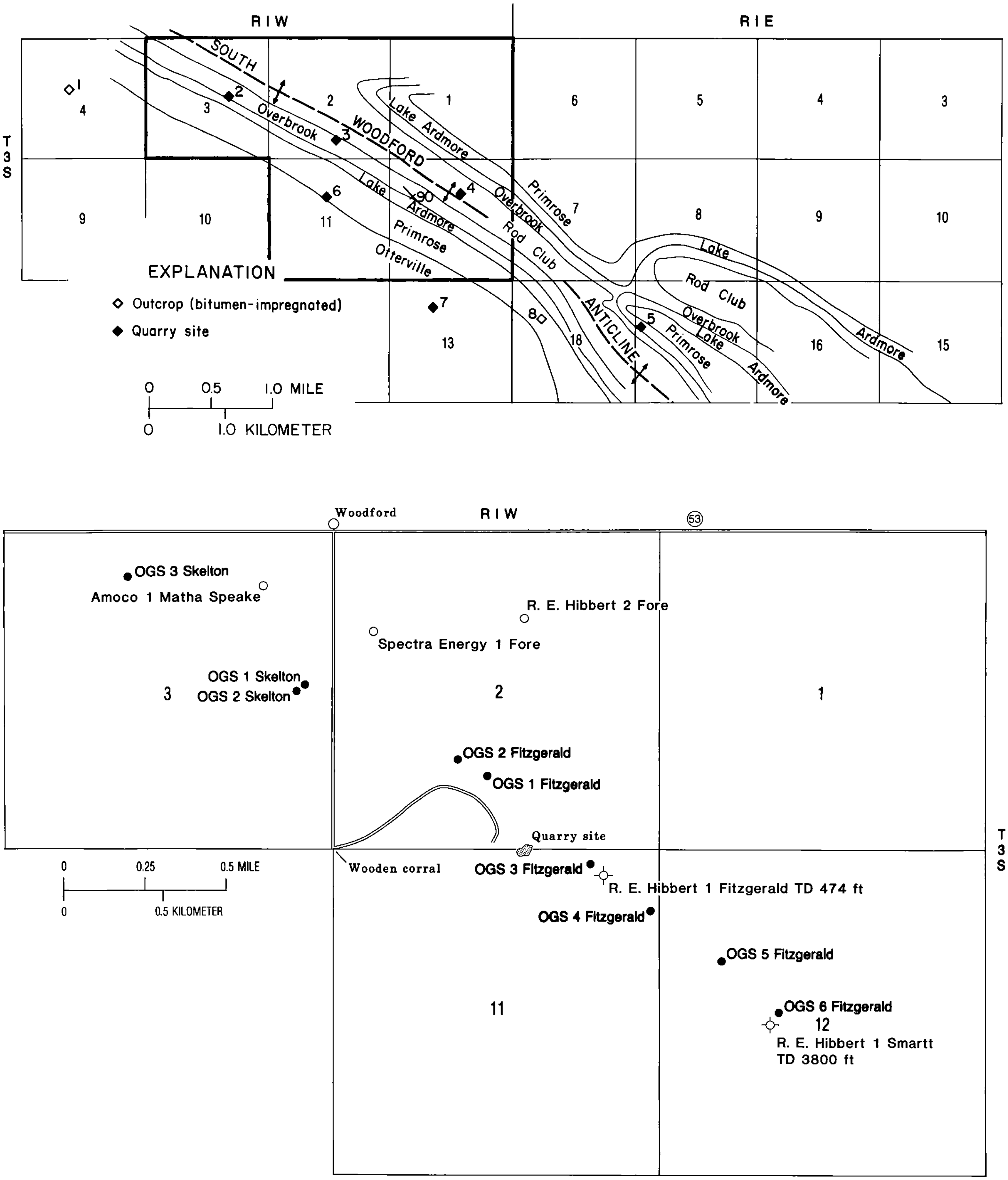

Figure 12. Upper map shows geology of South Woodford area in Carter County, along with sites of shallow wells producing heavy oil, and of quarries or prospect pits in tar sands. Lower map is enlarged to show location of Stop 2, together with various boreholes drilled to evaluate tar sands and petroleum potential.

Figure 13. Two photographs of Woodford Asphalt Pit. At left is view of pit while it was being mined to a depth of about 76 feet (23 m) in the early 1900's (Snider, 1913). At right is a modern view of pit filled with water.

Figure 14. View of outcropping tar sands at Stop 2. Rock layers are vertical in this outcrop and extend 500 feet (150 m) southeast to Woodford Asphalt Pit (see fig. 13).

In-Place Bitumen—The total amount of bitumen at South Woodford is estimated to be 8.0 million barrels. Several factors are favorable for some type of development program at this site. The overburden is thin, the bitumen-bearing sequence is relatively well confined, and the bitumen yields are among the highest encountered in the present study. Because the bitumen yields at the terminal wells in the transect are quite good, it is reasonable to expect bitumen-bearing strata to continue for some distance beyond the area evaluated in this study.

Stop 3: Tar Sands of Sulphur Area

The bitumen-impregnated sandstones and limestones which exist in much of T. 1 S., R. 3 E., have been known for many years. The two major quarry areas, Sulphur and Dougherty, were exploited as sources of road-paving material until 1958 and 1960 respectively. The Sulphur area, in sections 15, 21, and 22, T. 1 S., R. 3 E., contains 10 major quarries and several smaller ones (fig. 15). Most of the bitumen occurs in the sandstone member of the Oil Creek

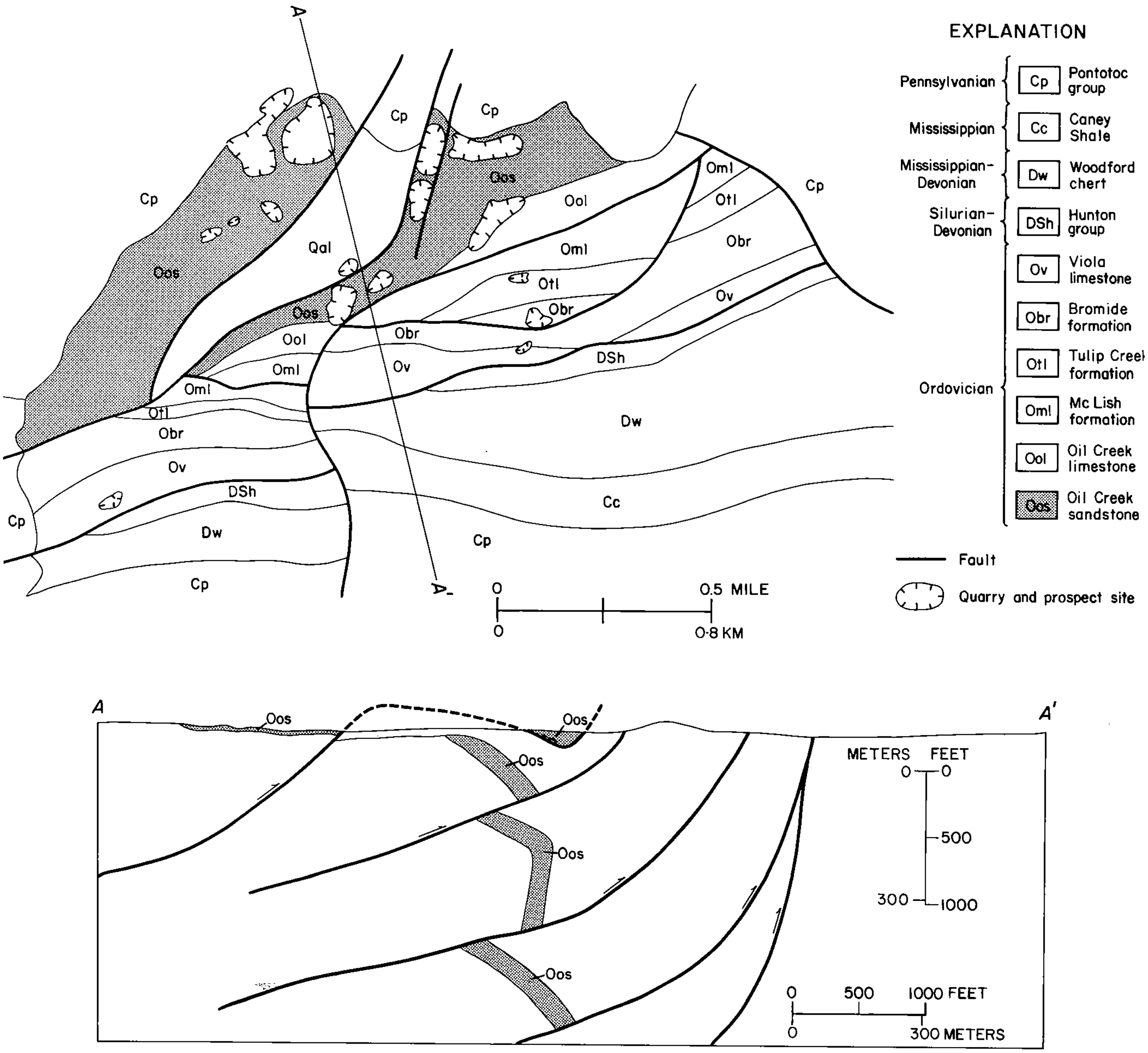

Figure 15. Geologic map (above) and interpretive cross section (below) of Sulphur asphalt area (Stop 3). Modified from Gorman and others (1944) and Williams (1983).

Figure 16. Two photographs of tar-sands quarry south of Sulphur. Above is view of open-pit mine that reached a depth of about 90 feet (27 m) before being abandoned in the 1950's. Below is a modern view of abandoned tar-sand quarry.

Formation of Ordovician age. The Dougherty area is located in sec. 25, T. 1 S., R. 2 E., and in sec. 30, T. 1 S., R. 3 E., and consists of two major quarries and a number of smaller quarries and prospect pits. At this location, the bitumen occurs in the Ordovician Viola Limestone. These deposits are well known from the literature (Grandone and others, 1955; Ball and Associates, 1965) as well as from more detailed studies (Gorman and Flint, 1944; Gorman and others, 1944; Williams, 1983). The Sulphur deposit has been of sporadic interest to industry and has been evaluated by at least two major companies. The results of these coring programs have not been generally available to the public, however.

The studies by Gorman and Flint (1944) and Gorman and others (1944) include brief historical summaries of production from each of the areas. The Dougherty area was being actively worked as early as 1890 and was operated more or less continuously until 1960. The bitumen content of the Viola Limestone at this locality is fairly consistent and varies between 3.0 and 3.5 weight percent. Approximately 800,000 short tons of bitumen-impregnated limestone was removed from the Dougherty area as of 1943 (Gorman and Flint, 1944), and it is reasonable to assume total production in excess of a million short tons.

The Sulphur area also has been worked since about 1890 and has yielded at least 1.5 million short tons of bitumen-bearing sandstone (fig. 16). Most of the bitumen occurs in the Oil Creek sandstone and varies between 0.4 and 13.0 weight percent.

The material from the Sulphur deposit was mixed with that obtained from Dougherty, and the resulting material, when used for paving purposes, apparently possessed superior qualities (Snider, 1913, 1914).

Figure 15 shows the geology of the Sulphur tar-sand area. Rock units that crop out in the Sulphur area include all formations of the Simpson Group, Viola Formation, Hunton Group, Woodford Formation, and Caney Formation (Williams, 1983). Bitumen stains are found in most of the rock units in the Sulphur area, with the most significant accumulation being in the Ordovician Oil Creek Formation of the Simpson Group. The Oil Creek is composed of two members: the upper Oil Creek limestone unit, a sequence of thinly interbedded limestones and shales, has a maximum thickness of 350 feet (105 m); the underlying Oil Creek sandstone member is a thick, massive, fine-grained sandstone. It is extremely well sorted and poorly cemented, which makes it an excellent reservoir rock. Layers of fine-grained dolomite or sandy dolomite are found within the unit, as well as locally hardened seams in which silica has been precipitated around the sand grains. The thickness of the Oil Creek sandstone ranges from 130 to 400 feet, or 39 to 122 m (Ham, 1945).

The structure of the Sulphur area is characterized by a northeast–southwest trending anticline cut by numerous faults. Gorman and others (1944) interpreted the faulting in the area as horst and graben-type block faulting. Williams (1983) reinterpreted the structure of the Sulphur area as being characterized by numerous thrust faults with associated high-angle reverse faulting. Figure 15 illustrates the structure of the Sulphur area in cross section. Williams' conclusions on the origin of faulting in the Sulphur area fit a model for right-handed wrench faulting preceded by left-handed wrenching. This corresponds with the currently popular theory of wrench tectonics as a mechanism for explaining structural features in southern Oklahoma.

According to Williams, it appears that hydrocarbons were first emplaced into the anticlinal structure. Subsequent faulting brought the hydrocarbon-saturated rocks into a position that left them susceptible to degradation of the hydrocarbons by processes of bacterial action, water washing, and inorganic oxidation. A second sequence of migration along faults and fractures may explain bitumen occurrences in overlying units such as the Vanoss conglomerate and the Viola limestone. In fact, pebbles of bitumen-saturated Oil Creek sandstone are found in the Vanoss conglomerate along with bitumen saturation in the sandy matrix of the conglomerate. This clearly suggests two periods of migration.

Bitumen saturation in the Oil Creek sandstone averages about 8 percent by weight. API gravity of the bitumen has an average value of 4.22°. Based on current data, it is estimated that the Sulphur deposit contains about 33.8 million barrels of in-place heavy oil, with an additional 12.6 million barrels considered as probable reserves (Harrison and Burchfield, 1983).

Stop 4: Hunton Limestone Quarry and Woodford Oil-Shale Pit

At this stop is an excellent exposure of a plunging anticline formed in the Hunton Group limestones of Silurian and Devonian age (fig. 17). In particular, the stone quarried is at the top of the Hunton (fig. 18) and includes the Haragan–Bois d'Arc Formations of Early Devonian age (about 400 million years ago). Strata dip about 20° on both flanks of the anticline, and the axis of the anticline plunges toward the west-northwest at an angle of about 15° to 20°

– A single fault (a thrust fault) cuts diagonally across the south limb of the anticline. The thrust dips about 30° toward the south, has a throw of about 30 feet (10 m), and passes through the axis of the fold at the top of the quarry face (fig. 19). Compressive forces

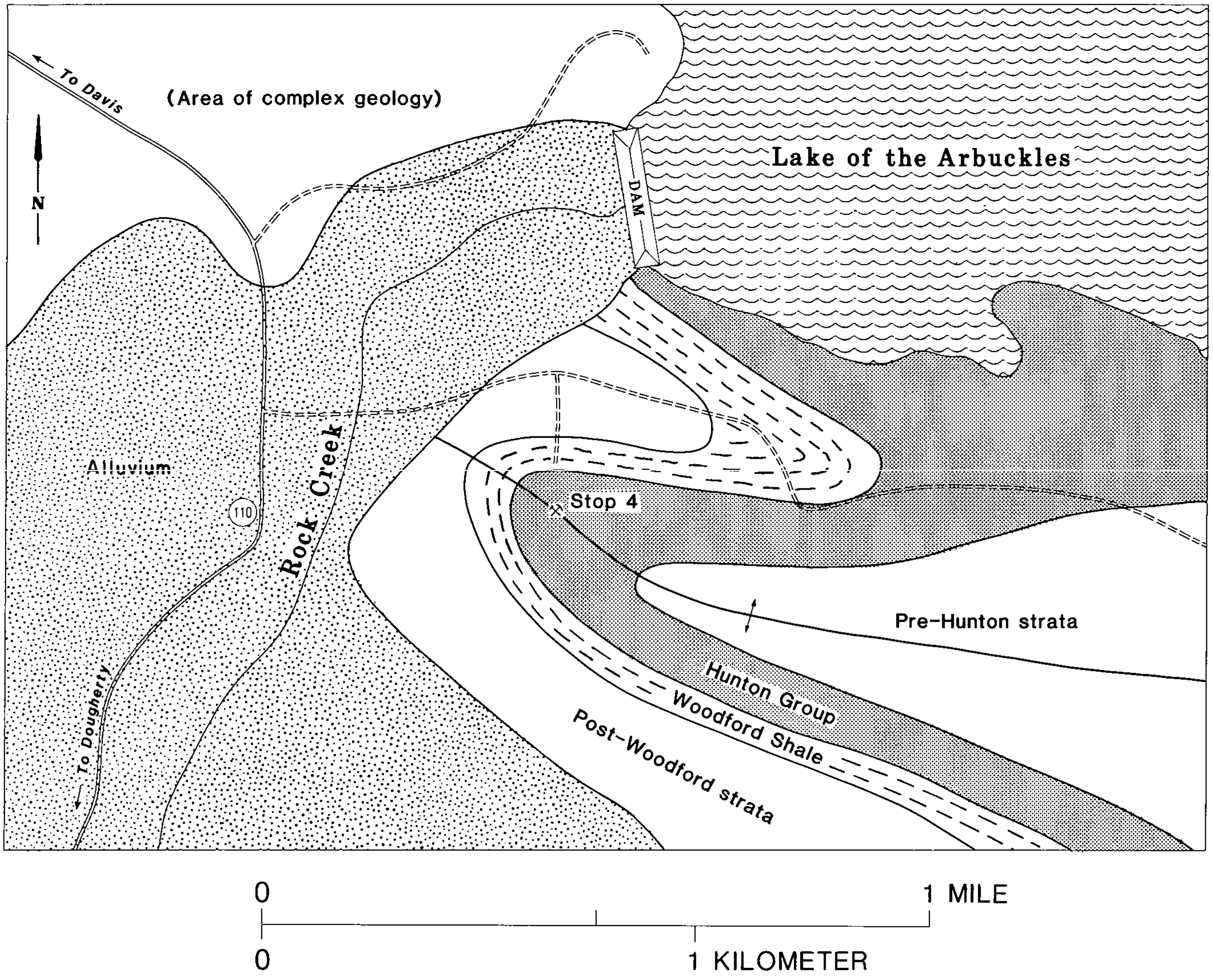

Figure 17. Generalized geologic map of Stop 4 area, showing quarries along axis of northwest-plunging anticline.

from the south caused the fold, and probably at a late stage of this folding the south block was thrust northward over the north block. This type of compression, folding, and thrusting is a small-scale representation of the movements that influenced the main Arbuckle anticline, as seen in the road cuts of Interstate 35.

Limestone has been quarried from this site (fig. 18) and used as riprap in building the Lake of the Arbuckles dam just 0.5 mile (0.8 km) north of the quarry. Also being mined at this site is the Woodford Shale of Late Devonian-Early Mississippian age (about 360 million years ago). The shale is being used at the present time as base material for county roads in the area.

The Woodford Shale is an organic-rich unit that is stratigraphically equivalent to shales such as the Chattanooga, New Albany, Ohio, Antrim, and others in the central and northeastern parts of the United States. In the Midcontinent region the Woodford is exposed at the surface at relatively few localities and is usually found in the subsurface at depths from a few thousand to more than 27,000 feet (8,200 m). The Woodford Shale typically has organic-carbon values from 1 to 9 percent (wt.) and EOM (extractable organic matter) yields of up to 6,000 ppm. This unit is considered to be an excellent petroleum source rock in areas such as the Anadarko Basin. The Woodford Shale lies unconformably on the Hunton Group in much of Oklahoma, and thus an ideal source-reservoir situation exists in many parts of the State.

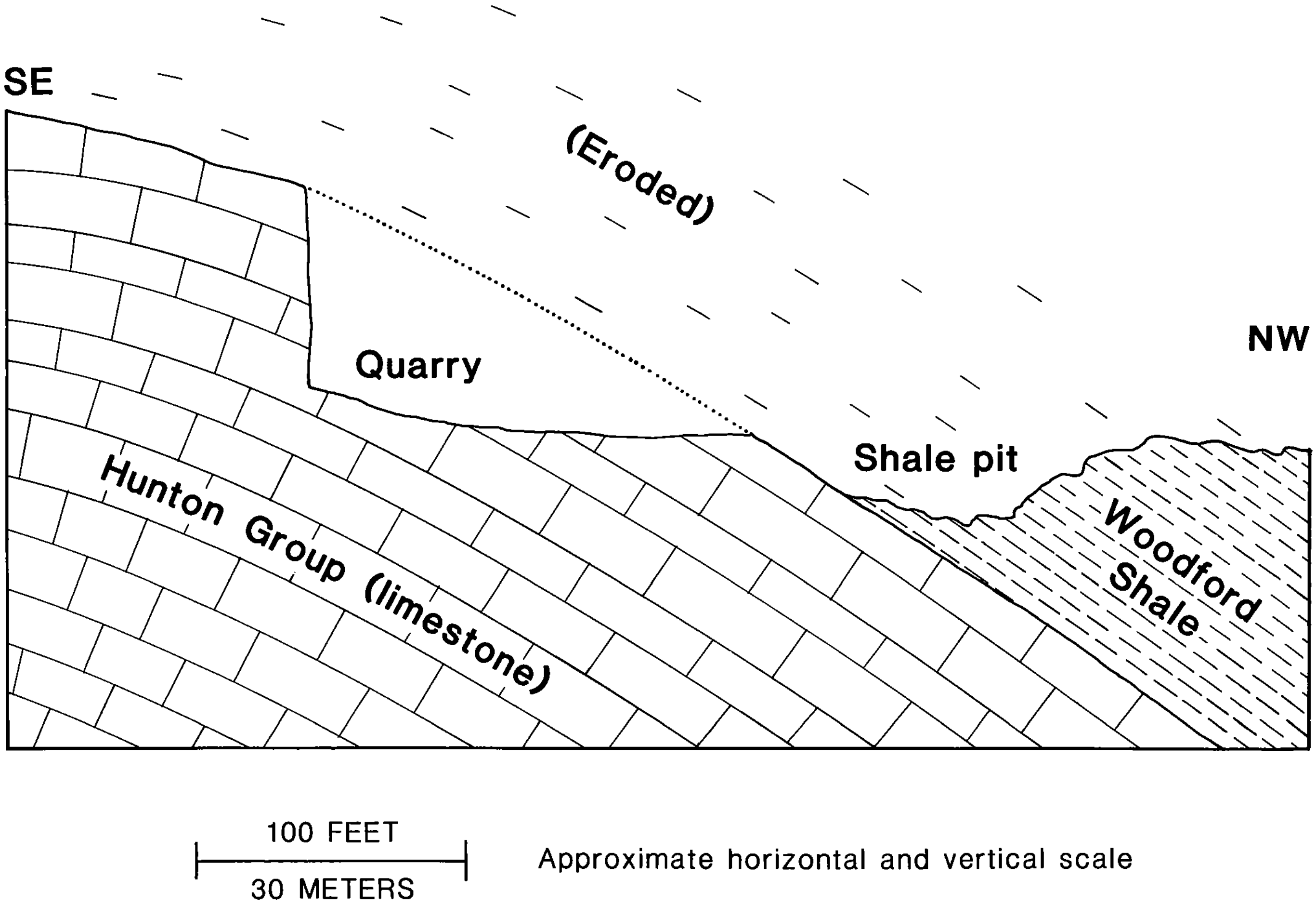

Figure 18. Generalized cross section showing relationship of Hunton Group and Woodford Shale along axis of plunging anticline at Stop 4. View looking toward southwest.

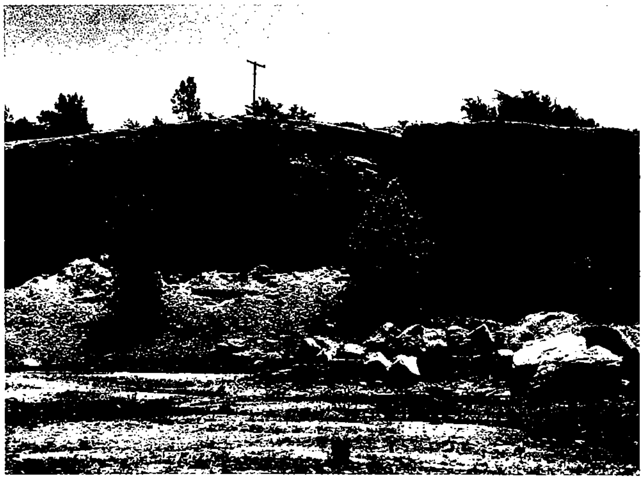

Figure 19. View of limestone quarry, looking toward southeast along axis of anticline. Thrust fault dips about 30° to right (south) and cuts top of quarry area.

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