OKLAHOMA GEOLOGY

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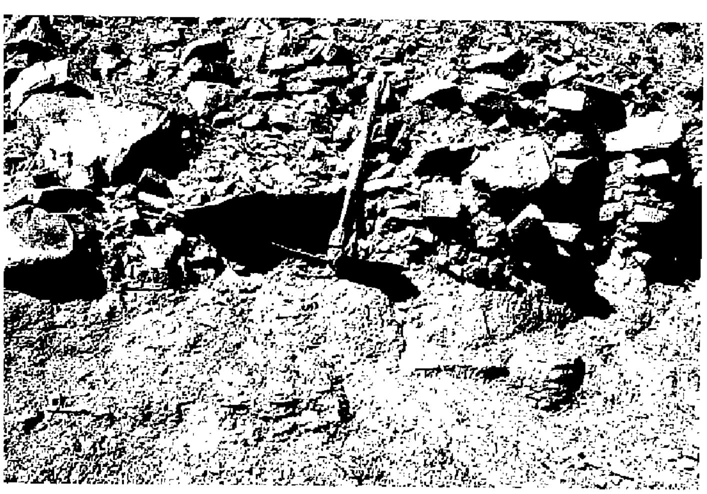
On the cover—

Great Unconformity along Coal Creek, Northwestern Le Flore County, Oklahoma

The cover photograph shows an angular unconformity exposed ~1 ft above Coal Creek in the SE¼SE¼SE¼SW¼ sec. 18, T. 6 N., R. 23 E., Le Flore County, Oklahoma, in the Arkoma basin. Flat-lying, coarse Quaternary conglomerate rests upon shales of the Savanna Formation (Pennsylvanian), that dip S. 34° E. at 4–5°. Imbrication of the clasts exposed in the stream bank shows that the current flowed from right to left.

An unconformity is a substantial gap in the geologic record where a rock unit is overlain by another that is not the next youngest in stratigraphic succession. Approximately 300 million years of time elapsed between deposition of the two units shown. This lapse in time is termed a hiatus. Rocks that would normally be present in a stratigraphic sequence are missing either because they were never deposited or because they were eroded before deposition of the beds directly overlying the break. Much of the geologic record is missing because of nondeposition, but certainly some of the rock sequence was eroded subsequent to uplift in the Arkoma basin area.

(continued on p. 62)



Close-up view of the contact shown in the cover photo. Shovel blade marks the unconformity.

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OKLAHOMA GEOLOGY NOTES

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SOVIET SEISMIC COMPOUND AT THE OGS OBSERVATORY, LEONARD, OKLAHOMA, AND SHALLOW SUBSURFACE STRATIGRAPHY OF THE AREA

LeRoy A. Hemish[1] *and James E. Lawson, Jr.*[2]

Introduction

The Oklahoma Geological Survey (OGS) operates a geophysical observatory near Leonard, Oklahoma, in southern Tulsa County (Fig. 1). The Observatory maintains a number of sophisticated instruments that measure magnetic fields, solar radiation, wind velocity, precipitation, cosmic radio noise, atmospheric-pressure fluctuations, and most importantly, seismic activity. The OGS Observatory at Leonard is one of three seismic stations in the United States (U.S.) where Union of Soviet Socialist Republics (U.S.S.R.) scientists will monitor nuclear testing as part of the new pact signed by U.S. President George Bush and Soviet leader Mikhail Gorbachev on June 1, 1990. Other monitoring sites are in the Black Hills, South Dakota, and Newport, Washington. Similar monitoring stations will be located in the U.S.S.R. and manned by U.S. scientists. U.S. nuclear weapon tests are carried out in southern Nevada.

Because geologic knowledge of the area is essential for emplacement of the Soviet monitoring equipment, a study of the rocks in the vicinity of the Leonard seismic station was undertaken by the OGS staff. This article provides background information concerning the U.S.–U.S.S.R. treaty, presents the results of the geologic study, and describes the Soviet seismic compound.

Background Information

The Treaty

In 1963, the U.S., United Kingdom (U.K.), and U.S.S.R. signed a "Treaty Banning Nuclear Weapon Tests In The Atmosphere, In Outer Space, and Under Water" (U.S., U.K., U.S.S.R., 1963). In 1974, the U.S. and the U.S.S.R. signed a treaty generally called the Threshold Test Ban Treaty (TTBT) (U.S., U.S.S.R., 1974). Beginning March 31, 1976, neither party was allowed to carry out an underground nuclear weapon test with energy yield exceeding 150 kt (the energy released by an explosion of 150,000 metric tons [165,300 tons] of TNT). The TTBT was not ratified until 1990. Energy yields were calculated from seismic P-wave magnitudes (usually P-waves with periods near one second) and seismic surface-wave magnitudes (Love and Rayleigh waves with periods between 20 and 50 seconds). The magnitudes were determined from seismic waves produced by nuclear tests recorded outside of the testing country.

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[2]Oklahoma Geological Survey Observatory, Leonard.

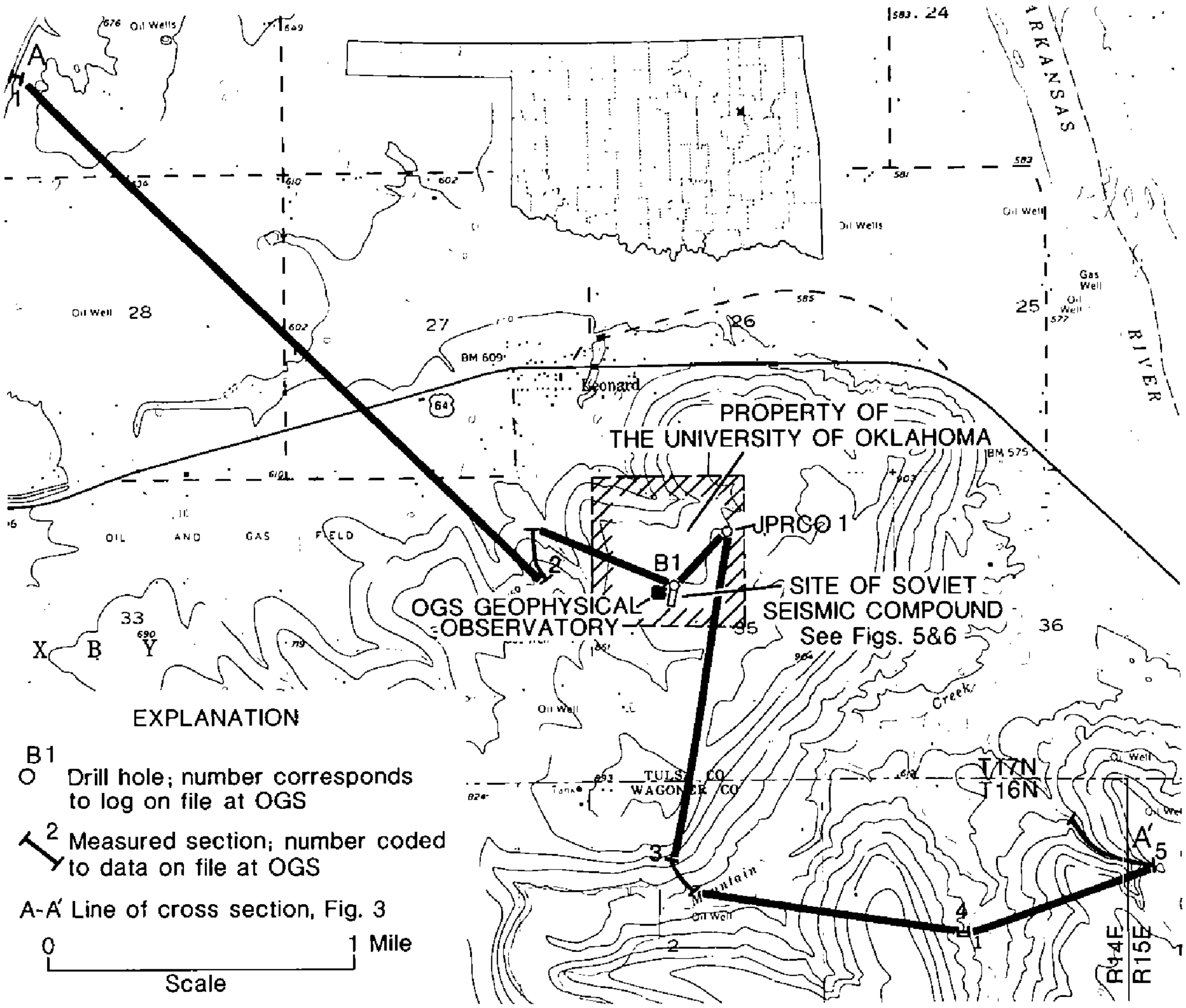

Figure 1. Excerpt from Leonard, Oklahoma, 7.5′ quadrangle map showing location of Oklahoma Geological Survey Observatory and proposed Soviet monitoring site. Study area shown by "X" on index map of Oklahoma (inset).

Systematic and random errors created uncertainties in the yield calculations from magnitudes. The statistical uncertainties at one time led the President of the U.S. to accuse the U.S.S.R. of exceeding the 150-kt (165,300-tons) threshold (Reagan, 1987). However, some scientific studies suggest that the Soviets have been in compliance (U.S. Congress, Office of Technology Assessment, 1988, p. 124–126).

One possible way for reducing the uncertainty was to use a third type of seismic-wave magnitude based on the propagation of surface waves through the upper ("granitic") layer of continental crust (Lg-waves). This magnitude, named mbLg, is considered independent of P-wave and surface-wave magnitudes. The uncertainty of a yield based on all three magnitudes is less than the uncertainty on yields calculated from one or two of them (U.S. Congress, Office of Technology Assessment, 1988, p. 121).

There were several political and technical considerations which led to the negotiations for TTBT verification protocol. The authors are not aware of all considerations, and therefore, are not able to assess their relative importance. However, Lg waves only travel over paths which traverse continuous continental crust. The necessity of a continuous continental path for recording of Lg-waves may have been a reason for the verification protocol to specify that each party could monitor the other's larger (expected yield exceeding 50 kt [55,100 tons]) nuclear weapon tests at three designated seismic stations within the testing party's country. The treaty, with a new 107-page protocol, which Presidents Bush and Gorbachev signed on June 1, 1990, specified the Oklahoma Geological Survey's Observatory site near Leonard as a designated seismic station.

The treaty specifies a signal criterion: "[A designated seismic station] shall have an Lg-wave signal-to-noise ratio not less than nine to one for any test in [United States] territory having a yield of 150 kt [165,300 tons]." An Air Force Technical Applications Center Report (unclassified, but available for official use only), based on the study of many OGS seismograms of past nuclear tests, concludes that the OGS seismic station at Leonard meets that criterion. From a recent blast, "Bullion," at the Nevada test site, June 13, 1990, Lawson and Harben (in press) found a signal-to-noise ratio of 36 to one for Lg at the OGS location.

Besides the signal-to-noise ratio for Lg, a designated seismic station has only one other geotechnical requirement: the United States must inform the U.S.S.R. of "types of rock on which it is located." Minimal information concerning only surface rocks was apparently provided before the pact was signed. In order to acquire more data concerning the shallow subsurface stratigraphy at the designated seismic station at Leonard, a test hole (B-1, Figs. 1,3,6) was drilled to a depth of 31.1 m (102 ft) in August 1990. A description of the core recovered is given in the Appendix. Additional information concerning the subsurface geology is presented in the following section.

Geology

Location of the Monitoring Site

The Observatory at Leonard is located in extreme southeastern Tulsa County (Fig. 1), ~40 km (~25 mi) south of the Tulsa International Airport in northeastern Oklahoma. U.S. Highway 64 connects Leonard with the city of Tulsa. A winding blacktop road ascends the north flank of the Conjada Mountains and leads to the Observatory site, ~1.6 km (~1 mi) south of Leonard. The sandstone-capped Conjada Mountains lie just southwest of the Arkansas River. They have a maximum relief of almost 122 m (400 ft) in neighboring Wagoner County. Elevation at the OGS Observatory is just above 259 m (850 ft). The Observatory is constructed on property owned by the University of Oklahoma in the NW¼ sec. 35, T. 17 N., R. 14 E. (Fig. 1).

Geologic Setting

The study area lies within the Claremore Cuesta Plains geomorphic province, which is characterized by resistant sandstones and limestones that dip gently westward (generally <1°) away from the Ozark uplift. The sandstones and limestones form cuestas between broad shale plains (Curtis and Ham, 1972, p. 3). Erosion by the Arkansas River and headward cutting by tributary streams (Snake Creek and Mountain Creek) have formed the promontory on which the Observatory is located. Relatively hard sandstone beds cap thick, non-resistant shales that have been removed by weathering to form steep escarpments facing the Arkansas River and its tributary streams (Oakes, 1952, p. 14).

Deep Subsurface Stratigraphy

A thick section of little-deformed sedimentary rocks of Paleozoic age overlie basement rocks in the study area. Denison (1981, p. 34, pl. 1) showed that micrographic granite porphyry of the Spavinaw Granite Group is the basement rock. It occurs at sea-level depths between –762 and –914 m (–2,500 and –3,000 ft) at the Observatory. The Wilcox Oil & Gas No. 1 Hulputta Well drilled in the NW¼NW¼ NW¼NW¼ sec. 27, T. 17 N., R. 14 E. reached basement rock at –839.4 m (–2,754 ft) (Denison, 1981, appendix, part 1). This well is located ~2.9 km (~1.8 mi) northwest of OGS test hole B-1. The elevation at OGS test hole B-1 is ~260 m (~853 ft). Assuming minor change in relief on the buried basement-rock surface (although Denison [1981, p. 1] states that the buried topography is rugged), the depth to granite at the Observatory should be ~1,097 m (~3,600 ft). The age of the Spavinaw Granite Group was calculated by Denison (1981, p. 12) to be 1,277 ± 38 million years, based on Rb/Sr determinations.

The Precambian basement rocks were peneplaned prior to transgression of the sea in Dresbachian (early Late Cambrian) time. However, scattered hills with as much as 549 m (1,800 ft) of relief remained in northeastern Oklahoma (Chenowith, 1968, p. 1670). The study area lies just off the southeastern end of one such buried ridge, which extends southwest of Leonard for ~48 km (~30 mi), and has >366 m (>1,200 ft) of relief (Denison, 1981, pl. 1).

Available information (from a test hole drilled by the Jersey Production Research Co. [JPRCO] in June 1961, in the SE¼SE¼NE¼NW¼ sec. 35, T. 17 N., R. 14 E. [JPRCO 1, Fig. 1], prior to acquisition of the property by the University of Oklahoma) indicates that dolomite is the rock type present at depths from 682.8 to 775.7 m (2,240 to 2,545 ft) (total depth). These rocks are Cambrian–Ordovician in age and belong to the Arbuckle Group. Strata from 775.7 m (2,545 ft) depth to the top of basement rock are unknown at this site. However, using data from the nearby Hulputta 1 Well, an additional 290.5 m (953 ft) of Arbuckle Group rocks, underlain by ~38 m (~125 ft) of Upper Cambrian Reagan sandstone should be present. "Reagan" is the subsurface term used for a reddish to buff sandstone and quartzitic sandstone resting on Precambian rocks in most of Oklahoma (Jordan, 1957, p. 164).

It is not the purpose of this article to describe at great length the deep subsurface stratigraphy in the study area, but the reader should be aware that some information does exist on the subject. Downhole runs were made in the JPRCO 1 Well, by the Jersey Production Research Co., that record Spontaneous-Potential, Resistivity, Conductivity, Sonic, Gamma Ray, and Neutron Log data. Lithology of the bit cuttings was described by W. R. Robinson (1961), a geologist with the company. All of the logs and descriptions are on file at both the OGS office in Norman and the Observatory office in Leonard.

Stratigraphic picks at the top of units, in depth from the surface, made by W. R. Robinson (1961) on the JPRCO logs are as follows: Burgen sandstone (Middle Ordovician), 660.8 m (2,168 ft); Wilcox sand (Middle Ordovician), 612.7 m (2,010 ft); Woodford Shale (Mississippian–Devonian), 579.1 m (1,900 ft); Fayetteville Shale (Mississippian), 499 m (1,637 ft); Pitkin Limestone (Mississippian), 464.8 m (1,525 ft); Lower Dutcher sand (Pennsylvanian–Morrowan), 457.5 m (1,501 ft); Dutcher limestone (Pennsylvanian–Atokan?), 445.3 m (1,461 ft); Bartlesville sand (Pennsylvanian–Desmoinesian), 287.4 m (943 ft); and Red Fork sand (Pennsylvanian–Desmoinesian), 216.4 m (710 ft).

Shallow Subsurface Stratigraphy

For purposes of this report the shallow subsurface stratigraphy at the Observatory test hole site includes only the rocks that crop out in the Conjada Mountains area south and west of the Arkansas River. Figure 2 is a generalized stratigraphic column showing that these rocks are of Pennsylvanian age, in the Desmoinesian Series, and that they belong to the Cabaniss and Marmaton Groups. Four formations are mappable in different parts of the Conjada Mountains: the Senora, Fort Scott, Calvin, and Wewoka Formations. Oakes (1963, p. 33) found that the base of the Calvin Sandstone is at virtually the same stratigraphic position as is the base of the Fort Scott Limestone. Both formations pinch out in the study area, as does another formation, the Wetumka Shale, which is not mappable in the Conjada Mountains. The Calvin Sandstone is absent north of the Arkansas River, where the base of the Fort Scott Formation marks the base of the Marmaton Group (Oakes, 1963, p. 33). Oakes placed the lower limit of the Marmaton at the base of the Calvin Sandstone south of the Arkansas River, but Hemish (1990) found several exposures of the Little Osage Shale and Blackjack Creek Limestone Members of the Fort Scott Formation in the Conjada Mountains, so the southern limit of the Fort Scott was extended a few miles south of the Arkansas River where pinch-out occurs.

Information was developed from a core recovered from a shallow test hole drilled at the site of the Soviet seismic compound to establish correlations with rocks from an adjacent test hole and with measured surface sections in the area. An accurate description of the rocks was needed before emplacement of the sensitive seismic-monitoring equipment. A description of the core recovered from the test hole (B-1) is presented in the Appendix. The information from test holes B-1 and JPRCO 1 was used in conjunction with several sections measured by Hemish (1990, appendix 2) to construct a cross section (Fig. 3), which correlates several key beds in the study area. Figure 4 shows the upper part of geophysical logs from JPRCO 1, which record characteristics of the near-surface strata. They begin in the lower part of the cored interval from B-1.

The Senora Formation is the sole representative of the Cabaniss Group in the study area. The contact with the underlying Boggy Formation of the Krebs Group is not exposed in the Conjada Mountains. The base of the Weir-Pittsburg coal marks the base of the Senora Formation in adjacent areas to the east (Hemish, 1990, pl. 2). No evidence was found in the logs of JPRCO 1 to show that the Weir-Pittsburg coal is present at that site. Using the top of the Red Fork sand (as picked by W. R. Robinson) as the base of the Senora Formation, the maximum thickness of the Senora is ~187.5 m (~615 ft) in the Conjada Mountains. The lower part of the formation consists of sandy to silty shale, fine-grained to silty sandstone, thin coals, and a few limestone beds. The Tiawah Limestone with its associated black shales and Tebo coal bed are the oldest markers that crop out in the Conjada Mountains area (Fig. 2). The Chelsea Sandstone (Skinner sand of subsurface terminology [Jordan, 1957, p. 179]) is well exposed in the hills just east of the east-facing es-

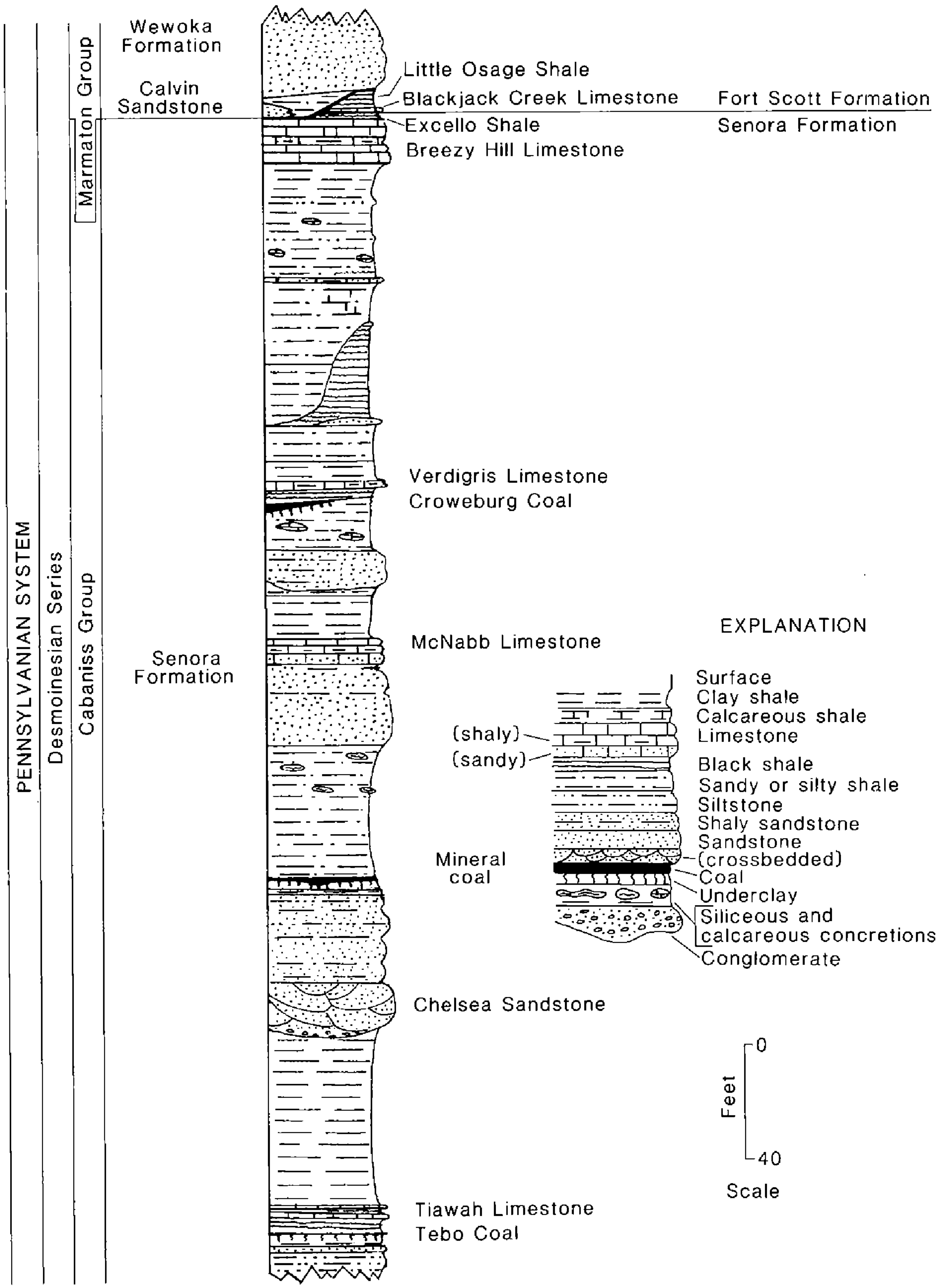

Figure 2. Generalized columnar section of the strata in the Conjada Mountains area, Tulsa and Wagoner Counties, Oklahoma.

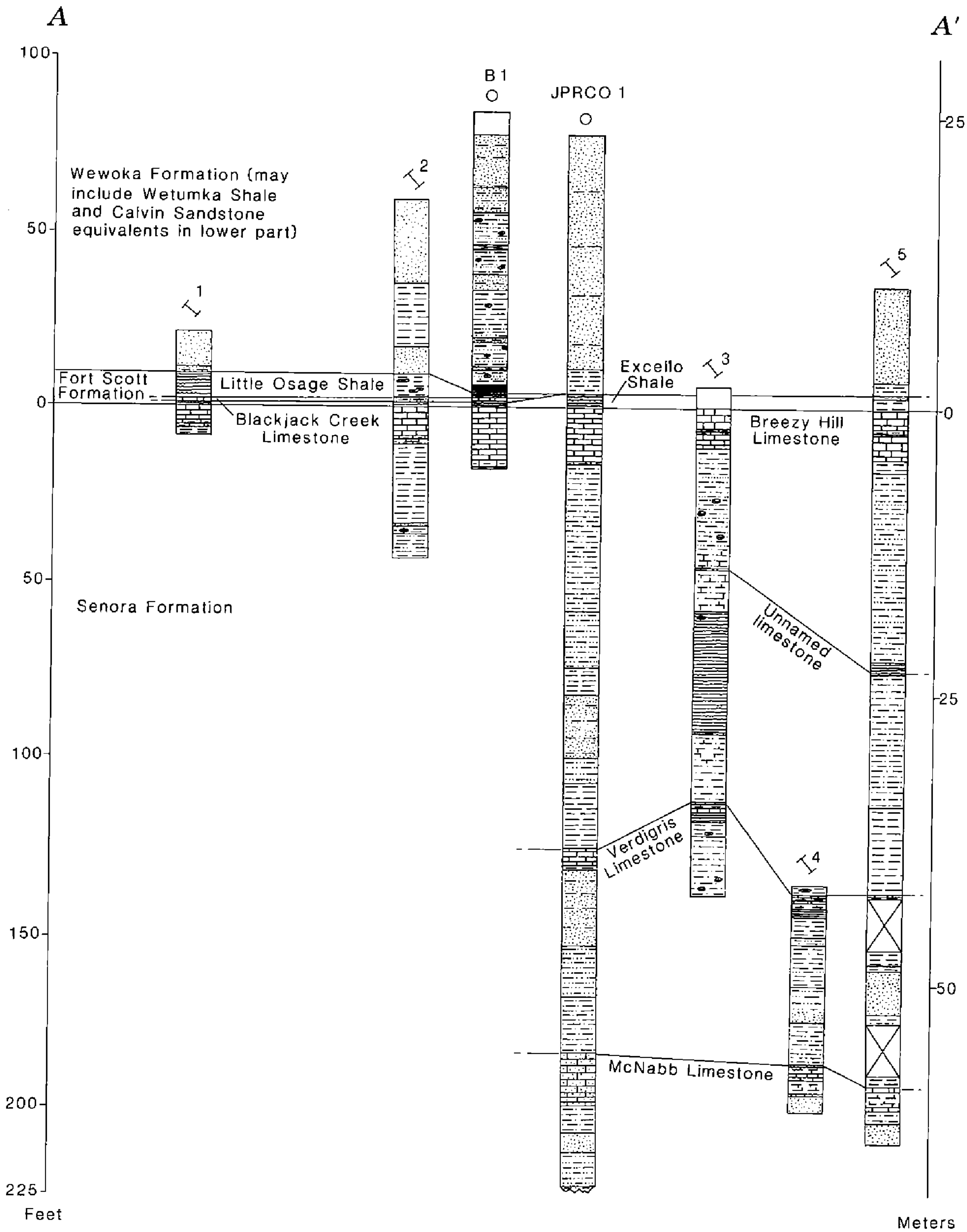

Figure 3. Cross section showing correlations of key units in the Leonard, Oklahoma, area. Line of cross section A–A′ shown in Figure 1. No horizontal scale.

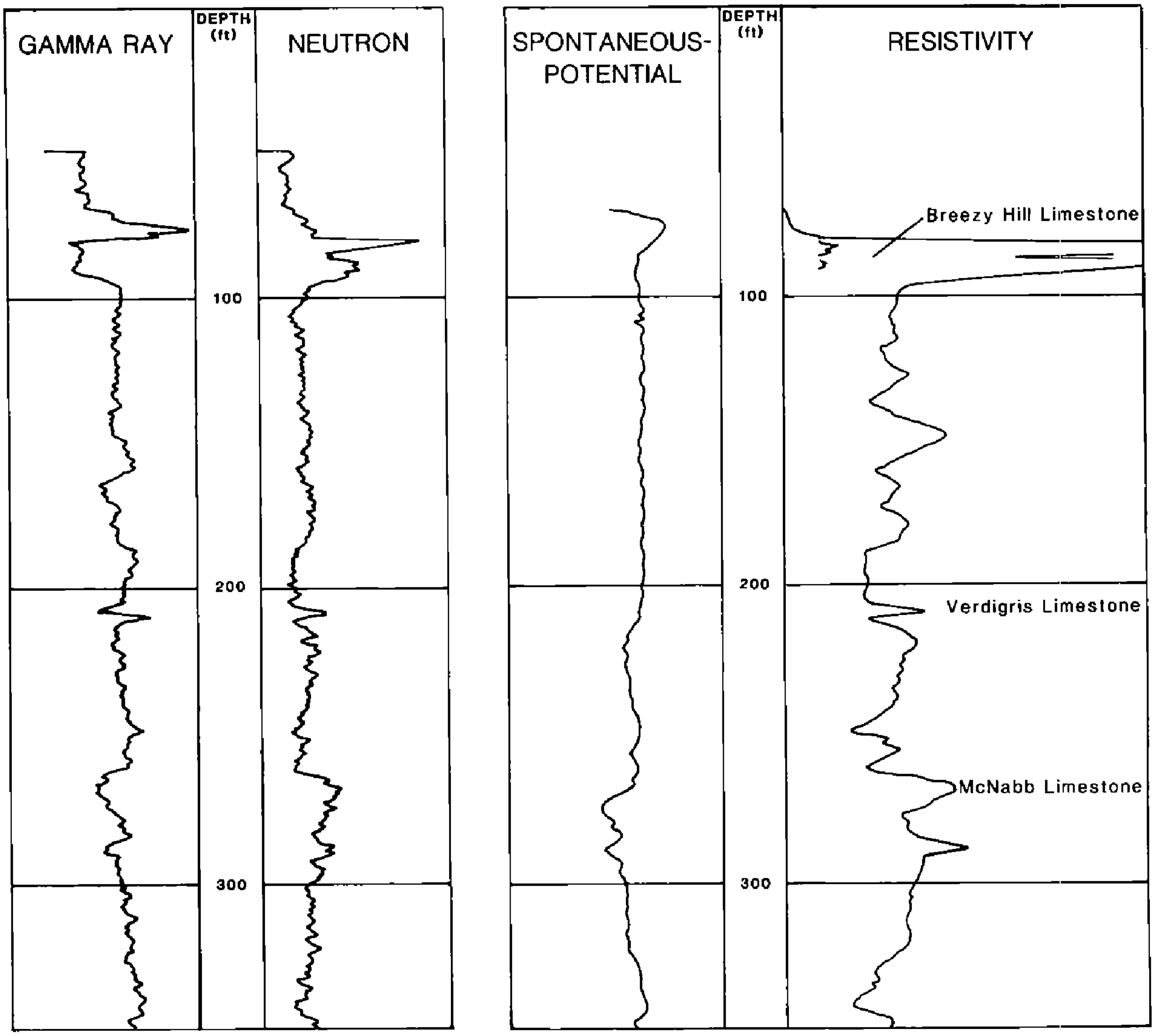

Figure 4. Abbreviated geophysical logs from Jersey Production Research Co. Instrument Test Hole #1, sec. 35, T. 17 N., R. 14 E., showing selected key beds and characteristics of the near-surface strata at the Soviet monitoring site near Leonard, Oklahoma.

carpment of the Conjada Mountains proper. Thickness of the unit is variable. Oakes (1963, p. 29) said that the lower unit of the Chelsea is 25.9 m (85 ft) thick where it extends into nearby Okmulgee County from Muskogee County across the north line of T. 14 N., R. 15 E. Oakes (1963, p. 30) said that the upper part of the Chelsea is ~14 m (~45 ft) thick in the same general area. Evidence for such thicknesses in the subsurface was not found in the vicinity of the Observatory.

The Mineral coal crops out at the foot of the east-facing escarpment of the Conjada Mountains, where it is 25.4–45.7 cm (10–18 in.) thick (Hemish, 1990, appendix 2; pl. 3). Exposures were not found in the vicinity of the Observatory, nor was coal recorded in the logs of JPRCO 1.

The stratigraphically lowest marker bed shown in Figure 3 is the McNabb Limestone. It is a sandy, micritic, fossiliferous limestone that commonly includes layers of calcareous shale and averages about 2.1–2.4 m (7–8 ft) thick where observed in outcrop (Hemish, 1990, appendix 2).

The Verdigris Limestone is the next higher marker bed. To the east of the Observatory, in the east-facing escarpment of the Conjada Mountains, the Verdigris Limestone and Croweburg coal bed crop out continuously. The coal bed is about 46–56 cm (18–22 in.) thick and occurs about 1.8–2.4 m (6–8 ft) below the base of the Verdigris, which is 0.76–0.91 m (2.5–3.0 ft) thick (Hemish, 1990, appendix 2; pl. 2). The Croweburg coal was apparently never deposited in the vicinity of the Observatory at Leonard. It was not found in a well-exposed section near Lake Bixhoma, just south of the Observatory, nor was it recorded in the logs of JPRCO 1.

About 30.5 m (~100 ft) of silty shale with minor sandstone and siltstone beds separates the Verdigris Limestone from the base of the Breezy Hill Limestone, essentially, the lowest unit cored in OGS test hole B-1 (Fig. 3; Appendix). The Breezy Hill is 5.3 m (17.5 ft) thick in B-1, and is a micritic, fossiliferous limestone that grades downward into calcareous shale.

The Breezy Hill Limestone is overlain by 0.58 m (1.9 ft) of black fissile shale (Excello Shale). The top of the Excello marks the top of the Cabaniss Group and the top of the Senora Formation.

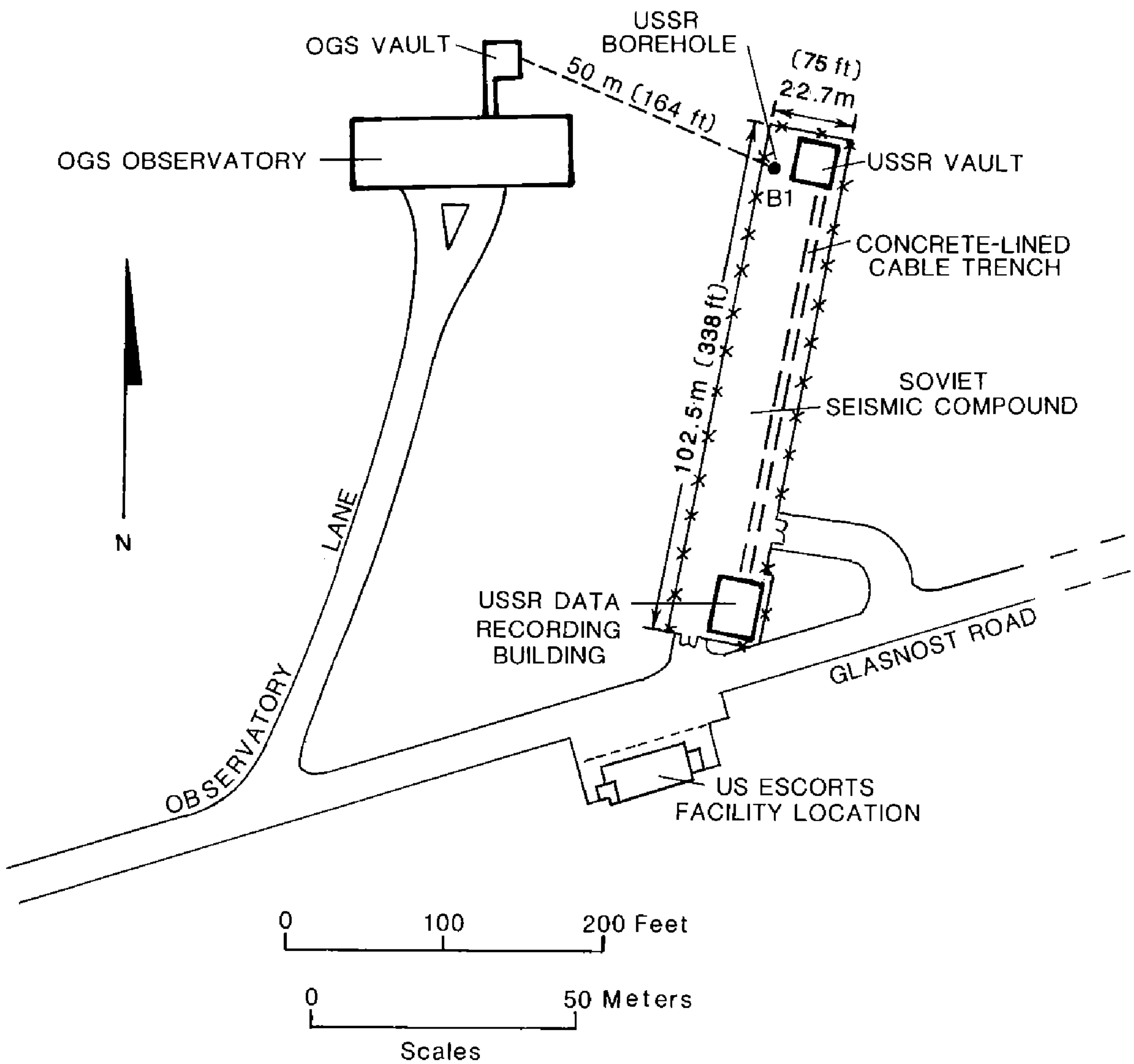

Figure 5. Plan of the Soviet seismic compound at Leonard.

At the site of B-1, the overlying Fort Scott Formation is represented by only 0.27 m (0.9 ft) of the fossiliferous, shaly Blackjack Creek Limestone Member, and 0.21 m (0.7 ft) of black fissile shale of the Little Osage Shale Member. The base of the Blackjack Creek Member marks the base of the Marmaton Group.

The next higher mappable unit is the Wewoka Formation, which, although predominantly sandstone in the Conjada Mountains area (see JPRCO 1; Fig. 3), does include in places numerous sandy and silty shale beds in the lower part. These beds may be equivalent to the Calvin Sandstone and Wetumka Shale in this difficult-to-map area of pinch-outs and intertonguing relationships. The Wewoka Sandstone weathers to various shades of reddish-brown and grayish-orange and is the resistant rock at the surface at the Observatory site. Total thickness is not known because the top of the formation has been eroded away.

Dissemination of Geologic Data

Copies of this article will be given to United States representatives for possible use in providing the Soviets with more than the minimum required rock information. The actual cores will be retained temporarily at Leonard for direct inspection by contractors and for inspection by the first Soviet verification team. Later they will be stored in the OGS Core and Sample Library in Norman.

Knowledge of the strata in the vicinity of Leonard also is important to OGS scientists who are conducting borehole seismic research in the area. The OGS, in cooperation with Lawrence Livermore National Laboratories, is continuing a study of seismic signal and noise in a borehole 770 m (2,526 ft) deep (Harben and Lawson, 1990). This borehole is ~390 m (~128 ft) northeast of test hole B-1. Layers of rock having a seismic wave velocity lower than the seismic wave velocity of strata above and below may act as waveguides to concentrate undesirable wind and cultural noise. Because of this effect, borehole seismometers should not be placed in such low velocity layers, and where possible, should be in layers with seismic wave velocities higher than the rock above and below. For example, a limestone formation between shales is liable to have much lower noise than a shale between limestones. Therefore, knowledge of the rock layers gained from the present study will provide additional benefits for the ongoing seismic research.

Site Facilities

The Soviet compound at Leonard will be a 102.5- × 22.7-m (338- × 75-ft) fenced area with a borehole and vault for seismometers at the north end where the test hole described in this report was drilled, and an office and electronics building at the south end. The borehole will be 305 mm (12 in.) inside diameter, and will end at 32.3 m (106 ft) depth. The vault floor will be 3.35 m (11 ft) below the surface. The seismometer pier will extend from 0.71 m (2.3 ft) to 0.61 m (2 ft) beneath the floor. This will require excavation of up to 2 m (6.6 ft) of the Wewoka Sandstone. The rock cannot be blasted because of the sensitivity of instruments at the Observatory. It was the specific wish of the Soviets that their borehole and vault be located close to the "historic" vault from which all of the OGS past recordings were made. The separation of 50 m (164 ft) was agreed upon by both parties in lieu of the TTBT specification of 100–200 m (328–656 ft). Figure 5 is a plan showing the dimensions of the Soviet compound and its position in relation to the existing facilities at the Observatory. A small facility will be built just south of the Soviet compound for use by U.S. escorts during times when Soviet scientists will be monitoring nuclear tests.

The Soviet compound will have a status similar to the Soviet Embassy, although a Soviet team and their equipment will probably be present only 14 days for each

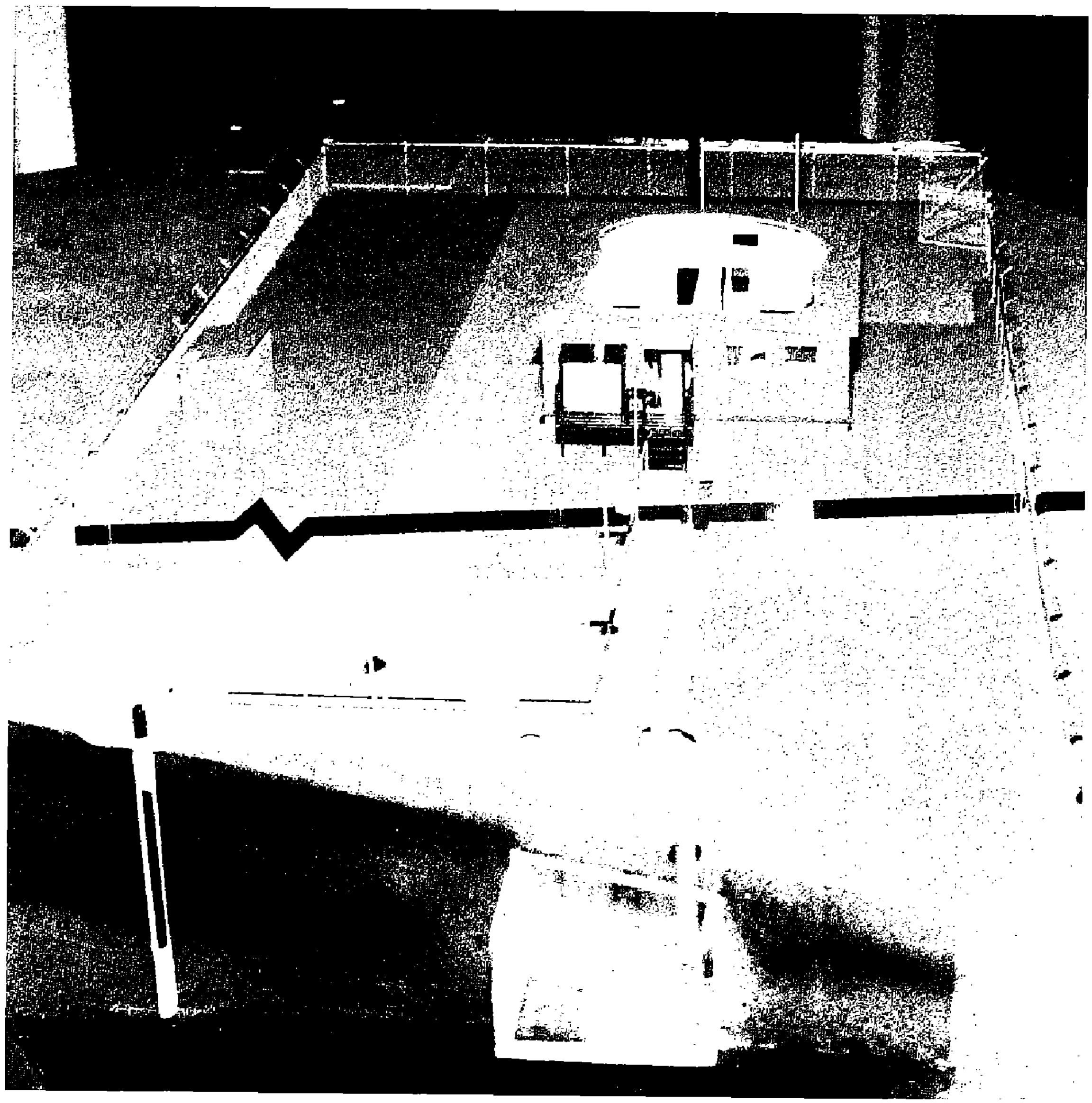

Figure 6. Three-dimensional model of the Soviet seismic compound at Leonard (view from the north). The cut-away view at the north end shows the borehole (left) and vault (center) in which Soviet seismometers will be located. A sidewalk, drive, and concrete-lined and covered cable trench connect the vault and borehole to the Soviet electronics office building (shown with the roof partly cut away). For display purposes, the overall length of the compound has been shortened by omitting the central part of the fenced area, shown by the jagged, heavy black line. The U.S. escorts office building is outside the fence (left background). In final blueprints there are minor changes in the location of the Soviet and American buildings, drives, and parking. The locations of the vault and borehole are reversed. The Soviet borehole is 50 m (164 ft) east of the U.S. seismometer vault. Unlike the surroundings shown in the model, the Leonard site is heavily wooded.

blast of 50 kt (55,100 tons) or larger. Figure 6 is a three-dimensional model of the Soviet seismic compound. The same basic format will be used at all three of the designated seismic compounds in the U.S. The model is in the headquarters of the U.S. On-Site Inspection Agency at Herndon, Virginia. Construction on the Soviet compound is in progress.

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Appendix: Core-Hole B-1

SW¼NW¼SE¼NW¼ sec. 35, T. 17 N., R. 14 E., Tulsa County, Oklahoma. Well cored by Tulsa Testing Co.; lithologic descriptions by LeRoy A. Hemish, OGS geologist. Drilled in wooded area ~200 ft east of the Oklahoma Geological Survey Observatory office. (Surface elevation, estimated from topographic map, 853 ft.)

	Depth to unit top (ft)	Thickness of unit (ft)
MARMATON GROUP		
Wewoka Formation (may include Wetumka Shale and Calvin Sandstone equivalents in lower part)		
Surface material (drilled with auger, cuttings not saved; weathered sandstone boulders and sandy clay exposed at drill site)	0.0	6.5
Sandstone, grayish-orange (10 YR 7/4)[1], very fine- to fine-grained, quartzose, oxidized, silica- and iron-oxide-cemented, grains rounded, noncalcareous, massive to cross-bedded in part; includes some shale layers from 9.4 to 9.7 ft, 12.8 to 13.3 ft, and 21.3 to 21.4 ft; contains minor carbonaceous shale layers and fossil plant material; liesegang-banded in places	6.5	15.2
Sandstone, light-gray (N 7), with medium-dark-gray (N 4) bands, very fine-grained, interbedded with silty shale, laminated to massive, noncalcareous, ripple-laminated in places; contains abundant black carbonized plant fragments, some clay galls, and some bioturbation features	21.7	7.0
Shale, medium-gray (N 5), silty, noncalcareous, includes very fine-grained lenses and layers of light-gray (N 7) sandstone, bioturbated in part; includes some soft-sediment deformation features, black carbonized plant fragments, and small sideritic concretions up to 1 in. in diameter and 0.25 in. thick	28.7	9.3
No recovery	38.0	1.4
Shale (same description as interval from 28.7 to 38.0 ft)	39.4	7.0
Sandstone, light-gray (N 7), very fine-grained, noncalcareous, quartzose; mostly massive, but contains some medium-dark-gray (N 4), cross-laminated, sandy shale layers up to 7 in. thick that contain scour-and-fill, bioturbation, and soft-sediment deformation features; black carbonized plant fragments abundant in unit	46.4	4.8
Shale, medium-gray (N 5), noncalcareous, burrowed; contains rare, small sideritic concretions; is banded in lower 4 ft of unit and is interstratified with light-gray (N 7), siltstone and very fine-grained sandstone containing abundant black carbonized plant fragments; basal contact sharp	51.2	13.1
Sandstone, light-gray (N 7), very fine-grained, silty, noncalcareous; faintly stratified, with some low-angle cross-stratification; interbedded with medium-dark-gray (N 4), bioturbated shale in lower 10 in. of unit	64.3	1.7

Shale, medium-gray (N 5), noncalcareous, bioturbated; includes laminae and contorted layers of light-gray (N 7), very fine-grained, bioturbated sandstone; contains numerous, small sideritic nodules	66.0	7.2
Sandstone, light-gray (N 7), very fine-grained, calcareous, faintly laminated	73.2	0.2
Shale (same description as interval from 66.0 to 73.2 ft); contains two 1.5-in.-thick layers of light-gray (N 7), very fine-grained sandstone ~2.5 ft from base of unit; lower contact gradational	73.4	6.0
Shale, medium-dark-gray (N 4), very calcareous; contains abundant small shells and shell fragments in lower 3 in. of unit	79.4	0.5
Shale, black (N 1), noncalcareous; burrowed	79.9	0.1
Shale, dark-gray (N 2), calcareous	80.0	0.3
Sandstone, medium-dark-gray (N 4), very calcareous, very shaly, churned from drilling or bioturbated	80.3	0.5
Fort Scott Formation		
Shale, black (N 1), fissile, noncalcareous (Little Osage Shale Member)	80.8	0.7
Limestone, very light-gray (N 8), shaly, subtly stratified; contains abundant fossil fragments and crinoid columns up to 0.5 in. in diameter (Blackjack Creek Limestone Member)	81.5	0.9
CABANISS GROUP		
Senora Formation		
Shale, grayish-black (N 2), noncalcareous, fissile; contains rare laminae of fine-grained limestone (Excello Shale Member)	82.4	1.9
Limestone, medium-light-gray (N 6) to light-brownish-gray (5 YR 6/1), very fine-grained, micritic, impure in lower 2 ft; contains scattered fossil shells concentrated in thin layers in places; irregularly laminated; cross-laminated in part; vugular in places; grades into medium-gray (N 5), calcareous shale in lower 1 in. of unit (Breezy Hill Limestone Member)	84.3	17.5
Shale, medium-gray (N 5), very calcareous	101.8	0.2
Total depth		102.0

[1]Letter and number designation in parentheses refers to standard color classifications used in the Munsell color system (Rock-Color Chart Committee, 1948).

OKLAHOMA EARTHQUAKES, 1990

James E. Lawson, Jr.[1], *Kenneth V. Luza*[2], *and Dan Moss*[1]

Introduction

More than 930,000 earthquakes occur throughout the world each year (Tarbuck and Lutgens, 1990). Approximately 95% of these earthquakes have a magnitude of <2.5 and are usually not felt by humans (Table 1). Only 20 earthquakes, on average, exceed a magnitude 7.0 each year. An earthquake that exceeds a magnitude 7.0 is considered to be a major earthquake and serious damage could result.

Earthquakes tend to occur in belts or zones. For example, narrow belts of earthquake epicenters coincide with oceanic ridges where plates separate, such as in the

TABLE 1. — ESTIMATED NUMBER OF WORLDWIDE EARTHQUAKES PER YEAR BY MAGNITUDE
(Modified from Tarbuck and Lutgens, 1990)

Magnitude	Estimated number per year	Earthquake effects
<2.5	>900,000	Generally not felt, but recorded
2.5–5.4	30,000	*Minor to moderate earthquakes* Often felt, but only minor damage detected
5.5–6.0	500	*Moderate earthquakes* Slight damage to structures
6.1–6.9	100	*Moderate to major earthquakes* Can be destructive in populous regions
7.0–7.9	20	*Major earthquakes* Inflict serious damage if in populous regions
≥8.0	1–2	*Great earthquakes* Produce total destruction to nearby communities

[1]Oklahoma Geological Survey Observatory, Leonard.
[2]Oklahoma Geological Survey.

mid-Atlantic and east Pacific Oceans. Earthquakes also occur where plates collide and/or slide past each other. Although most earthquakes originate at plate boundaries, a small percentage occur within plates. The New Madrid earthquakes of 1811–12 are examples of large and destructive intraplate earthquakes in the United States.

The New Madrid earthquakes of 1811 and 1812 are probably the earliest historical earthquake tremors felt in Oklahoma (Arkansas Territory) by residents in southeastern Oklahoma settlements. The earliest documented earthquake in Oklahoma occurred near Jefferson, Grant County, on December 2, 1897 (Stover and others, 1981). The next oldest known Oklahoma earthquake happened near Cushing in December 1900. This event was followed by two additional earthquakes in the same area in April 1901 (Wells, 1975).

The largest known Oklahoma earthquake occurred near El Reno on April 9, 1952. This magnitude-5.5 (mb) earthquake was felt in Austin, Texas, as well as Des Moines, Iowa, and covered a felt area of ~362,000 km^2 (Docekal, 1970; Kalb, 1964; von Hake, 1976). From 1900 through 1990, more than 840 earthquakes have been located in Oklahoma.

Instrumentation

A statewide network of 12 seismograph stations was used to locate 37 earthquakes in Oklahoma for 1990 (Fig. 1). The Oklahoma Geological Survey Observatory station, TUL, located near Leonard, Oklahoma, in southern Tulsa County, operates seven seismometers, three long-period and four short-period. The seismic responses at TUL are recorded on 12 paper-drum recorders. Accurate timing is assured by a microprocessor clock that is continuously locked to the National Bureau of Standards cesium-beam clocks by low-frequency radio transmissions broadcast by WWVB (Lawson, 1980). Seven semipermanent volunteer-operated seismograph stations and three radio-telemetry seismograph stations complete the Oklahoma Geological Survey's seismic network. The operation and maintenance of 10 of the stations is partially supported by the U.S. Nuclear Regulatory Commission (Luza, 1978).

Each of the seven volunteer-operated seismograph stations consists of a Geotech S-13 short-period vertical seismometer; a Sprengnether MEQ-800-B unit, including amplifier, filters, hot-stylus heat-sensitive-paper recording unit, and a clock; and a Kinemetrics time-signal-radio receiver for high-frequency WWV time signals. Each radio-telemetry system consists of one Geotech S-13 seismometer and one radio-telemetry unit. The telemetry unit amplifies the seismometer output and uses this output to frequency-modulate an audiotone. The signals are transmitted to Leonard in the 216- to 220-MHz band with 500-mW transmitters and 11-element beam antennas, giving an effective radiated forward power of 12.9 W. Transmission path lengths vary from 50 to 75 km. Seismograms from the radio-telemetry stations are recorded at the OGS Observatory.

Station OCO, which contains equipment similar to the volunteer-operated stations, is located at the Omniplex museum in Oklahoma City. Omniplex staff members change the seismic records daily as well as maintain the equipment. OGS Observatory staff help interpret the seismic data and archive the seismograms with all other Oklahoma network seismograms.

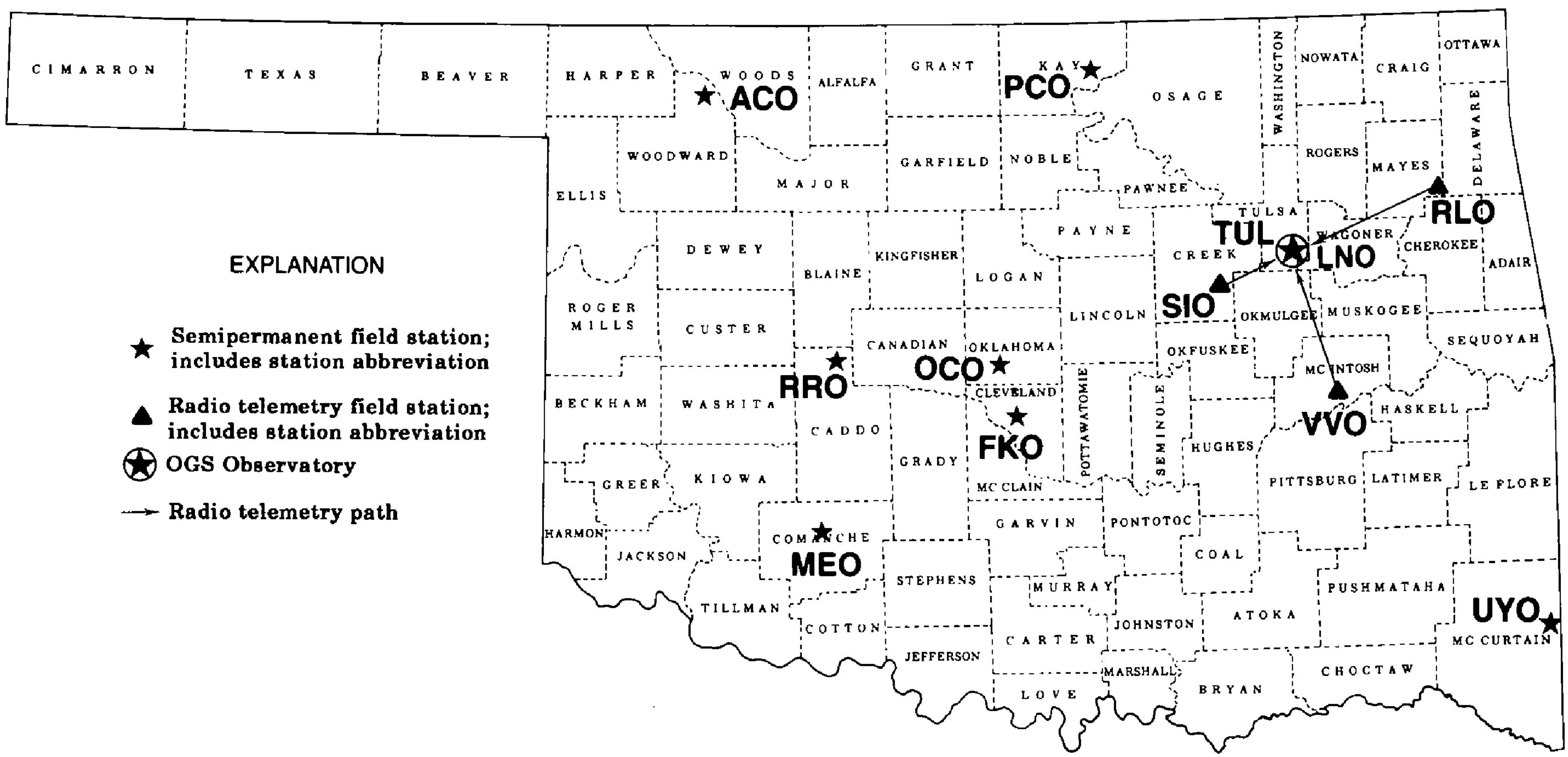

Figure 1. Active seismographs in Oklahoma.

Station LNO consists of two Geotech 23900 seismometers placed near the bottom of a 770-m-deep borehole located on Observatory property. The responses from the borehole seismometers are digitally recorded at 200 samples/sec near the well bore. Also, the responses are continuously recorded on analog seismograms at the Observatory.

In the last quarter of 1990, continuous digital recordings from six new seismometers in the Leonard vault were made by the GSE digital seismic system. The OGS is the development (beta) site for this Defense Advanced Research Projects Agency system. Forty 24-bit samples per second are recorded from three short-period GS-13 Geotech seismometers (vertical, north-south, and east-west). Ten 24-bit samples per second are recorded from vertical, north-south, and east-west Geotech BB-13 broadband seismometers.

The GSE system is superior in many ways to the analog (paper) seismographs. The digital system provided the only on-scale recordings of the Lindsay earthquake of November 15. Most paper recordings were blanks from pens hitting the stops and moving too rapidly to mark; however, these seismograms do provide a precise P-wave arrival time for location. The ability of the system to rapidly and interactively overlay multiple seismic traces on different seismic wave travel-time tables allowed estimation of depth of the Lindsay earthquake.

The various filtering and zooming functions of the GSE digital system allow measurement of amplitudes of one and three Hertz waves from almost any recordable earthquake. The OGS can, as a result, assign mbLg and m3Hz magnitudes to smaller earthquakes, which in the past often had only MDUR assigned. An example of a GSE seismogram is on the cover of the February issue of *Oklahoma Geology Notes*, with an explanation by Lawson (1991).

Data Reduction and Archiving

Arrival times from all visible teleseisms (phases from distant earthquakes) at TUL, MEO, UYO, and ACO are sent to the U.S. National Earthquake Information Service and the International Seismological Centre in England. P-wave and surface-wave amplitudes from TUL, plus selected arrival times from RLO, VVO, SIO, FKO, TCO, RRO, and OCO, are also included. These reduced seismic data are sent to more-specialized agencies such as the USAF Technical Applications Center, which monitors underground nuclear tests worldwide.

From station TUL, at the OGS Observatory near Leonard, five short-period vertical seismograms (with differing frequency responses) and one short-period vertical seismogram from the LNO borehole seismometer signal are searched exhaustively for local and regional earthquake phases. Also searched are two TUL short-period horizontal seismograms; two short-period vertical seismograms from each of RLO, SIO, and OCO; and one short-period vertical seismogram from each of the seven other stations.

Twelve daily TUL seismograms, as well as 11 daily seismograms from the remote stations, are permanently archived at the OGS Observatory. Digital data from the six channels of the GSE system are permanently archived on Exabyte™ tape cartridges. Each 2.2 gigabyte (billion byte) tape cartridge records 45 days of continuous digital data.

Earthquake Distribution

All Oklahoma earthquakes recorded on seismograms from three or more stations are located. In 1990, 37 Oklahoma earthquakes were located (Fig. 2; Table 2). Three earthquakes were reported felt (Table 3). The felt and observed effects of earthquakes are generally given values according to the Modified Mercalli intensity scale, which assigns a Roman numeral to each of 12 levels described by effects on humans, man-made constructions, or natural features (Table 4).

The felt areas for two of the earthquakes listed in Table 3, Hartshorne earthquake (event no. 828) and Garvin County earthquake (event no. 841), are probably restricted to a few tens of square kilometers away from the epicentral location. The Hartshorne earthquake produced intensity-MM V effects. However, no damage was reported.

At 5:44 a.m. on November 15, 1990, a magnitude 3.9 (mbLg) earthquake occurred 10 km southeast of Lindsay. The earthquake shook northern Garvin County and parts of McClain, Stephens, and Grady Counties (Fig. 3). The felt area covered >856 km^2 and intensity-MM VI effects were reported in the vicinity of the epicenter. Minor damage was reported. The earthquake caused items to be thrown off shelves in a grocery store and some knickknacks fell from shelves.

The Lindsay quake was the largest Oklahoma earthquake since the Latimer County earthquake of April 27, 1961. That event measured 4.1.

Although earthquakes are common west and south of Oklahoma City, the November 8 earthquake was only the second known earthquake within Oklahoma County.

Earthquake-magnitude values range from a low of 1.2 (m3Hz) in Pottawatomie County to a high of 3.9 (mbLg) in Garvin County. Almost half, 16 earthquakes, occurred in Garvin, McClain, and Grady Counties, one of the most active areas in the State since 1979. Three earthquakes were located in Pontotoc County; Pottawatomie, Hughes, and Garfield Counties experienced two earthquakes.

Catalog

A desk-top computer system, including linked HP-9825T and HP-9835-A computers, hard and flexible disks, and printers, is used to calculate and catalog local earthquake epicenters. Any earthquake within Oklahoma or within about 100–200 km of Oklahoma's borders is considered a local earthquake. A catalog containing date, origin time, county, intensity, magnitude, location, focal depth, and references is printed in page-sized format. Table 2 contains 1990 Oklahoma earthquake data displayed in a modified version of the regional earthquake catalog. Each event is sequentially numbered and arranged according to date and origin time. The numbering system is compatible with the system used for the *Earthquake Map of Oklahoma* (Lawson and others, 1979) and subsequent additions (Lawson and Luza, 1980–90).

The date and time are given in UTC. UTC refers to Coordinated Universal Time, formerly Greenwich Mean Time. The first two digits refer to the hour on a 24-hour clock. The next two digits refer to the minute, and the remaining digits are the seconds. To convert to local Central Standard Time, subtract 6 hours.

Earthquake magnitude is a measurement of energy and is based on data from

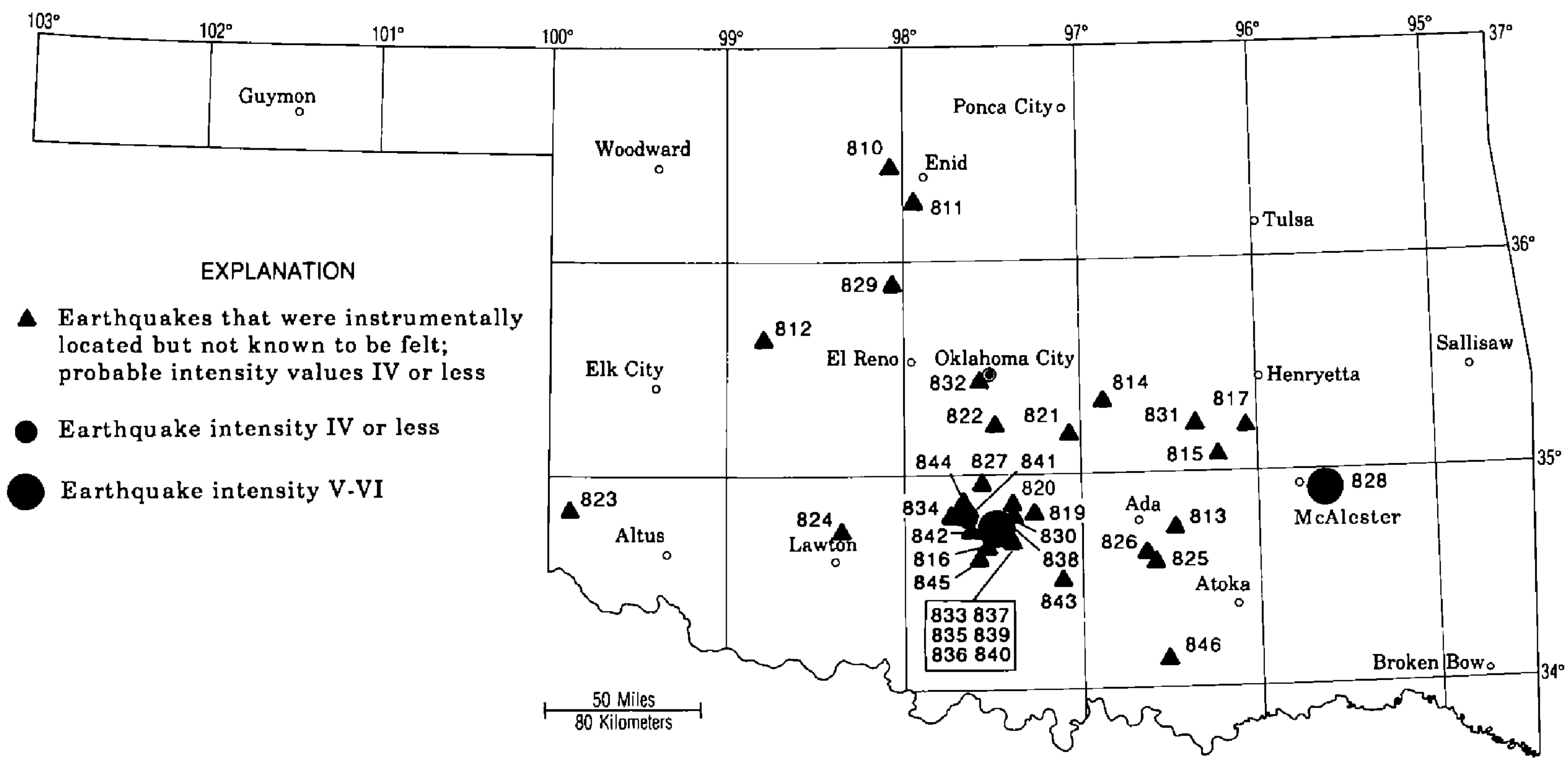

Figure 2. Distribution of Oklahoma earthquakes for 1990. Numbers correspond to event numbers in Table 2.

TABLE 2. — OKLAHOMA EARTHQUAKE CATALOG FOR 1990

Event no.	Date and origin time (UTC)[a]		County	Intensity MM[b]	Magnitudes 3Hz	bLg	DUR	Latitude deg N	Longitude deg W	Depth (km)[c]
810	JAN 8	092701.74	Garfield				2.2	36.402	98.093	5.0R
811	JAN 15	211537.51	Garfield				1.7	36.293	97.964	5.0R
812	FEB 7	120214.06	Custer		2.6	2.1	2.5	35.629	98.827	5.0R
813	FEB 16	193510.18	Pontotoc		2.2		1.8	34.732	96.476	5.0R
814	FEB 25	073120.76	Pottawatomie		1.2		1.5	35.418	96.837	5.0R
815	APR 2	204307.84	Hughes				2.6	35.057	96.239	5.0R
816	APR 19	213504.58	Garvin		2.8		2.2	34.734	97.578	5.0R
817	APR 23	222649.61	Hughes		2.5	1.8	2.4	35.223	96.050	5.0R
818	MAY 16	111238.25	Caddo		1.6		1.8	35.325	98.464	5.0R
819	MAY 25	013833.66	Garvin		2.6	2.0	2.2	34.816	97.394	5.0R
820	JUN 22	161218.56	Garvin				2.0	34.831	97.483	5.0R
821	JUL 15	002623.96	Pottawatomie		2.1		2.1	35.170	97.044	5.0R
822	JUL 16	005755.33	Cleveland				1.6	35.248	97.518	5.0R
823	JUL 17	011319.61	Harmon			2.8	2.8	34.885	99.905	5.0R
824	JUL 24	084351.41	Comanche		1.5		1.7	34.758	98.351	5.0R
825	AUG 12	012223.16	Pontotoc		2.6		2.2	34.593	96.578	5.0R
826	AUG 12	012930.54	Pontotoc		2.1		2.0	34.601	96.574	5.0R
827	SEP 4	223225.78	McClain		2.4		2.0	34.976	97.585	5.0R
828	SEP 16	211333.38	Pittsburg	5	3.2	2.4	3.0	34.855	95.577	5.0R
829	OCT 2	031405.89	Kingfisher				1.8	35.941	98.042	5.0R
830	OCT 11	110722.14	Garvin		3.6	3.0	1.9	34.777	97.503	5.0R
831	OCT 21	180715.54	Hughes				0.8	35.234	96.374	5.0R
832	NOV 8	145155.89	Oklahoma		2.6	1.8	2.0	35.455	97.572	5.0R
833	NOV 15	102948.68	Garvin		1.8	1.5	2.2	34.761	97.550	10.0R
834	NOV 15	104931.49	Grady				2.0	34.794	97.677	10.0R
835	NOV 15	110613.97	Garvin				1.3	34.761	97.550	10.0R
836	NOV 15	111539.61	Garvin		2.1	1.7	2.0	34.761	97.550	10.0R
837	NOV 15	111810.46	Garvin				1.2	34.761	97.550	10.0R
838	NOV 15	114441.63	Garvin	6	4.0	3.9	3.0	34.761	97.550	10.0R
839	NOV 15	121439.29	Garvin		2.3	1.6	2.0	34.761	97.550	10.0R
840	NOV 15	125431.97	Garvin				1.6	34.761	97.550	10.0R
841	NOV 16	204715.06	Garvin	F	2.5		2.4	34.787	97.611	5.0R
842	NOV 19	153911.45	Garvin		1.8	1.4	2.3	34.765	97.599	5.0R
843	NOV 19	211127.41	Murray		1.8	1.4	2.2	34.484	97.130	5.0R
844	NOV 20	172517.87	Garvin		2.6	2.1	2.2	34.836	97.644	5.0R
845	NOV 22	024553.47	Stephens		2.7	2.2	2.2	34.668	97.570	5.0R
846	DEC 12	075327.80	Johnston		2.5	2.1	1.8	34.152	96.542	5.0R

[a]UTC refers to Coordinated Universal Time, formerly Greenwich Mean Time. The first two digits refer to the hour on a 24-hour clock. The next two digits refer to the minute, and the remaining digits are the second. To convert to local Central Standard Time, subtract 6 hours.

[b]Modified Mercalli (MM) earthquake-intensity scale (see Table 4).

[c]The hypocenter is restrained (R) at an arbitrary depth of 5.0 km, except where indicated, for purposes of computing latitude, longitude, and origin time.

TABLE 3. — EARTHQUAKES THAT WERE REPORTED FELT IN OKLAHOMA, 1990

Event no.	Date and origin time (UTC)[a]		Nearest city	County	Intensity MM[b]
828	SEP 16	211333.38	Hartshorne	Pittsburg	V
838	NOV 15	114441.63	SE Lindsay	Garvin	VI
841	NOV 16	204715.06	S Lindsay	Garvin	felt

[a]UTC refers to Coordinated Universal Time, formerly Greenwich Mean Time. The first two digits refer to the hour on a 24-hour clock. The next two digits refer to the minute, and the remaining digits are the second. To convert to local Central Standard Time, subtract 6 hours.

[b]Modified Mercalli (MM) earthquake-intensity scale (see Table 4).

TABLE 4. — MODIFIED MERCALLI (MM) EARTHQUAKE-INTENSITY SCALE (Abridged) (Modified from Wood and Neumann, 1931)

I Not felt except by a very few under especially favorable circumstances.

II Felt only by a few persons at rest, especially on upper floors of buildings. Suspended objects may swing.

III Felt quite noticeably indoors, especially on upper floors of buildings. Automobiles may rock slightly.

IV During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, doors, windows disturbed. Automobiles rocked noticeably.

V Felt by nearly everyone, many awakened. Some dishes, windows, etc., broken; unstable objects overturned. Pendulum clocks may stop.

VI Felt by all; many frightened and run outdoors.

VII Everybody runs outdoors. Damage negligible in buildings of good design and construction. Shock noticed by persons driving automobiles.

VIII Damage slight in specially designed structures; considerable in ordinary substantial buildings; great in poorly built structures. Fall of chimneys, stacks, columns. Persons driving automobiles disturbed.

IX Damaged considerable even in specially designed structures; well-designed frame structures thrown out of plumb. Buildings shifted off foundations. Ground cracked conspicuously.

X Some well-built wooden structures destroyed; ground badly cracked, rails bent. Landslides and shifting of sand and mud.

XI Few if any (masonry) structures remain standing. Broad fissures in ground.

XII Damage total. Waves seen on ground surfaces.

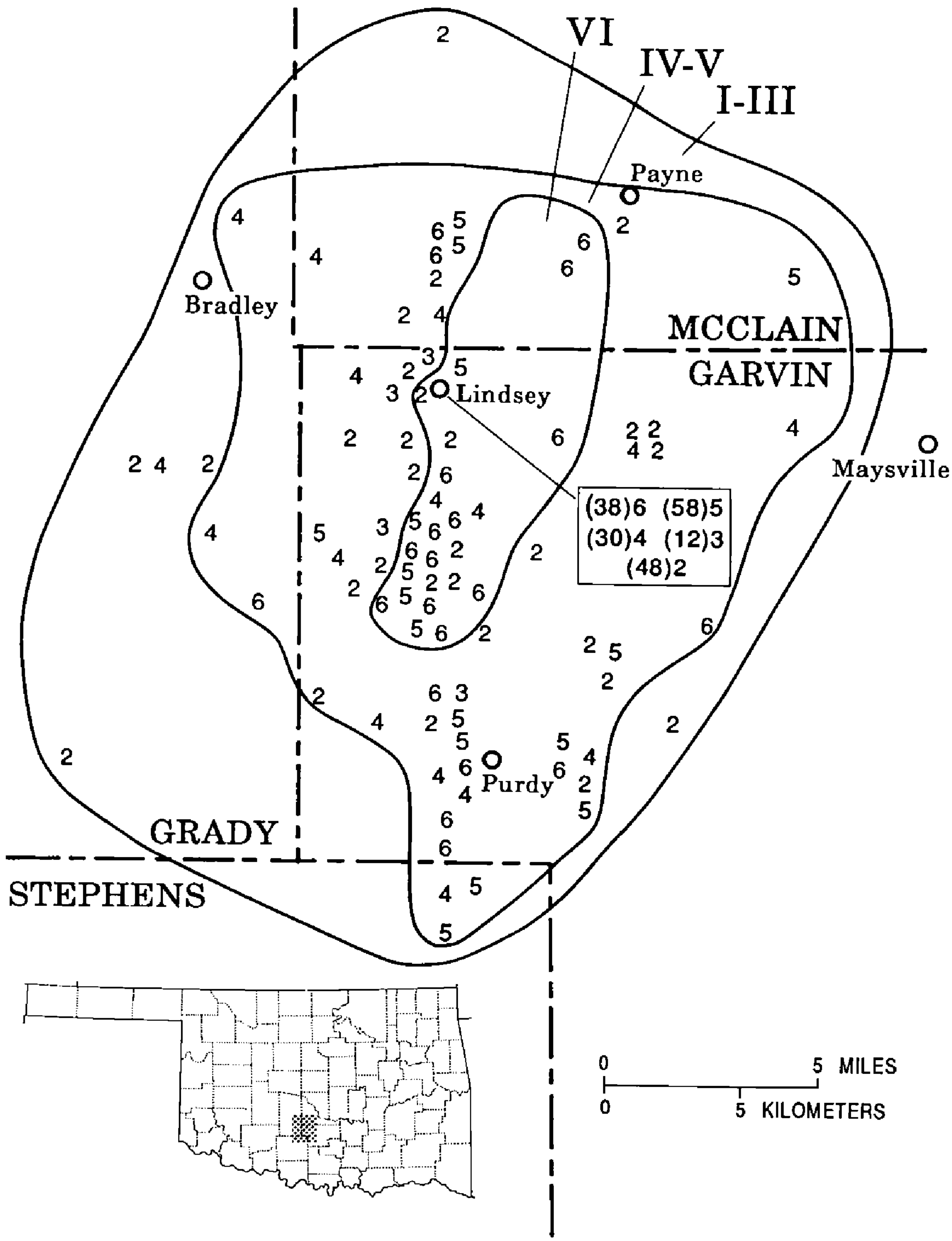

Figure 3. Modified Mercalli intensity values for the November 15 Lindsay earthquake (see Table 4). Each value represents an individual felt report, and the felt area was ~856 km².

seismograph records. There are several different scales used to report magnitude. Table 2 has three magnitude scales, which are mbLg (Nuttli), m3Hz (Nuttli), and MDUR (Lawson). Each magnitude scale was established to accommodate specific criteria, such as the distance from the epicenter, as well as the availability of certain seismic data.

For earthquake epicenters located 11 km to 222 km from a seismograph station, Otto Nuttli developed the m3Hz magnitude scale (Zollweg, 1974). This magnitude is derived from the following expression:

$$m3Hz = \log(A/T) - 1.63 + 0.87 \log(\Delta),$$

where A is the maximum center-to-peak vertical-ground-motion amplitude sustained for three or more cycles of Sg waves, near 3 Hz in frequency, measured in nanometers; T is the period of the Sg waves measured in seconds; and Δ is the great-circle distance from epicenter to station measured in kilometers.

In 1979, St. Louis University (Stauder and others, 1979) modified the formulas for m3Hz. This modification was used by the OGS Observatory beginning January 1, 1982. The modified formulas had the advantage of extending the distance range for measurement of m3Hz out to 400 km, but also had the disadvantage of increasing m3Hz by about 0.12 units compared to the previous formula. Their formulas were given in terms of log(A) but were restricted to wave periods of 0.2 sec to 0.5 sec. In order to use log(A/T), we assumed a period of 0.35 sec in converting the formulas for our use. The resulting equations are:

(epicenter 10–100 km from a seismograph)

$$m3Hz = \log(A/T) - 1.46 + 0.88 \log(\Delta)$$

(epicenter 100–200 km from a seismograph)

$$m3Hz = \log(A/T) - 1.82 + 1.06 \log(\Delta)$$

(epicenter 200–400 km from a seismograph)

$$m3Hz = \log(A/T) - 2.35 + 1.29 \log(\Delta).$$

Otto Nuttli's (1973) earthquake magnitude, mbLg, for seismograph stations located between 55.6 km and 445 km from the epicenter, is derived from the following equation:

$$mbLg = \log(A/T) - 1.09 + 0.90 \log(\Delta).$$

Where seismograph stations are located between 445 km and 3,360 km from the epicenter, mbLg is defined as:

$$mbLg = \log(A/T) - 3.10 + 1.66 \log(\Delta),$$

where A is the maximum center-to-peak vertical-ground-motion amplitude sustained for three or more cycles of Sg waves, near 1 Hz in frequency, measured in nanometers; T is the period of Sg waves measured in seconds; and Δ is the great-circle distance from epicenter to station measured in kilometers.

The MDUR magnitude scale was developed by Lawson (1978) for earthquakes in Oklahoma and adjacent areas. It is defined as:

$$MDUR = 1.86 \log(DUR) - 1.49,$$

where DUR is the duration or difference, in seconds, between the Pg-wave arrival time and the time the final coda amplitude decreases to twice the background-noise amplitude. Before 1981, if the Pn wave was the first arrival, the interval between the earthquake-origin time and the decrease of the coda to twice the background-noise amplitude was measured instead. Beginning January 1, 1982, the interval from the beginning of the P wave (whether it was Pg, P*, or Pn) to the decrease of the coda to twice the background-noise amplitude was used.

The depth to the earthquake hypocenter is measured in kilometers. For most Oklahoma earthquakes the focal depth is unknown. In almost all Oklahoma events, the stations are several times farther from the epicenter than the likely depth of the event. This makes the locations indeterminate at depth, which usually requires that the hypocenter depth be restrained to an arbitrary 5 km for purposes of computing latitude, longitude, and origin time. All available evidence indicates that no Oklahoma hypocenters have been deeper than 15 to 20 km.

Earthquake detection and location accuracy have been greatly improved since the installation of the statewide network of seismograph stations. The frequency of earthquake events and the possible correlation of earthquakes to specific tectonic elements in Oklahoma are being studied. It is hoped that this information will provide a more complete data base that can be used to develop numerical estimates of earthquake risk, giving the approximate frequency of the earthquakes of any given size for various regions of Oklahoma. Numerical risk estimates could be used for better design of large-scale structures, such as dams, high-rise buildings, and power plants, as well as to provide the necessary information to evaluate insurance rates.

Acknowledgments

Shirley Jackson, Ruth King, and Rick Watkins maintained the OGS Observatory at Leonard. Ruth King coded letters from persons who experienced the November 15 Lindsay earthquake for MM intensity and, with Shirley Jackson, mapped the intensity. Volunteer seismograph-station operators and landowners at various locations in Oklahoma make possible the operation of a statewide seismic network.

This work was funded directly by the Oklahoma Geological Survey, with partial funding by the Nuclear Regulatory Commission. In the fourth quarter of 1990, the GSE digital seismic system, provided by the Defense Advanced Research Projects Agency/Nuclear Monitoring Research Office, particularly enhanced the OGS's ability to analyze Oklahoma earthquakes. In the first quarter of 1991, a borehole seismic system, a joint project with the Lawrence Livermore National Laboratories, was useful in recording Oklahoma earthquakes. The Observatory exists because of building and land-purchase gifts from Jersey Production Research Co. (now merged into Exxon) and the Sarkeys Foundation.

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NEW OGS PUBLICATIONS

Geologic Maps of the Leflore, Talihina, and Blackjack Ridge Quadrangles, Latimer and Le Flore Counties.
Scale 1:24,000. Ozalid copies. Price: $6 each, rolled in tube.

The Ouachita COGEOMAP Project is a joint effort of the U.S. Geological Survey, Oklahoma Geological Survey, and Arkansas Geological Commission to prepare a series of new geologic maps of the Ouachita Mountains in Oklahoma and Arkansas. The project includes review and compilation of existing information and maps on the Ouachita Mountains, and new geologic mapping at a scale of 1:24,000 (7.5′ topographic base). The purpose of the mapping is threefold: The new maps should provide a basis for (1) resource exploration and development, (2) land-use planning such as highway construction, and (3) university field trips and future theses.

Based on existing geologic maps and resource interest and potential, the Oklahoma Geological Survey elected to focus its mapping effort on a west-to-east strip of 7.5′ quadrangles starting immediately southeast of Hartshorne, Oklahoma, and ending at the Arkansas state line. The mapping effort was designed to begin where the geologic map by Hendricks and others (1947) ended, and to include all the area within the quadrangles south of the Choctaw fault. Later, it was decided to map those parts of the Arkoma basin affected by Ouachita tectonics and included in quadrangles that contain the Choctaw fault. Mapping began in 1986 and is continuing. The first three maps (Higgins, Damon, and Baker Mountain) were released in 1989. The Panola, Wilburton, and Red Oak Quadrangles were released in 1990. The Leflore Quadrangle (by LeRoy A. Hemish), Talihina Quadrangle (by Neil H. Suneson and Charles A. Ferguson), and Blackjack Ridge Quadrangle (by Neil H. Suneson) are now available as black-and-white, author-prepared ozalids, comprising geologic map, cross sections, description and correlation of units, and a list of wells.

COGEOMAP geologic quadrangle maps of the Ouachita Mountains can be purchased over the counter or by mail from the Survey at 100 E. Boyd, Room N-131, Norman, OK 73019; phone (405) 325-3031. For mail orders of 1–10 maps, add $1.50 to the cost for postage and handling.

Great Unconformity—*continued from p. 34*

The provenance of the coarse conglomerate is the nearby ridge area where Pennsylvanian sandstones are exposed in the flanks of the Cavanal syncline adjacent to Coal Creek. The nearness of the source area is indicated by the size of the clasts (up to boulder size), and the angularity of the blocks of sandstone (inset photo, p. 34). Deposition of the alluvium along Coal Creek probably occurred in the last few thousand years, creating an unusual geologic setting in which the older Pennsylvanian rocks exposed along the flanks of the Cavanal syncline have been reworked and these clasts now rest upon younger, uneroded Pennsylvanian shales.

LeRoy A. Hemish

REVIEW: Appalachian–Ouachita Orogen

Neil H. Suneson[1]

Any attempt to review as monumental a work as any one of the Geological Society of America's recent DNAG (Decade of North American Geology) volumes would be incomplete without the reviewer describing his or her background and interest in that volume. I was initially asked to review volume F-2, *The Appalachian–Ouachita Orogen in the United States.* I declined, explaining that I knew nothing at all about Appalachian geology and little about Ouachita geology outside of Oklahoma. However, persistence in the form of second and third requests paid off, and I agreed to review those parts of volume F-2 that deal with the Ouachita tectonic belt, exclusive of the Marathon Mountains. I intended to focus on those aspects of Ouachita geology that have a direct bearing on what we see in Oklahoma.

My work in the Ouachita Mountains of Oklahoma is limited and has focused on detailed surface geologic mapping in the eastern frontal belt between the Choctaw and Windingstair faults. The strata in this area are entirely Carboniferous and consist predominantly of deep-water turbidites. To date, the Oklahoma Geological Survey has released nine 1:24,000 geologic maps as part of the COGEOMAP (Cooperative Geologic Mapping) program, a project jointly funded by the Oklahoma Geological Survey, the Arkansas Geological Commission, and the U.S. Geological Survey. In addition, I have reviewed the history of hydrocarbon exploration and development in the Ouachita Mountains and in the immediately adjacent Arkoma basin. In the truest sense of the word, I consider myself a "student" of Ouachita geology.

The Ouachita orogenic belt is discussed in chapters 15–30 of GSA's DNAG volume F-2, *The Appalachian–Ouachita Orogen in the United States.* In addition, volume A, *The Geology of North America—An Overview*, includes "The Ouachita System" by Kaspar Arbenz (chapter 14). This chapter is essential reading for anyone attempting to review or anyone not having the time to read the Ouachita chapters in F-2. It is the best introduction to Ouachita geology available. In volume F-2, chapters 20 and 24 discuss the orogenic belt in the Marathon Mountains, Texas, and will not be reviewed here. Almost every aspect of Ouachita geology is discussed in the remaining chapters: the subsurface connection to the Appalachians and in Texas, the stratigraphy and sedimentology of the pre-orogenic (Cambrian to early Mississippian) and orogenic (early Mississippian to early Pennsylvanian) strata, the structure of the fold and thrust belt and the highly deformed early and middle Paleozoic strata in the Broken Bow and Benton uplift anticlinoriums, the foreland and transverse basins north and west of the orogenic belt, geophysics, mineral deposits, and hydrocarbons. Little is said, however, about post-orogenic sedimentation (i.e., Where are the mountains now?).

[1]Oklahoma Geological Survey.

While volume F-2 appears to contain the most current compilation of geologic work on the Ouachita Mountains, a cursory examination of the different chapters indicates that although the volume was published in 1989, seven of the 14 chapters were accepted in 1985 or 1986. Evidently, this publication delay forced three authors to add notes at the end of their chapters. Most geological thought moves slowly and a four-year publication delay may not seem like a long time; however, the hydrocarbon exploration boom (1987 to present) in the frontal belt of the Oklahoma Ouachita Mountains and Arkoma basin has forced many geologists to reevaluate the structural geology of this area. This new information could have been, but is not, reflected in volume F-2. In addition, a glance at the authors of the different chapters might lead one to suspect that the Ouachita Mountains are in Missouri. The University of Missouri, Columbia, has clearly done much outstanding work in the Ouachita Mountains; however, six out of 14 chapters authored or co-authored by Columbia seems excessive. Conspicuous (to this reviewer) omissions in the list of authors are Charles Stone and Boyd Haley (Arkansas Geological Commission) who have studied all aspects of Ouachita geology in Arkansas; Patrick Sutherland (University of Oklahoma) who has studied Arkoma basin stratigraphy in Oklahoma; Robert Fay (Oklahoma Geological Survey) who has studied all aspects of Ouachita geology in Oklahoma; and Dave Houseknecht (University of Missouri, Columbia) who has studied Arkoma basin sedimentology and thermal maturation in Oklahoma and Arkansas.

Chapter 15 by Bill Thomas (University of Alabama) is entitled "The Appalachian–Ouachita orogen beneath the Gulf Coastal Plain between the outcrops in the Appalachians and Ouachita Mountains." As he readily admits, his chapter was modified from a paper he published in 1985. Most of the chapter is devoted to a discussion of the Black Warrior basin, a foreland basin similar in some respects to the Arkoma basin, separating the craton from the Appalachian and Ouachita orogenic belts. Less discussion is reserved for the buried Ouachitas and Appalachians, and even less for the buried Arkoma basin in east-central Arkansas. One sentence describes the Ouachita–Appalachian connection: ". . . northwest-trending Ouachita thrust faults are overridden by east-trending Appalachian thrust faults . . ." (p. 550). Similarly, one sentence describes an alternative tectonic evolution to Thomas's model of a Late Precambrian to Middle Cambrian rifted continental margin offset by transform faults: "An alternative interpretation attributes the shape of the margin to triple junctions at which failed arms are represented by the Southern Oklahoma aulacogen . . . and the Mississippi Valley (Reelfoot) graben . . ." (p. 547). In summary, chapter 15 is an excellent review of the geology of the Black Warrior basin and one model of early Paleozoic tectonics. Thomas's reference list is current, but perhaps biased—22% of the papers cited are authored or co-authored by him or his students.

Plates 6 and 9, compiled by Thomas, depict well the current state of knowledge about the subsurface Ouachitas from Mississippi to west Texas. The idea of printing map information on both sides of the sheet (plate 6) is extremely clever. Plate 11 (by different authors) contains many of the cross sections located on plate 9; the difference in scale between the map and sections makes interpretation difficult. At the very least, C–C′, D–D′, and E–E′ should have been located on plate 8, discussed below.

George Viele's (University of Missouri, Columbia) short chapter 16 entitled "The Ouachita orogenic belt" is an excellent introduction to the remaining chapters on Ouachita geology and on the history of geological investigations in the mountains and in the subsurface. This chapter, plus Viele's epilogue (chapter 30), should preface any reading of the Ouachita part of volume F-2.

Current research on the biostratigraphy of Ouachita strata is excellently reviewed in the paper by Ray Ethington (University of Missouri, Columbia), Stan Finney (Cal State, Long Beach), and John Repetski (U.S. Geological Survey), entitled "Biostratigraphy of the Paleozoic rocks of the Ouachita orogen, Arkansas, Oklahoma, west Texas" (chapter 17). Anyone reading the other chapters in F-2 should photocopy the correlation chart (fig. 1) and refer to it regularly. The authors correctly point out the difficulty in dating the synorogenic strata in the Ouachita Mountains; fossils are exceedingly rare because of the tremendous amount of terrigenous detritus in the sediments and the only successful method for dating certain formations has been determining the minimum age of olistoliths contained within them. An interesting addition, apparently in haste, was their addition of a Collier "tail" onto the bottom of the correlation chart.

Don Lowe (presently at Stanford University, formerly at Louisiana State) abruptly changes the tone with a controversial paper on the "Stratigraphy, sedimentology, and depositional setting of pre-orogenic rocks of the Ouachita Mountains, Arkansas and Oklahoma" (chapter 18). His thesis is that much of the early and middle Paleozoic strata (Collier, Crystal Mountain, Mazarn, Blakely, Womble, Bigfork at Black Knob Ridge, Blaylock, and Missouri Mountain) was deposited by sediment gravity flows and turbidity currents. Equally, if not more controversial is his proposal that the lower and upper members of the Arkansas Novaculite were deposited under shallow-marine, possibly subaerial conditons. Based on sandstone petrography, paleocurrent indicators, and facies changes, Lowe proposes that a long-lived (late Cambrian through early Mississippian), E–W-trending basin alternately received sediment from a southern sedimentary and metamorphic source terrane and from a northern cratonic source terrane. He suggests this basin is part of a Cambrian failed rift system (in contrast to the transform model of Thomas, described earlier).

To his credit, Lowe has looked at the rocks; but this paper falls short in its attempt to convince this reviewer that the supposed Cambrian to Mississippian basin ever existed, which is unfortunate, because his tectonic model (fig. 8B) is appealing. Lowe's outcrop and location map (fig. 2) indicates that only one locality in the Broken Bow uplift was examined, and none in either the Potato Hills or Black Knob Ridge; any attempt to describe pre-orogenic tectonics must include these areas. His figure 5 includes paleocurrent data from the Stanley Group, which is part of the orogenic sequence; adding these data makes his proposed basin look more real than it should be. In addition, Lowe's basin maintained a persistent geometry and remained remarkably narrow (120 miles according to his fig. 8A) for 150 million years. This problem is related to our inability to restore the present Ouachitas to their pre-deformed state; exactly what was the size of the original basin? If this were not enough, Lowe's insistence on verbing nouns ("structuring," "positioning") is a distraction.

Robert Morris (University of Arkansas) worked in the Ouachita Mountains for many years and, with help from his wife, Ellen Mullen-Morris, following his death in 1985, wrote an excellent summary of the Carboniferous strata (chapter 19, "Stratigraphy and sedimentary history of post-Arkansas Novaculite Carboniferous rocks of the Ouachita Mountains"). He reviews and compares the petrography of the orogenic sediments and correctly points out the difficulty in identifying the Johns Valley Formation where it does not contain olistoliths. (My experience in the frontal belt in Oklahoma suggests that perhaps 10% of the Johns Valley is olistostromal; the remainder is very similar to the Atoka.) Morris devotes a paragraph to the popular idea that at least part of the Carboniferous section represents an accretionary wedge, but comments that such "hallmarks" of convergent margins as volcanic detritus, high-pressure metamorphic rocks, and ophiolites are sparse or absent. Morris states (and I heartily agree) that ". . . the disrupted bedding of the Ouachita trough is . . . primarily a product of soft-sediment deformation or submarine mass wasting, . . . rather than solely the result of offscraping or other tectonic process" (p. 600). Unfortunately, Morris's paper suffers from several typographical and/or editing mistakes: locations of measured sections on figure 1 are impossible to decipher; spelling and labeling errors on figure 6 (does F really represent sedimentary rock fragments, or feldspar?); and spelling and labeling errors on table 2 (D2 and D1 are missing less than and greater than symbols).

Chapter 21, entitled "Ouachita thrust belt and Arkoma basin," by Kaspar Arbenz (consultant, Denver), is the best paper on Ouachita geology in volume F-2. Similarly, plate 8, compiled by Arbenz, is the best geologic–structural map of the entire exposed part of the tectonic belt available. Arbenz first presents an historical perspective that reviews the controversies over the origin of the Johns Valley Formation and the overall structural style of the Ouachitas. Most of the paper focuses on current research; perhaps most interesting is Arbenz's speculation that the merging of the thrust faults in the frontal belt from northeast to southwest near the town of Atoka was caused by late Pennsylvanian uplift of the southeastern extension of the Arbuckle Mountains. Arbenz's multi-storied structural division of the Ouachita strata into four "packages" based on ductility differences is a clever attempt to explain the differences in fold and fault geometries observed at the surface. He states that ". . . the frontal thrust belts of the Appalachian and Cordillera are composed of a typical miogeoclinal sequence of carbonate platform rocks at the base overlain by more ductile foredeep packages, while the Ouachita sequence is dominated at its base by an overall ductile sequence of deep-water shales, limestones, sandstone, and cherts topped by very massive competent turbidite fan complexes, having thus a basically inverted ductility spectrum" (p. 630). This statement is clearly an oversimplification because the youngest orogenic sequence, the Atoka Formation, is mostly shale and most likely extremely incompetent. Arbenz asserts that we cannot yet palinspastically restore the thrust sheets to their original positions; this should be kept in mind when looking at cross sections through any part of the Ouachita Mountains.

I am neither a structural geologist nor a metamorphic petrologist; therefore, chapter 22, "Structural setting of the Benton–Broken Bow uplifts," by Kent Nielson (University of Texas at Dallas), George Viele (Missouri, Columbia), and Jay Zimmerman (Southern Illinois), is very difficult for me to review. In addition, the uplifts are the sites of some extremely complex geology. The uplifts are separated into 14 different tectonic subdivisions and the detailed structural fabric of each is described. Black Knob Ridge and the Potato Hills, two relatively small but critical areas of early and middle Paleozoic rocks, are not discussed. The descriptions of the polyphase histories of the Cross Mountain and Carter Mountain anticlinoria are particularly relevant to Oklahoma geology. The discussion of the Hochatown Dome suffers from an inadequate figure 16; neither the Dyer Mountain fault nor the proposed low-angle detachment are shown on the map of the dome. Nielson, Viele, and Zimmerman present an excellent summary of regional metamorphism in the Ouachitas and recognize the role of ". . . a combination of burial under increasing sedimentary load, burial beneath imbricate thrust sheets, and, probably, movement of fluids . . ." (p. 655). Like the detailed descriptions of structural fabrics, the proposed tectonic history is difficult for me to evaluate; two observations seem particularly noteworthy, however. One is that the uplifts ". . . record multiple periods of deformation that probably represent a tectonic continuum rather than a series of events separated in time . . ." (p. 657). The other is that ". . . the relationship of the thrust faults of the Benton uplift to those of the frontal thrust belt is not clear . . ." (p. 657). A major point of disagreement with this reviewer is their claim that the strata represent an accretionary prism, particularly one that extends into Le Flore County, Oklahoma, where I have mapped.

Chapter 22 contains a good list of references to the geology of the Benton and Broken Bow uplifts. Unfortunately, the list is heavily weighted with papers by the authors and their students (29%) and abstracts (23%).

Most of the Ouachita tectonic belt is buried beneath Mesozoic and Cenozoic strata of the Gulf Coastal Plain. Chapter 23 by Richard Nicholas (Shell Oil) and Dwight Waddell (Pecten Syria Petroleum) is a welcome update on this part of the mountain range. "The Ouachita system in the subsurface of Texas, Arkansas, and Louisiana" is largely based on well data in the north-central gulf basin. Despite the many problems with correlating stratigraphy and structure between distantly spaced wells, Nicholas and Waddell make some interesting and critical observations: (1) Foreland carbonates extend beneath low-grade metamorphic rocks similar to those in the Benton and Broken Bow uplifts at least as far south as the Waco uplift. (2) The Devils River uplift is similar in geometry and origin to the Waco, Broken Bow, and Benton uplifts. (3) Early Carboniferous volcanic rocks occur in two wells in the Sabine uplift area; these may represent the source terrane (arc system?) for the tuffs in the Stanley Group. (4) Gently tilted Desmoinesian and younger shallow-water marine strata unconformably overlie deformed Carboniferous flysch south of the Ouachita Mountains; these strata constrain the timing and location of Ouachita tectonism.

Tim Denison's (Mobil Oil) chapter 25 on "Foreland structure adjacent to the Ouachita foldbelt" would be better entitled "Transverse structure . . ." Denison's primary research in the past has been on the basement (Precambrian) rocks of the southern Midcontinent; as a result, little effort is expended describing the structural geology of the foreland basins of the Ouachita tectonic belt—the Black Warrior, Arkoma, Fort Worth, Kerr, and Val Verde basins. (Better descriptions of these are in the chapters by Thomas and Arbenz.) This is as surprising as it is disappointing considering the high level of recent hydrocarbon exploration in the Arkoma basin. Denison's conclusion regarding the relation of the Tishomingo–Belton anticline to the Ouachita thrusts differs slightly from that of Arbenz; he suggests that an eroded anticline was present in front of the advancing thrusts prior to their emplacement and that the anticline was reactivated after thrusting. This chapter recognizes that certain important distinctions should be made in any discussion of orogenesis and foreland basin formation: timing of (1) initiation of deformation, (2) folding and/or faulting, (3) cessation of deformation, and (4) uplift and erosion.

Chapter 26, "The Ouachita system; a geophysical overview," and plate 10, "Geophysical maps of the Ouachita region," by Randy Keller (University of Texas at El Paso), J. M. Kruger (now at Marathon Oil, Casper, formerly from UTEP), K. J. Smith (UTEP), and W. M. Voight (UTEP) illustrates El Paso's preeminence in Ouachita mega-geophysics. Unfortunately, this paper contains no new seismic reflection data or interpretations, even of the extensively shot Oklahoma part of the tectonic belt; this is unfortunate because seismic reflection is going to play a key role in determining thrust and fold geometry and palinspastic restoration. Keller and his colleagues correlate gravity maxima and magnetic highs with the early Paleozoic continental margin and the interior zone in the Texas subsurface; however, this had been demonstrated in previous papers by the same authors. They also note that the absense of a gravity anomaly associated with the Benton and Broken Bow uplifts suggests to them that the uplifts are allochthonous and "have traveled a significant distance to their present position" (p. 691). Geophysics may one day tell us what that "significant" means. Of the 43 papers cited by the authors, they have authored or coauthored 21%; in addition, eight unpublished student theses are cited.

Chapter 28 by Kevin Shelton (University of Missouri, Columbia) is entitled "Mineral deposits and resources of the Ouachita Mountains." (Chapter 27 on tectonic synthesis is reviewed below.) It is an excellent and thorough review of existing literature but contains few new or original ideas on the origin of the different types of deposits. Shelton's review of current thought on the relation between Ouachita tectonism and the Mississippi Valley-type Pb–Zn–Ba deposits is particularly welcome. The reference list is comprehensive, albeit somewhat dated; nearly 50% of the papers cited by Shelton were published before 1960.

Petroleum occurrences in the Ouachita Mountains are described in chapter 29 by Phil Chenoweth (consultant, Tulsa), "Hydrocarbons of the Ouachita trend." This chapter is the most obvious victim of the delay in publication of F-2; the manuscript was accepted by GSA in November 1985 and is clearly of "pre-Zipperer" vintage. (The Amoco 1 Zipperer, which had an initial potential of about 50 mcfgd, is generally credited with discovering the "unofficial" South Hartshorne gas field and starting the ongoing exploration activities in the surrounding areas.) If it had been written later (for example, chapter 27, discussed below, was accepted in May 1989), it would probably have been "post-Zipperer" and have contained much new information on the hydrocarbon resources of the Ouachitas. Chenoweth describes four types of hydrocarbons that occur in the Ouachita tectonic belt: solid hydrocarbons, asphalt-saturated rocks, oil (both shallow and deep), and dry gas. Chenoweth's discussion of the oil and gas occurrences contains many errors of omission and fact. He uses the apparent absence of oil fields between Isom Springs and McKay Creek to support his model relating oil in the Ouachitas to foreland facies strata in the southern Oklahoma aulacogen; he fails to distinguish between "absence of" and undiscovered or deep. Chenoweth's statement that the hydrocarbon-bearing areas in the Oklahoma Ouachitas are situated across the aulacogen is contradicted by his figures 1 and 2; in fact, most of the hydrocarbons in the Ouachitas are unrelated spatially to the buried aulacogen. There is no discussion of gas in the Arkoma basin, despite the clear relation of Arkoma basin accumulations to Ouachita tectonics. The source-rock analyses that Chenoweth uses are unpublished. In summary, unlike the review of mineral deposits in the Ouachitas, this review of hydrocarbons is, at best, incomplete, and at worst, inaccurate.

Chapter 27, "Tectonic synthesis of the Ouachita orogenic belt" by George Viele (Missouri, Columbia) and Bill Thomas (Alabama), should have been the final chapter of volume F-2. The paper can be separated into two parts: the first describes the tectonic history of the orogenic belt in terms of the Wilson cycle, and the second describes the different structural provinces. Viele and Thomas are careful to point out at the very beginning that their tectonic model differs from other models presented in preceeding chapters. Some of the questions they raise center on: (1) Are the similarities or differences more impressive when comparing the transverse structures, namely, the Mississippi Valley graben, South Oklahoma basin (aulacogen), and Tobosa basin? (2) What was the nature and role of the southern landmass that rifted away from the early and middle Paleozoic continental margin? (3) What was the source of the sediments that filled the synorogenic basins? (4) Are the Arkansas serpentinites olistoliths or obducted remnants of the seafloor? What is the significance of the volcanic component in the synorogenic sediments? (5) What is the relative role of syn- vs. post-sedimentation (soft-sediment vs. tectonic) deformation? Can any part of the sequence be considered part of an accretionary wedge? (6) What is the significance of the south-verging structures? In summary, chapter 27 is an excellent synthesis, if the reader can bear in mind that it is but one view and is willing to delve back into the preceeding chapters or the literature to seek out the alternative views.

The questions raised by Viele and Thomas in their tectonic synthesis are reiterated by Viele in the epilogue (chapter 30). Here, in a short, concise statement, the right questions are asked. In my opinion, Viele has laid out what work will have to be done in the future and has correctly admonished young geologists to look at the rocks, measure them, map them, and try to understand what they are telling us. Clearly, Viele has had fun in the Ouachitas, as have many geologists. And he is correct when he states that our understanding of an orogenic belt is never complete. This means, of course, that many more geologists will also have fun in the Ouachitas.

NOTES ON NEW PUBLICATIONS

Computerized Stratified Random Site-Selection Approaches for Design of a Ground-Water-Quality Sampling Network

In this USGS water-resources investigations report, Jonathon C. Scott first presents the theoretical discussion of various approaches for designing a ground-water-quality sampling network. The discussion is followed by a description of software that can be used for applying the approaches, including application of the software to a hypothetical study region. Statistical analysis of the approaches is described in an appendix. The 109-page report was produced as part of the pilot National Water-Quality Assessment Program.

Order WRI 90-4101 from: U.S. Geological Survey, Water Resources Division, 215 Dean A. McGee Ave., Room 621, Oklahoma City, OK 73102; phone (405) 231-4256. A limited number of copies are available free of charge.

Annual Yield and Selected Hydrologic Data for the Arkansas River Basin Compact, Arkansas–Oklahoma, 1989 Water Year

M. A. Moore, T. E. Lamb, and L. D. Hauth wrote this 35-page USGS open-file report.

Order OF 90-0131 from: U.S. Geological Survey, Books and Open-File Reports, Federal Center, Box 25425, Denver, CO 80225; phone (303) 236-7476. The price is $4 for microfiche and $6 for a paper copy; add 25% to the price for foreign shipment.

GEONAMES Data Base of Geologic Names of the United States through 1988; Oklahoma, Kansas, and Missouri

Compiled by G. W. Luttrell, M. L. Hubert, and C. R. Murdock, this USGS open-file report includes an 11-page text and one 5¼-inch DS/DD IBM-compatible diskette.

Order OF 90-0466-H from: U.S. Geological Survey, Books and Open-File Reports, Federal Center, Box 25425, Denver, CO 80225; phone (303) 236-7476. The price is $7.75; add 25% to the price for shipment outside North America.

GRI COMPARTMENT AND SEAL SYMPOSIUM TO BE HELD IN STILLWATER

The School of Geology at Oklahoma State University is sponsoring a "Symposium on Deep Basin Compartments and Seals," May 16–18, 1991, on the OSU campus in the Noble Research Center, Stillwater. The event will include an ice-breaker meeting on May 15 and a banquet May 16. A field trip on Saturday, May 18, will visit the Cement Oil Field project in southern Oklahoma where seal breeching by faulting has allowed hydrocarbon migration from Pennsylvanian pressure compartments into overlying Permian reservoirs and the surface.

The Gas Research Institute compartmentalization and seal research was initially proposed by Amoco. Basin compartmentalization is an important concept in the exploration and production of hydrocarbons in deep sedimentary basins. Compartmentalization can arise in a number of distinct ways through the interplay of sedimentological, mechanical, and chemical factors. The focus of this symposium will be case studies involving the Alberta, Anadarko, Gulf Coast, Michigan, and Powder River basins.

For more information contact: Conference Coordinator, School of Geology, Oklahoma State University, 105 NRC, Stillwater, OK 74078; (405) 744-6358.

UPCOMING MEETINGS

Artificial Intelligence in Petroleum Exploration and Production Meeting, May 15–17, 1991, College Station, Texas. Information: Technical Program Committee, Dept. of Petroleum Engineering, Texas A&M University, College Station, TX 77843; (409) 845-6950.

Geological Association of Canada—Mineralogical Association of Canada Annual Meeting held jointly with the Society of Economic Geologists, May 27–29, 1991, Toronto, Ontario. Information: J. J. Fawcett, Dept. of Geology, University of Toronto, 22 Russell St., Toronto, Ontario M5S 3B1, Canada; (416) 978-3027.

American Nuclear Society, Annual Meeting, June 2–6, 1991, Orlando, Florida. Information: Meetings Dept., ANS, 555 N. Kensington Ave., La Grange Park, IL 60525; (312) 352-6611.

Soil and Water Conservation Society, Annual Meeting, August 4–7, 1991, Lexington, Kentucky. Information: SWCS, 7515 Northeast Ankeny Rd., Ankeny, IA 50021; (515) 289-2331.

American Association of Petroleum Geologists, Mid-Continent Section, Annual Convention, September 22–24, 1991, Wichita, Kansas. Information: Convention Dept., AAPG, P.O. Box 979, Tulsa, OK 74101; (918) 584-2555.

Geological Society of America, Annual Meeting, October 21–24, 1991, San Diego, California. *Abstracts due July 3.* Information: Meetings Dept., GSA, P.O. Box 9140, Boulder, CO 80301; (303) 447-2020.

OKLAHOMA ABSTRACTS

The Oklahoma Geological Survey thanks the American Association of Petroleum Geologists, the Geological Society of America, and the authors for permission to reprint the following abstracts of interest to Oklahoma geologists.

Diapiric Origin of the Blytheville and Pascola Arches in the Reelfoot Rift, East-Central United States: Relation to New Madrid Seismicity

F. A. McKEOWN, U.S. Geological Survey, Federal Center, Denver, CO 80225; R. M. HAMILTON, U.S. Geological Survey, 922 National Center, Reston, VA 22092; S. F. DIEHL and E. E. GLICK, U.S. Geological Survey, Federal Center, Denver, CO 80225

Most of the earthquakes in the New Madrid seismic zone correlate spatially with the Blytheville arch and part of the Pascola arch, which are interpreted to be the same structure. Both arches may have formed by diapirism along the axis of the Reelfoot rift. Seismic, geophysical, and drill-hole data indicate that the rocks in the arches are highly deformed and fractured and have gross lithologic properties that make them weaker than rocks adjacent to the arches. The weaker rocks are inferred to fail seismically more readily than the stronger rocks adjacent to the arches.

Reprinted as published in *Geology,* v. 18, p. 1158, November 1990.

Paleomagnetism of the Cambrian Royer Dolomite and Pennsylvanian Collings Ranch Conglomerate, Southern Oklahoma: An Early Paleozoic Magnetization and Nonpervasive Remagnetization by Weathering

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The Cambrian Royer Dolomite in the Arbuckle Mountains, Oklahoma, contains an early Paleozoic magnetization and a nonpervasive, late Paleozoic remagnetization caused by meteoric fluids. The Royer was uplifted and underwent karst conditions, and eroded clasts were deposited in the Collings Ranch Conglomerate during the Pennsylvanian. An early Paleozoic, depositional or chemical remanent magnetization (Dec. = 109°, Inc. = 10°, tilt corrected) residing in magnetite is found in gray-brown, ferroan dolomite. A Pennsylvanian–Permian chemical remanent magnetization (CRM) residing in hematite (Dec. = 147°, Inc. = 4°, *in situ*) is associated with dedolomitized rocks in an alteration zone around and below the karst

features. Clasts of the Royer in the Pennsylvanian Collings Ranch Conglomerate, correlated with the parent rock by petrographic, isotopic, and rock magnetic methods, also contain two magnetizations. The clast centers contain a predepositional magnetization, whereas the clast margins contain a postdepositional CRM (Dec. = 152°, Inc. = 4°, *in situ*). Conglomerate tests using these magnetization components constrain the timing of remanence acquisition in the Royer Dolomite.

Field relations and the results of oxygen and carbon stable-isotope analyses indicate that the dedolomitization events were caused by near-surface, meteoric fluids that altered the Royer around the margin of the karst dissolution caves and the outer rims of Royer Dolomite clasts. Remagnetization was not pervasive, and an early Paleozoic magnetization is preserved in the dolomite below the zone affected by weathering.

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Hydrocarbons and Magnetizations in Sedimentary Rocks

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Hydrocarbons can have variable effects on the magnetic properties of sedimentary rocks. Understanding the nature of these effects has implications for dating hydrocarbon migration and magnetic prospecting. Previous work on hydrocarbon saturated calcite speleothems has established that hydrocarbons can create the chemical conditions that lead to precipitation of magnetite and acquisition of an associated chemical magnetization. The mechanism(s) of magnetite authigenesis, however, is unresolved. Geochemical studies of the speleothems provide some information on the nature of the relationship. For example, there is a positive correlation between the amount of extractable organic material and magnetic intensity, although there is no apparent correlation between percent asphaltenes and magnetic intensity. The level of biodegradation is variable, and samples with high magnetic intensities have, in general, lower apparent biodegradation levels than those with low magnetic intensities. These results suggest that biodegradation is not the only mechanism of magnetite precipitation.

Although hydrocarbons can cause an increase in magnetization due to precipitation of magnetic phases in some rocks, in red beds there is an overall decrease in magnetization due to dissolution of hematite. For example, hydrocarbon migration into the Schoolhouse Member of the Maroon Formation (Pennsylvanian) in northwestern Colorado and the Rush Springs Formation (Permian) in Oklahoma caused dissolution of diagenetic hematite, bleaching, and a reduction in magnetic intensity. Magnetite and pyrrhotite are present in hydrocarbon-bearing sandstone and in some well cemented samples there are stable magnetizations that may be related to hydrocarbon migration.

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Paleomagnetic Dating of Diagenesis by Basinal and Meteoric Fluids, Ordovician Carbonates, Arbuckle Mountains, Southern Oklahoma

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Late Paleozoic chemical magnetizations can be directly related to migration of basinal fluids and exposure to meteoric fluids in Ordovician carbonates in the Arbuckle Mountains. The Viola Formation contains a pervasive synfolding (Pennsylvanian) magnetization residing in magnetite, but, around some mineralized fractures and veins, there are alteration halos that contain a Late Permian chemical magnetization residing in hematite. The veins contain calcites and associated MVT minerals that formed from fluids which were radiogenic, relatively warm, and saline. These fluids caused the alteration and acquisition of the chemical magnetization. The origin of the synfolding magnetization is not well constrained and preliminary studies suggest it is not related to basinal fluids. Hematite Liesegang bands around calcite-filled fractures in dolomitic beds in the Kindblade Formation contain an apparent Early Permian chemical magnetization whereas unbanded rock contains a weak and unstable magnetization. Fluids, probably basinal in origin, which emanated from the fractures, caused the hematite banding and acquisition of the chemical magnetization. In contrast, field relations and geochemical studies indicate that the Royer Dolomite and clasts of the Royer in the Pennsylvanian Collings Ranch Conglomerate contain a Permian magnetization which was acquired as a result of exposure to meteoric fluids. Although all the chemical magnetizations in these carbonates are related to orogeny, they were caused by different fluids at apparently different times at several locations in the Arbuckle Mountains.

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New Exploration Frontier for Southwestern Oklahoma, Mountain View–Meers Valley Area

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A new frontier area for Arbuckle oil and gas exploration now beginning to attract serious attention lies between the frontal fault system located along the southwestern edge of the Anadarko basin and the Wichita–Amarillo uplift. Recent discovery of Arbuckle oil and gas at the 1-1 Susie Pi-Hoodle well located in R6N, T13W has forced many explorationists to take a new look at the area's prospectivity.

For several years Arbuckle gas has been produced by six wells in the Mayfield field located in R10N, T26W in Beckham County, Oklahoma. Discovered in 1971 by Helmerich and Payne's 1 Cupp well, the field also includes 17 Hunton producers. During the 1960s, Arbuckle production was discovered even farther northwest in Wheeler County, Texas, in the Laketon pool. Several wells were drilled on faulted domes with production from fractured Arbuckle, which had undergone leaching, resulting in high-porosity development at the unconformity level.

Interpolating between these several producing fields indicates that Arbuckle production may be located along a fairway 10–30 mi wide, which may extend for more than 250 mi across southwestern Oklahoma from Ardmore northwestward as far as Wheeler County, Texas.

Looking for Arbuckle production in this new area is made practical now that modern-vintage high-channel, high-fold seismic data can be processed to resolve the structural complexities of these mountain-front thrust zones. New regional seismic lines have been completed across the area for a distance of more than 20 mi. The southwestern part of the regional lines cross severely folded and overthrusted rocks of the original shelf or platform. This mountain-front complex is certainly within a structural framework for hydrocarbon exploration considerably more difficult to resolve than that found along the leading edge of the boundary fault zone of the Anadarko basin where most drilling to date has occurred.

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Sand Distribution, Facies Relationships, and Structural Styles of the Spiro Formation, Frontal Ouachita Mountains, Southeastern Oklahoma

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Ongoing gas exploration in the overthrusted portion of the Arkoma basin continues to demonstrate the excellent reservoir characteristics of the early Atokan Spiro Formation. This activity is providing valuable new data for a comprehensive surface-to-subsurface study.

The Spiro Formation represents a mixed carbonate and terrigenous clastic platform complex that consists of laterally interfingering sandstone, shale, and limestone. Quartz sand derived from reworking of the previously deposited fluviodeltaic Foster "channel sands" was transported southwestward across the shelf where it accumulated as marine shelf bars and associated interbar facies. Spiro carbonate facies that developed between areas of sand bar accumulation indicate sediment bypass.

Three sand bar tracts can be delineated within the Spiro based primarily on surface control. The easternmost tract is the most areally extensive, and it is characterized by sand thickness in excess of 150 ft. There, Spiro sandstones consist predominantly of bar crest and bar flank facies. To the west, sand bar tracts are smaller in areal extent, sand thickness is less, and sandstone units consist mostly of bar margin and interbar facies.

South of the present-day Pine Mountain fault, terrigenous clastic and spiculitic slope and basinal sediments accumulated, whereas east of the surface exposures (along the frontal zone), the Spiro grades into a shale facies.

Late Pennsylvanian thrust faulting produced a narrow belt of fault repeated sequences that crop out only in the frontal Ouachita Mountains. Differences in thrusting styles between the eastern and western parts of the outcrop belt reflect variations in lithologic character and probably in subthrust structure.

Palinspastic restoration of thrust sheets established a basis to extend paleodepositional trends and sand bar geometries from the surface into the subsurface.

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Stratigraphic Facies Relationships and Structural Trends of the Spiro Formation, Frontal Ouachita Mountains, Southeastern Oklahoma

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The lower Atokan Spiro Formation is a well-known gas reservoir in the Arkoma basin. The recent explosion in gas exploration from the Spiro is providing valuable new data for a comprehensive stratigraphic study of this formation.

The Spiro Formation consists of laterally interfingering sandstone, shale, and limestone that can be categorized into bar crest, bar flank, bar margin, and interbar facies. The stacked shallow-marine shelf bars were derived from reworking of upper Morrowan Foster channel sandstones. In the eastern part of the outcrop belt, the Spiro primarily is sandstone with a thickness of up to 150 ft that represents predominantly bar crest, bar flank, and bar margin facies. To the west, the Spiro thins to about 60 ft in thickness and consists mostly of limestone with lesser amounts of sandstone. In this area, the sandstones exhibit sedimentary characteristics of bar margin and interbar facies. South of the present-day Pine Mountain fault, slope and basinal sediments accumulated, whereas east of the outcrop belt (along the frontal zone) the Spiro grades into a shale facies.

Late Pennsylvanian thrust faulting produced a narrow belt of several fault repeated sequences, which crop out only in the frontal Ouachita Mountains. Differences in thrusting styles between the eastern and western parts of the outcrop belt reflect variations in lateral lithologic character and perhaps subthrust structure. Palinspastic restoration of thrust sheets establishes a basis to determine paleodepositional trends and geometries.

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Exceptional Marine Sand Bodies in the Paleozoic of Oklahoma

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Of the wide variety of sandstone reservoirs in Oklahoma, the most unusual types of sand bodies are present in the Atokan Spiro Sandstone, Devonian Misener Sandstone, and Morrowan lower Morrow Sandstone. The common factors of these sand bodies are that, upon correlation and mapping, these units are channel-like (fluvial-deltaic) in geometry, but from petrographic evidence they are quartz-rich shallow-marine units with the exclusion of intraclastic and diagenetic constituents.

Stratigraphic mapping of the Spiro Sandstone of the Arkoma basin indicates two types of sand bodies: channel and sheet. The marine channel-like deposits, 10–150 ft thick, probably were deposited on a paleosurface produced by a pre-Atokan unconformity. Examination of cores and outcrops indicate that both the channel and sheet Spiro sandstones contain shallow-marine fossils, limestones, peloidal chamosite, burrows, and bioturbation, all indicative of a shallow-marine setting.

The Misener Sandstone of north-central Oklahoma ranges from 10–100 ft thick with sharp boundaries. The sandstone deposited in pre-Frisco/Woodford eroded paleochannels. Core evidence for shallow-marine deposition is glauconite, phosphatic fossils and clasts, burrows, and bioturbation. These rocks probably were deposited in an embayed, estuary-like environment.

The lower Morrow Sandstone of the Anadarko basin is similar in geometry, except that the sand bodies are multistoried and multilateral and do not appear to be associated with a regional unconformity. The lower Morrow sandstones, usually 30–60 ft thick, commonly are elongated and deposited parallel to the shoreline. Deposition is inferred to be shallow marine from marine fossils and glauconite.

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Reference Sections and Sequence Stratigraphic Model: Albian to Turonian Strata of Northeast New Mexico and Oklahoma Panhandle

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Cretaceous strata in the Dalhart and Tucumcari basins span late Albian (Lytle Sandstone) to early Turonian (Greenhorn Formation), and include Kiowa–Skull Creek and Greenhorn cyclothems. Reference sections for this interval are presented and a preliminary sequence stratigraphic working model proposed to include the Lytle through Graneros. Tucumcari and Dalhart basins responded differently to Cretaceous relative sea-level changes, resulting in contrasting development of sequence stratigraphic units. Stratal relationships in the Dalhart basin correspond with those of southern Colorado, except that late Albian Mowry deposits did not extend into New Mexico. The basal Kiowa–Skull Creek lowstand/transgressive systems tract is marked by: (1) estuarine backfilling of channels cut into Cretaceous Lytle and/or Jurassic Morrison sandstones, (2) coastal ravinement, and (3) deposition of marine Glencairn and Tucumcari sandstones and shales. Distinction between transgressive and highstand systems tracts within the marine units is currently under study. Mesa Rica Sandstone fluvial channels incised the Dalhart basin to produce an unconformity correlative with the Muddy surface from Colorado to

Wyoming, but synchronously fed the late Albian (lowstand) Mesa Rica delta in the deeper Tucumcari basin. Backfield Mesa Rica estuaries and marine-submergent delta plain (lower Pajarito Formation) apparently recorded rising Mowry (earliest Greenhorn) base level. The overlying fluvial Pajarito best fits within a highstand systems tract presumably capped by a third (yet unrecognized) sequence boundary near the formation top. Romeroville (= marine Dakota) sandstones and Graneros shales sharply overlay the Pajarito define ravinement and onset of a new transgressive systems tract in both Tucumcari and Dalhart basins.

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Sequence Stratigraphic Interrelationship of Lower Cretaceous Dakota and Purgatoire Formations in Northeast New Mexico/ Southeast Colorado and Correlative Strata (Muddy, Skull Creek, Plainview) of the Denver Basin

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The Albian Glencairn Member (Purgatoire Formation) and underlying Dakota Sandstone of southeastern Colorado and northeastern New Mexico are related depositionally to the Tucumcari, Mesa Rica, and Pajarito formations of east-central New Mexico and to the Plainview, Skull Creek, and Muddy formations of central Colorado. Depositional interrelationships of these strata are best understood when placed in a sequence-stratigraphic framework.

The Plainview Formation, Long Canyon sandstone bed (basal Glencairn) and Campana sandstone bed (basal Tucumcari) overlie a correlative lowstand surface of erosion (LSE) and represent backfilling of valleys during Kiowa–Skull Creek transgression. These strata are separated from overlying marine transgressive shale deposits of the lower Skull Creek, Glencairn, or Tucumcari, respectively, by a correlative transgressive surface of erosion. Lowermost Muddy and upper Skull Creek deposits represent progradation of highstand deposits over a marine flooding surface (Weimer, 1989) and are correlative to upper Glencairn sandstones that are also representative of highstand deposition.

Fluvial incision during maximum Kiowa–Skull Creek regression is manifest as an LSE atop Skull Creek and Glencairn marine deposits. Southward-flowing streams debouched into the maximum regressive sea forming a lowstand wedge, the remnants of which are represented by the Mesa Rica, Pajarito, and uppermost Tucumcari formations. Stable base level conditions developed near the maximum regressive shoreline resulting in widening of paleovalleys and deposition of a fluvial lowstand sheet sandstone (basal Dakota sandstone member) in southeastern Colorado and northeastern New Mexico. Transgression followed lowstand deposition and resulted in backfilling of paleovalleys represented by portions of the Muddy and Dakota sandstones.

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Mega Compartment Complex in the Anadarko Basin: A Completely Sealed Overpressured Phenomenon

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Integrated pressure, potentiometric, and geologic data demonstrate the existence of a basin-wide, completely sealed overpressured compartment in the Anadarko basin. All reservoirs within this complex exhibit pressure gradients ranging from 0.6 to 0.98 psi/ft, which exceeds the normal gradient of 0.465 psi/ft. These reservoirs have produced large quantities of natural gas, particularly from the Pennsylvanian Red Fork and Morrowan sandstones.

This mega compartment complex is enclosed by top, bottom, and lateral seals. The top seal, which is located between 8,500 and 11,000 ft below the surface, is relatively horizontal, dips slightly to the southwest, and appears to cut across stratigraphy. However, the basal seal is stratigraphically controlled and seems to coincide with the Devonian Woodford Shale. The complex is laterally sealed to the south by the Wichita Mountain uplift frontal fault zone and by the convergence of the top and basal seals along the eastern, northern, and western boundaries.

Nested within this complex is a myriad of smaller compartments with their own distinct pressure gradients. In addition, local overpressured compartments are present outside the mega compartment complex in normal and near-normal pressured regions.

Significant gas fields producing from the Morrow and Red Fork horizons are considered nested compartments within the mega compartment complex. The Southwest Leedey field contains a stratigraphically and/or lithologically sealed Red Fork sandstone compartment. The Upper Morrowan chert conglomerate reservoirs in the Cheyenne field area comprise a compartment with a distinct lateral seal associated with the frontal fault zone of the Wichita Mountain uplift.

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Porosity Trends of Nonreservoir and Reservoir Sandstones, Anadarko Basin, Oklahoma

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The porosity of nonreservoir sandstones in Caddo County, Oklahoma, is determined using compensated-neutron and formation-density logs. Our preliminary data set represents more than 3,000 net ft of Pennsylvanian and Permian age sandstones from 12 well locations. These porosity data and the average porosities of sandstone oil and gas reservoirs within the Anadarko basin of Oklahoma are each compared to a broad, composite set of porosity data from numerous basins that represent sandstones in general, and they are also compared to each other.

The porosity of nonreservoir sandstones in Caddo County declines predictably as a power function of increasing thermal maturity for vitrinite reflectance (R_o) of 0.5 to 1.3%. The rate of porosity decrease with increasing thermal maturity is more rapid than that of the average porosity-R_o trend of the composite set, but is still within the porosity-R_o envelope of sandstones in general.

Hydrocarbon reservoir sandstones of the Anadarko basin, however, follow a different pattern. Their rate of porosity loss is much slower than that of both sandstones in general, and nonreservoir sandstones of Caddo County. This slow rate of porosity decline with increasing R_o could be due to inhibiting effects of early hydrocarbon emplacement on diagenesis and (or) to the bias of economic selection. In any case, as R_o increases beyond about 1%, the porosity of Anadarko basin reservoir sandstones is anomalously high compared to both nonreservoir Anadarko basin sandstones and sandstones in general.

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