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April 1997

On The Cover —

Alabaster Caverns State Park Staff Completes 20 Years of Seismic Recording

In 1977 the Oklahoma Geological Survey (OGS) installed a continuous recording seismograph station at Alabaster Caverns State Park, with cooperation of the director of state parks and the Alabaster Caverns State Park staff. The staff in 1977 included Sherry Beagley, Sue Mitchell, and park manager L. H. Shepherd. In 1980 Bill Robinson became park manager. In 1985 Charles Orefice was appointed manager. These three managers and their staff put considerable effort into providing continuous operation of the station.

The station operation continues under the direction of Sherry Beagley (standing, middle), park manager since 1990, and park supervisor Sue Mitchell (standing, right). Sherry and Sue have helped operate the seismograph station for nearly 20 years. Besides Sherry and Sue, three historical property site attendants, John Gay (not pictured), Mike Caywood (standing, left), and Kim Hughes (seated), take turns at clock setting and record changing. Because Sherry lives on the property, she is the person who changes the daily record and sets the clock each Christmas Day.

Among seismologists, the seismograph at Alabaster Caverns is referred to by its international abbreviation, ACO. Anywhere in the world, a computer used in earthquake location has an entry for ACO. The ACO computer entry gives the latitude, longitude, and elevation of the sensor, which is in a shallow tank near park headquarters. The recorder is on public display in a transparent case at park headquarters.

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OKLAHOMA GEOLOGICAL SURVEY

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OKLAHOMA GEOLOGY NOTES, ISSN 0030-1736, is published bimonthly by the Oklahoma Geological Survey. It contains short technical articles, mineral-industry and petroleum news and statistics, abstracts, notices of new publications, and announcements of general pertinence to Oklahoma geology. Single copies, $1.50; yearly subscription, $6. Send subscription orders to the Survey at 100 E. Boyd, Room N-131, Norman, OK 73019. Short articles on aspects of Oklahoma geology are welcome from contributors; general guidelines will be sent on request.

This publication, printed by the Oklahoma Geological Survey, Norman, Oklahoma, is issued by the Oklahoma Geological Survey as authorized by Title 70, Oklahoma Statutes 1981, Section 3310, and Title 74, Oklahoma Statutes 1981, Sections 231–238. 1,500 copies have been prepared for distribution at a cost of $960 to the taxpayers of the State of Oklahoma. Copies have been deposited with the Publications Clearinghouse of the Oklahoma Department of Libraries.

OKLAHOMA GEOLOGY

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VOL. 57, NO. 2
APRIL 1997

Oklahoma Earthquakes, 1996

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

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 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. Before Oklahoma became a state, the earliest

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.

documented earthquake occurred October 22, 1882, probably near Fort Gibson, Indian Territory, although it cannot be located precisely (Ross, 1882; Indian Pioneer Papers, date unknown). The *Cherokee Advocate* newspaper reported that at Fort Gibson "the trembling and vibrating were so severe as to cause doors and window shutters to open and shut, hogs in pens to fall and squeal, poultry to run and hide, the tops of weeds to dip, [and] cattle to lowe" (Ross, 1882, p. 1). These observations indicate MM-VIII intensity effects. The next documented earthquake in Oklahoma occurred near Jefferson, Grant County, on December 2, 1897 (Stover and others, 1981). The next known Oklahoma earthquake happened near Cushing, Payne County, 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 (with the possible exception of the 1882 earthquake) occurred near El Reno, Canadian County, on April 9, 1952. This magnitude-5.5 (mb, Gutenberg-Richter) 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 1897 through 1995, 1,297 earthquakes have been located in Oklahoma.

Instrumentation

A statewide network of 11 seismograph stations was used to locate 75 earthquakes in Oklahoma for 1996 (Fig. 1). The Oklahoma Geological Survey Observatory station, TUL, located near Leonard, Oklahoma, in southern Tulsa County, records 15 continuous seismic signals from sensors located at four stations. The data are recorded, analyzed, and archived on a GSE digital seismic system provided by the Defense Advanced Research Projects Agency/Nuclear Monitoring Research Office.

Signals are digitized by one Geotech RDAS (Remote Data Acquisition System) unit at either 3,600 or 1,200 24-bit samples per second. The RDAS then applies digital anti-alias filtering to eliminate frequencies too high for the final sampling rate. After one to three digital filter and resampling stages, the RDAS produces 60, 40, 20, or 10 24-bit samples per second. The samples are time-tagged by RDAS clocks locked to low-frequency time signals from National Institute of Standards and Technology station WWVB. The signals are passed by RS422 serial links to an AST 386/25 RTDS (Real Time Data Server) computer, which has a Lynx™ real-time Unix-like operating system. The partially processed signals are passed by ethernet to a Sun Sparc 2+ Unix workstation with 64 megabytes of memory, two 660-megabyte disks, two 2.1-gigabyte disks, and two 2.5 gigabyte Exabyte™ tape drives. All of the data from the most recent two weeks are retained on disk. Each day, data from the preceding day (167 million bytes) are automatically archived onto Exabyte™ tape. All Oklahoma earthquakes, and other selected events, are placed in named de-archive directories on disk. An Oracle™ data base on the Sun Sparc 2+ keeps track of every second of data on the permanent archive tapes, the last 14 days' data on disk, and data in the de-archive directories. Data analysis is done by Teledyne-Geotech and Science Applications International Corp. software on the Sparc 2+ workstation.

The digital system signals are from three sensors in the Observatory vault (international station abbreviation TUL); from a three-component broadband sensor in a 120-m borehole; and from single sensors located at Rose Lookout (RLO) in Mayes County, at the Bald Hill Ranch near Vivian (VVO) in McIntosh County, and at the Jackson Ranch near Slick (SIO) in Creek County.

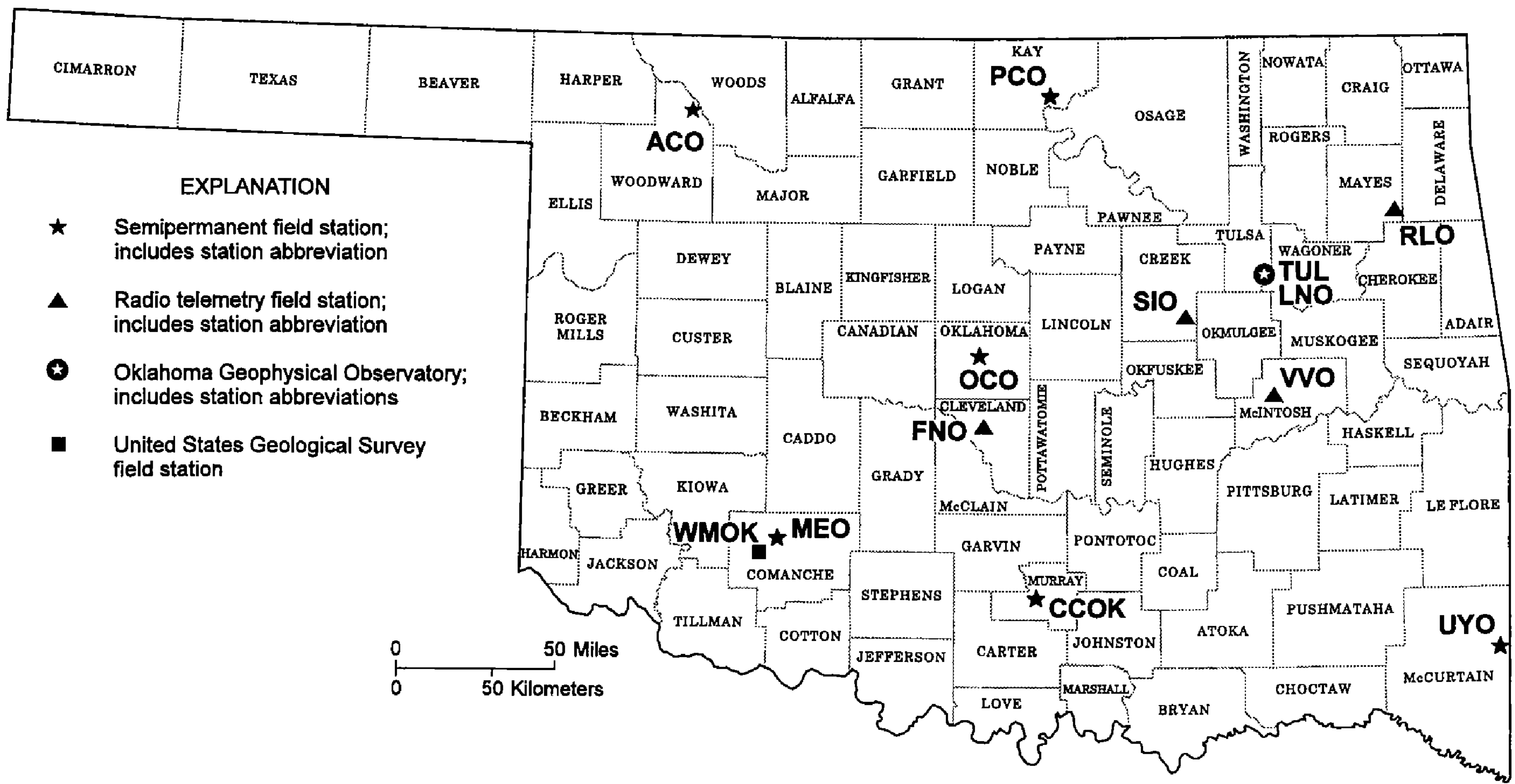

Figure 1. Active seismographs in Oklahoma.

TUL has three (vertical, north–south, east–west) Geotech GS-13 seismometers which produce 40-sample-per-second short-period signals. A three-component broadband Geotech KS54000-0103 seismometer in a 120-m-deep borehole produces seven digital data channels. Three are broadband signals from seismic signals in vertical, north–south, and east–west directions. From the broadband signals the Sparc 2+ workstation derives three long-period signals. A seventh signal, the vertical earth tides, is recorded from the vertical mass displacement signal from the KS54000-0103. The broadband signals are archived at 10 samples per second, and the long-period and vertical-earth-tide signals are recorded at one sample per second. On November 10, 1994, the broadband sample rate was increased from 10 samples per second to 20 samples per second. This increase was for two purposes. One was to allow the broadband borehole seismometer to record higher frequencies characteristic of Oklahoma earthquakes. The other was to make the signals compatible for the GSETT-3 (Group of Scientific Experts Technical Test-3), which began in 1995. GSETT-3 is a prototype international seismic-monitoring system to detect underground nuclear tests. Data segments will be copied automatically and sent to the International Data Center by Internet without affecting the recording and analysis of Oklahoma earthquakes.

How to Obtain the Oklahoma Earthquake Catalog and Maps Over the Internet

With a gopher client program, go directly to the top-level menu of the OGS gopher by typing:

gopher wealaka.okgeosurvey1.gov

From the top-level menu, select submenus, including "Oklahoma Earthquake Catalog" and "Oklahoma Earthquake Maps."

To go to the top-level menu with a Web browser (such as Xmosaic or Netscape), use this URL:

gopher://wealaka.okgeosurvey1.gov/

To go directly to the Oklahoma earthquake catalog or to Oklahoma PostScript earthquake maps, use one of these URLs:

gopher://wealaka.okgeosurvey1/11/okeqcat/
gopher://wealaka.okgeosurvey1/11/okmap/

Digital seismograms for about 90% of all Oklahoma earthquakes since late 1991 can be accessed on the OGS gopher. They are in U.S. Department of Defense (DOD) CSS3.0 format. They can be analyzed and displayed by the DOD public-domain geotool package. At present, geotool is available only in Sparc binaries. Some users have displayed these seismograms with simple XY-plotting software, although XY-plotting programs will not show time, date, or station labels. For information on the digital seismogram files or for information on obtaining seismograms use:

gopher://wealaka.okgeosurvey1.gov/11/waveforms/

and read all *READ*NOW* files.

An Internet gopher server running on a Sun Sparc SLC allows anyone on the Internet to copy digital data on disk, as well as several documents such as the Oklahoma Earthquake Catalog in one single list, or a series of two-year lists. The gopher can be contacted with "gopher [space] wealaka.okgeosurvey1.gov" or by WWW clients with "gopher://wealaka.okgeosurvey1.gov/" (see sidebar, this page). The broadband signals are seldom used in the study of Oklahoma earthquakes; the long-period signals are never used. The short-period signals are particularly useful in calculating the direction of arrival of waves by digital calculation of polarization.

RLO, VVO, and SIO have Geotech S-13 seismometers in shallow tank vaults. The seismic signals are amplified and used to frequency modulate an audio tone that is transmitted to Leonard with 500-mW FM transmitters at various frequencies in the 216–220-mHz band. The signals are received by antennas on a 40-m-high tower at

Leonard, the tones are discriminated to produce a voltage which is proportional to the remote seismometer voltage, and the voltages are digitized at 40 samples per second by the vault RDAS.

A fourth radio-telemetry station, FNO, was installed in central Oklahoma on April 28, 1992. The seismometer, Geotech S-13, is located on a concrete pad, ~7 km northeast of the Oklahoma Geological Survey's (OGS) building. A discriminator converts the audio-signal frequency fluctuations to a voltage output. The voltage-output is amplified and recorded by a Sprengnether MEQ-800 seismograph recorder (located in an OGS display case) at 60 mm/min trace speed.

In the Leonard vault, seven additional seismometers produce analog (wiggly-line) recordings on paper-drum recorders. Eleven such recordings are produced, five of which are the proper frequencies to record some aspect of nearby earthquakes. One paper recording is produced from each of RLO, VVO, and SIO. The paper records are used as a digital system backup, and to scan for earthquakes faster than is possible on computer screens.

In addition to the digital and analog seismograms recorded at the OGS Observatory and main office, seismograms are recorded by five volunteer-operated seismographs. Each consists of a Geotech S-13 short-period vertical-motion-sensing seismometer in a shallow tank vault, or in an abandoned mine shaft (station MEO) or large-diameter, hand-dug, shallow water well (station UYO). A new station, CCOK, opened on August 10, 1994, at Camp Classen (YMCA Camp) in Murray County. This station is operated by Jim Parry and his staff. (Red Rock Canyon station, RRO, has been closed.) The seismometer signal runs through 200–1,800 ft of cable in surface PVC conduit to the volunteer's house or other building. The volunteer has a Sprengnether MEQ-800B timing system amplifier-filter-drum recorder, which records 24 hours of seismic trace at 1 mm/min in a spiral path around the paper on the drum. The times are set by a time signal radio receiver tuned to the National Institute of Standards and Technology and high-frequency radio station WWV. The volunteers mail in the seismograms weekly (or more often, if requested). When an earthquake is felt in Oklahoma, the volunteer operators fax seismogram copies to the Observatory so that the earthquake can be located rapidly.

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.

The U.S. Geological Survey established a seismograph station 19 km from the OGS station at MEO at Meers. WMOK, the USGS station, does not record continuously. When triggered by moderately strong ground motion it transmits a short segment of data to the National Earthquake Information Service in Golden, Colorado. WMOK is used mostly for distant earthquakes, although it sometimes records some of the larger Oklahoma earthquakes. Because WMOK is so near MEO, its arrival times do not improve the accuracy of location of Oklahoma earthquakes.

Data Reduction and Archiving

Paper-recorded seismograms from short-period vertical records (SPZ) from TUL, RLO, VVO, and SIO, as well as short-period north–south (SPN), and short-period east–west (SPE) from TUL, are scanned initially for Oklahoma earthquakes. At this stage, >95% of Oklahoma earthquakes are seen.

When an Oklahoma earthquake is found on paper records, the digital system is used to analyze the SPZ, SPN, and SPE digital records from TUL, and the SPZ digital records from RLO, VVO, and SIO. This gives a preliminary location that is immediately posted on the earthquake catalog on the OGS gopher. This initial posting usually takes place within 24 hours of the earthquake's occurrence.

All digital traces are examined later in a systematic way for mainly distant earthquakes. At this stage, Oklahoma earthquakes are seen again, but few new Oklahoma earthquakes are spotted.

Near the beginning of each month, all paper records for the previous month from all stations in Oklahoma are examined. An occasional additional Oklahoma earthquake is found. All readings from the digital and paper records are then used to determine a final location. These final locations then replace the preliminary locations in the gopher catalog.

Earthquake Distribution

All Oklahoma earthquakes recorded on seismograms from three or more stations are located. In 1996, 75 Oklahoma earthquakes were located (Fig. 2; Table 2). One earthquakes was reported felt (Table 3). The felt and observed effects of earthquakes generally are 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 only Oklahoma earthquake reported felt in 1996 was a magnitude 2.2 (MDUR) earthquake that occurred on December 19 in western McClain County. The earthquake was felt mostly in Blanchard, Oklahoma. Very minor damage resulted from this earthquake.

Earthquake-magnitude values ranged from a low of 0.7 (MDUR) in McIntosh County to a high of 2.6 (m3Hz) in Kingfisher County. Sixteen earthquakes were located in Grady County in 1996. More than half (9) of these earthquakes occurred between June 29 and July 9. Six earthquakes were located in Pontotoc County; five earthquakes were located in McClain County; Garvin and Johnston Counties experienced four earthquakes.

Catalog

A desktop computer system, including linked HP-9825T and HP-9835A 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. This catalog is maintained in addition to the gopher catalog of earthquakes only in Oklahoma. Table 2 contains 1996 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 by Lawson and Luza (1980–90, 1993–96), Lawson and others (1991,1992), and for the *Earthquake Map of Oklahoma* (Lawson and Luza, 1995b).

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.

TABLE 2. — OKLAHOMA EARTHQUAKE CATALOG FOR 1996

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]
1298	JAN 09	22 05 51.14	Atoka		2.1	2.1	1.6	34.200	96.234	5.0R
1299	JAN 10	05 39 20.80	Hughes		2.1	2.0		35.005	96.411	5.0R
1300	JAN 12	04 24 36.26	McClain		1.5		1.6	34.856	97.441	5.0R
1301	JAN 16	12 43 38.18	Garvin		1.4		1.5	34.817	97.433	5.0R
1302	JAN 23	05 24 42.86	Haskell		1.2		1.2	35.270	95.343	5.0R
1303	JAN 31	08 03 55.95	McIntosh		0.8		1.5	35.306	95.894	5.0R
1304	FEB 01	16 03 24.74	Johnston				1.5	34.380	96.480	5.0R
1305	FEB 01	22 56 46.96	Johnston		1.6		1.6	34.403	96.671	5.0R
1306	FEB 04	22 21 47.59	Pawnee		1.7	1.7	1.8	36.474	96.826	5.0R
1307	FEB 09	17 29 49.64	Osage		1.4	1.5	1.2	36.961	96.672	5.0R
1308	FEB 11	21 25 55.83	Pontotoc				0.9	34.823	96.599	5.0R
1309	FEB 18	11 06 03.56	Choctaw		2.1	1.9	2.0	33.970	95.459	5.0R
1310	FEB 25	18 53 37.43	Atoka		2.2	2.0	1.8	34.655	95.890	5.0R
1311	FEB 26	13 03 58.71	Stephens		2.2	2.0	2.1	34.466	97.898	5.0R
1312	FEB 29	23 42 40.43	Bryan		1.8	1.7	1.5	34.106	96.335	5.0R
1313	MAR 03	13 41 38.40	Kiowa				1.9	34.909	98.717	5.0R
1314	MAR 05	09 00 26.05	Grady				1.5	34.916	97.811	5.0R
1315	MAR 05	13 21 14.82	Grady		1.6		1.6	35.265	97.799	5.0R
1316	MAR 05	19 25 02.96	Grady		1.9		1.7	35.226	97.776	5.0R
1317	MAR 07	22 42 48.54	Lincoln		1.9	1.8	2.2	35.902	96.632	5.0R
1318	MAR 09	10 44 34.53	Pittsburg		1.4	1.4	1.4	34.864	95.589	5.0R
1319	MAR 11	19 50 14.51	Garvin		2.2	1.8	1.8	34.853	97.643	5.0R
1320	MAR 12	01 24 30.34	Pittsburg		1.1		1.5	34.980	96.057	5.0R
1321	MAR 17	23 13 11.17	Ottawa		1.8	1.7	1.5	36.868	94.804	5.0R
1322	MAR 27	16 27 10.70	Atoka		1.8	1.9	1.6	34.301	96.249	5.0R
1323	MAR 28	23 29 45.07	Murray		1.4		1.4	34.481	97.199	5.0R
1324	APR 06	12 44 41.00	Grady		1.4		1.4	34.880	97.812	5.0R
1325	APR 11	13 24 49.17	Cleveland				1.4	34.991	97.158	5.0R
1326	APR 16	08 09 59.46	Noble		2.0	1.6	2.0	36.443	97.068	5.0R
1327	MAY 20	09 06 40.27	Logan		1.5	1.0	1.4	35.860	97.263	5.0R
1328	MAY 20	19 39 46.37	Grady		1.7		1.8	35.117	97.885	5.0R
1329	MAY 24	15 51 26.21	Choctaw		1.8		1.6	34.151	95.428	5.0R
1330	MAY 29	05 16 22.07	Cotton				2.1	34.315	98.311	5.0R
1331	MAY 29	22 11 40.84	Johnston		1.9	1.8	1.7	34.196	96.906	5.0R
1332	JUN 10	09 33 54.12	Canadian		1.4		1.8	35.547	97.755	5.0R
1333	JUN 13	11 40 48.76	Pushmataha		1.6		1.8	34.340	95.445	5.0R
1334	JUN 18	09 04 12.71	Garvin		1.3		1.5	34.768	97.632	5.0R
1335	JUN 18	21 14 36.58	Johnston		1.8	1.8	1.4	34.309	96.820	5.0R
1336	JUN 29	20 05 14.55	Grady		1.4		1.8	35.284	97.819	5.0R
1337	JUN 30	03 14 57.52	Grady		2.0	1.8	1.9	35.242	97.740	5.0R
1338	JUL 01	18 12 32.06	Pontotoc		1.7		1.7	34.575	96.788	5.0R
1339	JUL 02	13 26 26.18	Grady		1.8		1.6	35.273	97.737	5.0R
1340	JUL 03	12 40 04.20	Grady		2.0	1.8	1.7	35.257	97.760	5.0R
1341	JUL 06	00 14 47.14	Stephens				1.7	34.630	97.624	5.0R
1342	JUL 08	16 38 15.24	Grady		1.8		1.7	34.926	97.760	5.0R
1343	JUL 08	17 23 56.69	Grady		2.1	2.3	1.9	34.863	97.697	5.0R
1344	JUL 08	17 28 06.13	Grady		1.9	1.9	1.8	34.894	97.721	5.0R
1345	JUL 08	19 35 41.91	Grady				1.6	34.880	97.700	5.0R
1346	JUL 08	23 29 15.72	Murray		1.8	2.1	1.6	34.393	97.175	5.0R
1347	JUL 09	04 04 42.39	Grady		1.4		1.6	34.825	97.812	5.0R
1348	JUL 09	08 51 15.81	McClain		1.5		1.5	34.917	97.631	5.0R
1349	JUL 19	07 34 22.00	Noble				1.6	36.318	96.936	5.0R
1350	JUL 31	02 58 26.98	Garvin		1.7	1.8	1.8	34.786	97.656	5.0R
1351	AUG 01	22 57 51.89	Cleveland		1.8	1.9	1.5	35.363	97.610	5.0R
1352	AUG 03	06 25 20.57	Pushmataha		2.3	1.8	1.8	34.524	95.343	5.0R
1353	AUG 30	01 25 05.45	Okfuskee		1.4		1.0	35.496	96.526	5.0R

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]
1354	AUG 30	07	27	29.46	McIntosh				0.7	35.431	95.847	5.0R
1355	SEP 13	12	46	30.71	Kingfisher		2.6	2.2	1.9	35.927	97.867	5.0R
1356	SEP 26	21	00	13.20	Caddo		1.7		1.2	34.928	98.175	5.0R
1357	OCT 18	09	46	36.25	Blaine		1.7		2.0	35.792	98.552	5.0R
1358	OCT 25	02	12	55.19	Major		2.3	2.1	2.0	36.238	98.255	5.0R
1359	OCT 29	14	49	10.18	Latimer				1.3	35.023	95.035	5.0R
1360	NOV 19	10	27	40.51	Pontotoc		1.6		1.5	34.833	96.882	5.0R
1361	NOV 19	22	11	00.39	Pontotoc		1.6		1.6	34.723	96.906	5.0R
1362	NOV 21	20	59	54.82	Coal		1.9	1.8	1.8	34.538	96.291	5.0R
1363	NOV 22	18	24	26.62	McClain		1.8		1.7	34.898	97.455	5.0R
1364	NOV 22	19	16	17.37	McClain		1.9	2.0	1.7	35.034	97.506	5.0R
1365	DEC 01	08	03	21.91	Muskogee				1.2	35.609	95.491	5.0R
1366	DEC 04	10	32	09.71	Noble				1.0	36.256	97.186	5.0R
1367	DEC 10	22	03	53.45	Canadian				1.6	35.439	97.744	5.0R
1368	DEC 10	22	15	07.34	Grady				1.5	34.809	97.995	5.0R
1369	DEC 17	20	43	06.86	Pontotoc				1.5	34.839	96.525	5.0R
1370	DEC 19	14	55	51.78	Pontotoc				1.6	34.602	96.589	5.0R
1371	DEC 19	16	29	58.91	McClain	4			2.2	35.124	97.615	5.0R
1372	DEC 29	06	21	57.11	Grady				1.5	34.830	97.772	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.

Earthquake magnitude is a measurement of energy and is based on data from seismograph records. The magnitude of a local earthquake is determined by taking the logarithm (base 10) of the largest ground motion recorded during the arrival of a seismic-wave type and applying a standard correction for distance to the epicenter. When the magnitude value is increased one unit, the amplitude of the earthquake waves increases 10 times. 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 11–222 km from a seismograph station, Otto Nuttli developed the m3Hz magnitude scale (Zollweg, 1974). This magnitude is derived from the following expression:

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

where A is the maximum center-to-peak vertical-ground-motion amplitude sustained for three or more cycles of Lg waves, near 3 Hz in frequency, measured in nanometers; T is the period of the Lg 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

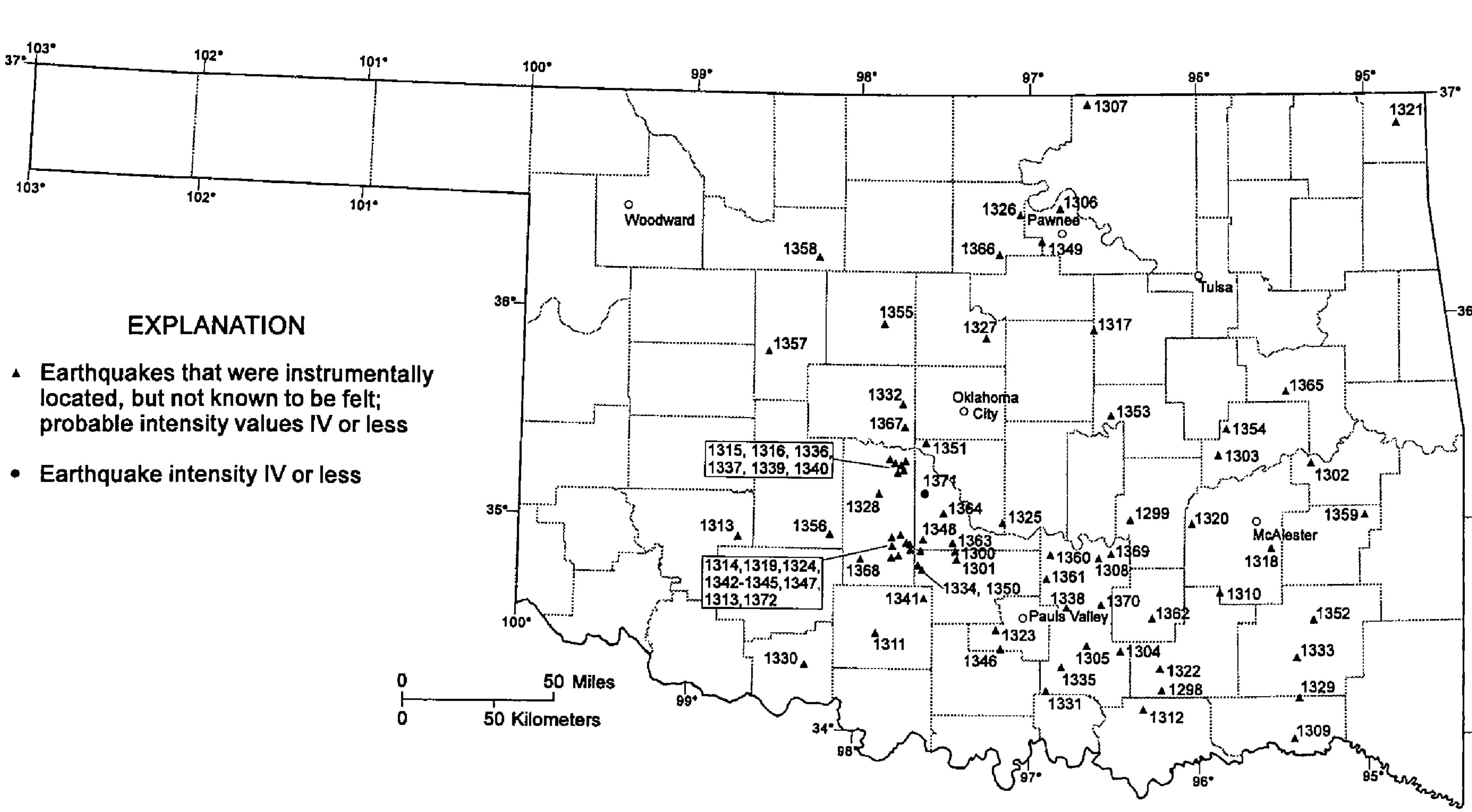

Figure 2. Distribution of Oklahoma earthquakes for 1996. Numbers correspond to event numbers in Table 2.

TABLE 3. — EARTHQUAKE REPORTED FELT IN OKLAHOMA, 1996

Event no.	Date and origin time (UTC)[a]	Nearest city	County	Intensity MM[b]
1371	DEC 19 16 29 58.91	near Blanchard	McClain	4

[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).

were given in terms of log(A) but were restricted to wave periods of 0.2–0.5 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)

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

(epicenter 100–200 km from a seismograph)

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

(epicenter 200–400 km from a seismograph)

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

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

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

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

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

where A is the maximum center-to-peak vertical-ground-motion amplitude sustained for three or more cycles of Lg waves, near 1 Hz in frequency, measured in nanometers; T is the period of Lg 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:

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

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,

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.

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 15–20 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 Todd McCormick maintained the OGS Observatory at Leonard. 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. The GSE digital seismic system, provided by the Defense Advanced Research Projects Agency/Nuclear Monitoring Research Office, considerably enhanced the OGS's ability to analyze Oklahoma earthquakes. 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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_____ 1986, Oklahoma earthquakes, 1985: Oklahoma Geology Notes, v. 46, p. 44–52.

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Alabaster Caverns Seismograph *(continued from p. 38)*

The most important function of seismograph station ACO is to improve the detection and location of Oklahoma earthquakes; it is part of a statewide network of 11 seismograph stations used to locate earthquakes in Oklahoma (see "Oklahoma Earthquakes, 1996," p. 40). ACO records have helped locate more than 1,000 earthquakes in the State.

Data from ACO are sometimes critical in the location of earthquakes in Texas, Kansas, and New Mexico. There are no seismographs in the Texas Panhandle, and there is only one in Kansas.

When ACO records P waves from distant earthquakes, OGS staff send the arrival times to the International Seismological Centre in England. Although ACO originally was not intended for location of distant earthquakes, its data have been used to locate approximately 8,000 earthquakes worldwide. During the Cold War, when there were about 40 underground nuclear tests per year worldwide, most of the tests were recorded at ACO. (The number of such tests started decreasing rapidly in 1990, to three in 1996; no tests are expected in 1997.)

ACO is the second oldest and second longest running seismograph station in Oklahoma (after the OGS Observatory near Leonard). On June 22, 1997, ACO will complete 20 years of nearly continuous recording (only a few days have been missed due to equipment breakdowns). It will have produced about 7,300 daily seis/mograms, each of which is analyzed and permanently archived at the OGS Observatory at Leonard.

James E. Lawson, Jr.
Photo by Amy Franklin

IOGCC Will Hold Midyear Meeting in Oklahoma City

"Moving Toward a National Energy Policy" is the theme for the Interstate Oil and Gas Compact Commission midyear meeting, June 8–10, 1997. This marks IOGCC's first meeting to be held in Oklahoma City, where its headquarters is located. Oklahoma Governor Frank Keating, IOGCC chairman, is hosting the meeting.

The meeting begins on Sunday, June 8, with the technical tour, "The Oklahoma City Oilfield: Yesterday, Today, and Tomorrow," followed by a welcoming reception at the National Cowboy Hall of Fame. On Monday evening a barbeque reception will take place at the Governor's mansion and visitors can tour IOGCC headquarters.

A seminar, "Groundwater Risk Assessment and Remediation," will be offered after the meeting.

For further information about the meeting and/or the seminar, contact the IOGCC, P.O. Box 53127, Oklahoma City, OK 73152; phone 525-3556, fax 524-3592. World Wide Web: http://www.iogcc.oklaosf.state.ok.us

July FDD Workshop Focuses on Tonkawa Play

The Oklahoma Geological Survey will present a one-day workshop, "Fluvial-Dominated Deltaic (FDD) Oil Reservoirs in Oklahoma: The Tonkawa Play," on July 9, 1997, at the U.S. Postal Service Technical Training Center in Norman.

The registration fee for operators in this play is $15; for other attendees it is $25. (Note: The $15 fee is for only one representative from each company; additional registrants must pay $25.) The cost includes lunch and a copy of the play workbook, *Fluvial-Dominated Deltaic (FDD) Oil Reservoirs in Oklahoma: The Tonkawa Play* (OGS Special Publication 97-3). Tonkawa operators have priority status to attend if registered by June 20th; after that date, registration will be on an as-received basis for all attendees.

The workshop is the seventh in a series of eight to be presented as part of the Fluvial-Dominated Deltaic Oil Reservoirs project. The FDD project is sponsored by the Oklahoma Geological Survey, in cooperation with the University of Oklahoma's Geo Information Systems and the OU School of Petroleum and Geological Engineering.

For more details or for registration forms, contact Michelle Summers, Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019; (405) 325-3031 or (800) 330-3996; fax 405-325-7069.

SPECIAL PUBLICATION 97-2. ***Lithologic Descriptions of Pennsylvanian Strata, North and East of Tulsa, Oklahoma,*** by LeRoy A. Hemish. 44 pages. Price: $6.

In a 1992 Oklahoma Geological Survey core-drilling project, nearly 850 ft of new core was collected from the Cabaniss and Marmaton Groups to fill a gap in the stratigraphic succession in the OGS core collection.

The new core comes from an interval extending downward from just above the Dawson coal bed of the Holdenville Formation (upper Desmoinesian) to the Tiawah Limestone ("Pink lime" in subsurface terminology) of the Senora Formation (lower Desmoinesian). With this addition to the OGS collection, continuous 2-in.-diameter core that extends stratigraphically downward from the top of the Coffeyville Formation (lower Missourian) to the top of the Mississippian System is now available to researchers at the OGS Core and Sample Library in Norman.

The results of the 1992 core-drilling project are presented in this report by LeRoy A. Hemish, an OGS mapping and coal geologist who has done extensive work in northeastern Oklahoma. The text describes the geology of the area and contains seven core-hole logs. Also included are two plates: (1) an oversized cross section showing diagrammatically 2,327.8 ft of overlapping core from this project and a previous project, with stratigraphic interpretations by the author, and (2) a columnar section with lithologic descriptions of >1,000 ft of continuous core from a single drill site.

GEOLOGIC MAP OF THE HARTSHORNE SOUTHWEST QUADRANGLE, PITTSBURG COUNTY, OKLAHOMA. One sheet, scale 1:24,000. Xerox copy. Price: $6, rolled in tube.

The Ouachita STATEMAP project, which began in 1993, is a joint effort of the Oklahoma Geological Survey and the U.S. Geological Survey to prepare new 1:24,000 geologic maps of the Ouachita Mountains and Arkoma basin in Oklahoma. STATEMAP is part of the National Cooperative Geologic Mapping Program and replaces the successful COGEOMAP program, which began in 1984. Under COGEOMAP, the OGS completed and published 15 7.5′ geologic quadrangle maps along the northern part of the Ouachita Mountains frontal belt and southern part of the Arkoma basin.

During the first year of STATEMAP, in early 1994, the Oklahoma Geologic Mapping Advisory Committee, chaired by OGS associate director Kenneth S. Johnson, was established to recommend mapping priorities for the State. The committee recommended Pittsburg County, especially near McAlester, as an important area for OGS efforts. The committee chose the McAlester area for several reasons: (1) Coal has been a major resource in the area, and substantial reserves still are present. (2) A number of natural-gas fields have been discovered recently and others are being developed in this part of the Arkoma basin, and the giant Wilburton deep gas field was discovered in 1987 immediately east of the area. (3) Environmental problems resulting from open mine shafts, undocumented underground mines, and poor reclamation practices in the past may impact urban development near McAlester, as well as rural development throughout the region. (4) Several type localities of Arkoma basin formations are in the area, but are unmeasured or otherwise poorly documented.

The Hartshorne Southwest Quadrangle, by Neil H. Suneson and LeRoy A. Hemish, is the fourth in a series of STATEMAP geologic maps of Pittsburg County. It is now available as a black-and-white, author-prepared xerox copy, comprising geologic map, cross sections, description and correlation of units, and a list of gas wells. This map is an important addition to the series of previously mapped quadrangles because of its proximity to the expanding urban area of McAlester. Planners for new highway construction, building construction, and abandoned coal-mine reclamation will find the map useful in addressing environmental concerns. Further economic assets of the area include gas reservoirs and documented coal reserves in several of Oklahoma's principal coal beds.

COGEOMAP and STATEMAP maps also are available for the Higgins, Damon, Baker Mountain, Panola, Wilburton, Red Oak, Leflore, Talihina, Leflore Southeast, Blackjack Ridge, Gowen, Summerfield, Hodgen, Hontubby/Loving, Wister, Heavener/Bates, Adamson, Hartshorne, and Krebs Quadrangles.

SPECIAL PUBLICATION 89-2. ***Geology of the Southern Midcontinent***, by Kenneth S. Johnson and others.
Second printing, 53 pages. Price: $10.

Originally published as a chapter in *Sedimentary Cover—North American Craton, U.S.*, a volume prepared for the GSA's Decade of North American Geology (DNAG) project, this popular OGS special publication is once again available.

The report discusses the regional geology of the southern Midcontinent, embracing all parts of Oklahoma except the Ouachita Mountains. Following a brief review of basement-rock geology for the region, each of the principal episodes of sedimentation and related epeirogenic movement from Cambrian through Mississippian time is discussed for the entire southern Midcontinent. Geologic history during Pennsylvanian and Permian times is dealt with basin-by-basin, and post-Permian rocks for the entire region are discussed. The report contains two color plates consisting of 25 maps (scale 1:5,000,000) showing geologic provinces, basement rocks, and thickness and dominant lithologies of sedimentary rocks in the southern Midcontinent.

LIST OF AVAILABLE OGS PUBLICATIONS, 1997/1998.
25-page catalog. Available free of charge.

OGS SP 97-2, SP 89-2, and COGEOMAP/STATEMAP geologic quadrangle maps can be purchased by mail from the Survey at 100 E. Boyd, Room N-131, Norman, OK 73019; phone (405) 325-3031 *or* (800) 330-3996; fax 405-325-7069. To mail order books, add 20% to the cost for postage, with a minimum of $1 per order. For mail orders of 1–10 maps, add $2 for postage; for 11–25 maps, add $3.

All OGS publications can be purchased over the counter at the OGS Publication Sales Office at 1218-B W. Rock Creek Road, Norman; phone (405) 360-2886; fax 405-366-2882.

AAPG Southwest Section Convention
San Angelo, Texas ★ June 4–8, 1997

Hosted by the Geological Societies of San Angelo and Graham, the theme of this year's AAPG Southwest Section meeting is "Southwest of Your Imagination." For further information about the meeting, contact Bruce Swartz, Swartz Oil Co., 4112 College Hills Blvd., Suite 201, San Angelo, TX 76904; phone (915) 949-8400, fax (915) 942-0032.

Technical Program

Investment Characteristics of Oil and Gas Properties
Exploring for Oil on the Internet: Resources for the Petroleum Geologist
Computerized Oil E-Log Analysis in Central and North Texas
Geological-Engineering Team Work: Key to Successful Development of Two Stratigraphic Traps
Ancient and Modern Deltas: Some Perspectives and Stratigraphic Implications
Microfacies Analysis of the Wapanucka Formation, Frontal Ouachita Mountains, Oklahoma
Seismic Description of Complex Carbonate Porosity System, Welch Field, Permian Basin, Texas
Patterns of Reciprocal Sedimentation with Middle and Late Pennsylvanian Carbonate-Bank Systems, Eastern Shelf of North-Central Texas
Syndepositional, Subtidal Dolomitization Model for the Formation of Some Paleozoic Reservoirs in the Permian Basin
Petrophysical and Petrographic Analysis of the 14,650–15,310-ft Interval in the Nellie #1 Well, Pecos County, Texas
Waterflood Characteristics of the Brushy Canyon Formation: Red Tank Field, Lea County, New Mexico
Provenance of the Delaware Mountain Sandstone Group of the Delaware Basin, Texas and New Mexico
Structural, Depositional, and Diagenetic Analysis of the Pennsylvanian Morrow Within the Cedar Lake Area in the Delaware Basin of Southeast New Mexico
The Role of High Resolution Aeromagnetics and Other Nonseismic Methods in the Exploration of Oil and Gas
The Precambrian—Important for Permian Basin Oil and Gas?
Gravity Prospecting for Pennsylvanian Carbonate Reservoirs of the Northern Shelf of the Permian Basin
The Dickens Project—Advances in Surface Geochem Technology
Stable Isotopes and Surface Geochemical Exploration: A Case Study at Little Buffalo Basin Oil Field, Wyoming
Predicting Fractured Reservoir Location and Attributes in the Permian Basin, West Texas: A Basin Modeling Approach Using CIRF.B
Tepee Structures in Boquillas Formation Near Del Rio, Texas, Resulting from Sub-Recent Calichification
Due Diligence and the Oil and Gas Manager
Technical Data Capture in Geological and Geophysical Data Management
Well Log Patterns and the Micro-Stratigraphic Framework of Important Clastic Reservoirs
Design and Operation of Mudlogging Equipment
Steps for Creating a Digital Ground-Water Data Base

Short Courses

Practical Oil and Gas Law for Geologists
Reservoir Engineering for Geologists

Field Trips

Terrell County, Texas
History and Environmental Aspects of the Big Lake Field, Reagan County, Texas

Conference on the History and Dynamics of Global Plate Motions, June 17–22, 1997, Marshall, California. Information: AGU Meetings Dept., Plate Motions Conference, 2000 Florida Ave. N.W., Washington, DC 20009; (202) 462-6900, fax 202-328-0566; e-mail: meetinginfo@kosmos. agu.org.

National Speleological Society Convention, June 23–27, 1997, Sullivan, Missouri. Information: Pam Saberton, 3820 Juniata St., St. Louis, MO 63116; (314) 772-6956.

Annual Rockhound Seminar, June 28–29, 1997, Ann Arbor, Michigan. Information: Cathy Hodgson, 1360 Roods Lake Road, Lapeer, MI 48446; (810) 664-8985.

Water Resources, Education, Training, and Practice: Opportunities for the Next Century, June 29–July 3, 1997, Keystone, Colorado. Information: American Water Resources Association, 950 Herndon Pkwy., Suite 300, Herndon, VA 22070; (703) 904-1225, fax 703-904-1228; e-mail: awrahq@aol.com.

Rocky Mountain Symposium on Environmental Issues in Oil and Gas Operations, July 14–15, 1997, Golden, Colorado. Information: Special Programs and Continuing Education, Colorado School of Mines; (800) 446-9488, ext. 3321, fax 303-273-3314; e-mail: space@mines.edu.

Ground Water Hydrology Conference, July 15, 1997, Dayton, Ohio. Information: Center for Ground Water Management, Wright State University, 3640 Colonel Glenn Hwy., 056 Library, Dayton, OH 45435; (513) 873-3648, fax 513-873-3649; e-mail: IRIS@desire.wright.edu.

American Crystallographic Association Annual Meeting, July 20–25, 1997, St. Louis, Missouri. Information: Marcia Vair; (716) 856-9600, ext. 321; e-mail: marcia@hwi.buffalo.edu.

Hedberg Conference: Applied Hydrogeology in Petroleum Exploration, July 27–30, 1997, Banff, Alberta. Information: AAPG Education Dept., P.O. Box 979, Tulsa, OK 74101; (918) 560-2621, fax 918-560-2678; e-mail: educate@aapg.org; World Wide Web: http://www.geobyte.com.

Geoscience Education International Conference, July 28–August 1, 1997, Hilo, Hawaii. Information: John Carpenter, Center for Science Education, University of South Carolina, Columbia, SC 29208; e-mail: carpenter-john@sc.edu.

PaleoForams '97 Conference and Field Trips, August 17–21, 1997, Bellingham, Washington. Information: Charles A. Ross, Dept. of Geology, Western Washington University, MS-9080, Bellingham, WA 98225; (360) 650-3634, fax 360-650-3147; e-mail: rossjrp@henson.cc.wwu.edu.

Large Meteorite Impacts and Planetary Evolution, August 30–September 5, 1997, Sudbury, Ontario. Information: B. O. Dressler, Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058; (713) 486-2112, fax 713-486-2162; e-mail: dressler@lpi.jsc.nasa.gov.

American Association of Petroleum Geologists International Conference, September 7–10, 1997, Vienna, Austria. Information: AAPG Conventions Dept., Box 979, Tulsa, OK 74101; (918) 584-2555, fax 918-584-0469.

Successful Drilling Practices Studies: Arkoma Basin, Final Report, March 1995, and Anadarko Basin, Final Report, July 1996

These two reports, prepared by OGCI Management, Inc., in Tulsa, Oklahoma, for the Gas Research Institute, are intended to be guides to effective drilling operations for gas wells in the featured areas. For both the Arkoma basin study and the Anadarko basin study, the authors surveyed the industry, found organizations that were drilling effectively, and gleaned the best drilling practices from them. Based on this information, a complete drilling operations plan for an archetypal well was developed.

For both reports, a narrowed region of study was selected so that similar wells could be compared. In the report on the Arkoma basin, by J. F. Brett and M. K. Gregoli, the Spiro play was chosen for evaluation. The report contains 72 pages and two unpaginated appendixes. The Anadarko basin study, by J. F. Brett, M. K. Gregoli, P. O. Way, and J. B. Williams, focuses on the Watonga-Chickasha Trend. The report contains 102 pages and three unpaginated appendixes.

Order *Successful Drilling Practices Study: Arkoma Basin* (no. 95/0132.2) or *Successful Drilling Practices Study: Anadarko Basin* (no. 95/0132.3) from: Gas Research Institute Information Center, 1100 Louisiana, Suite 3630, Houston, TX 77002; phone (713) 650-0788, fax 713-650-0789; e-mail gricentr@infocom.net. The reports are free.

Water-Quality Assessment of the Ozark Plateaus Study Unit, Arkansas, Kansas, Missouri, and Oklahoma; Summary of Information on Pesticides, 1970–90

Prepared by R. W. Bell, R. L. Joseph, and D. A. Freiwald of the National Water-Quality Assessment Program, this USGS water-resources investigations report contains 51 pages.

Order WRI 96-4003 from: U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225; phone (303) 202-4210. Cost is $4 for microfiche and $8.50 for paper copy, plus $3.50 per order for handling.

Hydrogeologic Data for the Blaine Aquifer and Associated Units in Southwestern Oklahoma and Northwestern Texas

A compilation of hydrogeologic data collected for an areal ground-water investigation of the Blaine aquifer is featured in this 214-page USGS open-file report. The purpose of the study was to determine the availability, quantity, and quality of ground water from the aquifer and associated units. Consisting of cavernous gypsum and dolomite beds, the aquifer provides water for a local agriculture based mainly on irrigated cotton and wheat. The study was a cooperative effort among the Oklahoma Water Resources Board, Oklahoma Geological Survey, and U.S. Geological Survey. Authors are D. L. Runkle, D. L. Bergman, and R. S. Sabian.

Order OF 97-50 from: U.S. Geological Survey, Water Resources Division, 202 N.W. 66th St., Bldg. 7, Oklahoma City, OK 73116; phone (405) 843-7570. A limited number of copies are available free of charge.

Digital Geologic Maps of Oklahoma on Diskette

Developed as part of a statewide aquifer vulnerability study, digital map data sets of surficial geologic features in Oklahoma are available on 3.5″ computer diskettes published as U.S. Geological Survey open-file reports. The data sets show surficial geology, faults, geologic beds, anticlines, synclines, and monoclines within Oklahoma. They are designed specially for use with Geographic Information Systems (GIS) for computerized mapping and spatial analysis. The Water Resources Division of the USGS in Oklahoma City also plans to make the reports available on the World Wide Web; Internet users can monitor the URL http://csdokokl.cr.usgs.gov.

The data sets for the Oklahoma Panhandle are based on 1:250,000-scale paper maps first published by the USGS as hydrologic investigations atlases; those for the rest of the State are based on 1:250,000-scale Oklahoma Geological Survey hydrologic atlases. All the data sets are available in nonproprietary and ARC/INFO formats.

Reports offered are: Cimarron (OF 96-372); Texas (OF 96-379); Beaver (OF 96-371); Woodward (OF 96-381); Enid (OF 96-374); Tulsa (OF 96-380); Clinton (OF 96-373); Oklahoma City (OF 96-378); Fort Smith (OF 96-375); Lawton (OF 96-378); Ardmore/Sherman (OF 96-370); and McAlester/Texarkana (OF 96-377). Order diskettes from: U.S. Geological Survey, Earth Science Information Center, Open-File Reports Section, Box 25286, Denver, CO 80225; phone (303) 202-4210. Each report contains one to four diskettes; cost is $10 *per diskette*, plus $3.50 per order for handling.

Endowed Professorship Created for OU's School of Geology and Geophysics

A gift of $250,000 from Lissa and Cy Wagner of Midland, Texas, will be used to establish an endowed professorship in the University of Oklahoma's School of Geology and Geophysics. The University will request matching funds from the Oklahoma State Regents Endowment Fund Program to create the Wagner Professorship, which is being targeted for an outstanding researcher and teacher in the general field of exploration seismology, the area of geophysics utilized in the search for oil and gas.

Cy Wagner, a Tulsa native, received a bachelor's degree in geology from OU in 1957. He and partner Jack Brown have transformed Wagner and Brown, Ltd., into one of the nation's largest independent oil and gas exploration and production firms.

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

Magmatic History of an Ancient Crustal Rift

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Recent petrologic, geochronologic, and isotopic studies are forcing revision of tectono-magmatic models for the evolution of the Cambrian Southern Oklahoma Aulacogen, an ancient rift formed during the breakup of the Laurentian Supercontinent.

Petrologic/geophysical studies indicate magma ascent through the crust, as well as emplacement as large relatively thin horizontal sheets, was in part regulated by interaction between magma driving pressure, the depth of the brittle ductile transition, rift-related faults, and local stress regimes (Hogan and Gilbert, in press).

Single crystal laser $^{40}Ar/^{39}Ar$ studies of primary hbl/bio from Mount Sheridan Gabbro and from Mount Scott Granite indicate a previously unrecognized close temporal association. Mount Scott Granite yielded a crystallization age of 539±2 Ma (hbl). Three surface samples of Mount Sheridan Gabbro yielded similar crystallization ages of 535±8 Ma (late hbl), 533±2 Ma (hbl), 533±4 Ma (bio). Thus demonstrating the importance of mafic magmastism in the later, as well as earlier phases, of development of this rift.

Isotopic tracer studies identified primitive sources for rift-related rhyolites and granites [e.g., Mount Scott Granite $^{87}Sr/^{86}Sr)i$=0.7030–0.7043; εNd+3.4-+3.7] which are similar to Late Diabase Dikes [$^{87}Sr/^{86}Sr)i$=0.7033–0.7041; Nd +2.8-+4.3] that cross-cut these felsic rock types. In contrast to earlier models, the recycling of old crust is severely limited in importance to the generation of these rift-related felsic A-type magmas.

The tectono-magmatic history of the Southern Oklahoma Aulacogen indicates substanial amounts of juvenile material can be added to the continental crust during lithospheric extension. The crustal level at which these new additions reside is in part controlled by feedback between magma driving pressures and rate of crustal extension.

Reprinted as published in the Geological Society of America *1995 Abstracts with Programs*, v. 27, no. 6, p. A-436.

Fluorine in A-Type Granites: Experimental Studies of the Mount Scott Granite

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Partial melting experiments were performed to examine the separate and combined effects of H_2O and F components on the petrogenesis of A-type granites. The shallowly emplaced, Cambrian Mount Scott A-type, amphibole and biotite hearing, alkali-feld-

spar granite (MSG), from the Wichita Igneous Province was used as a starting material. Experiments were conducted at 850°C, at pressures of 50 MPa (4 runs) and 200 MPa (12 runs) in R-41 cold-seal vessels. Starting materials were a finely milled MSG granite powder (LOI = 1.2 wt.%, F ~0.6 wt.%) with varying added amounts of H_2O and F (as Na_3AlF_6 or AgF).

In "dry" experiments without added F, initial melting occurs via dehydration of biotite, yielding 3–5 vol% melt. The addition of H_2O increases melting to 65 vol% at 3.0 wt.% H_2O in melt. The addition of F to dry MSG leads to an increase in the degree of melting to about 45 vol% at 2.5 wt.%F in melt. In increased H_2O, but vapor-undersaturated runs, the addition of F leads to a decrease in the percentage of melting. Most likely, this reflects the expansion of the quartz field past the MSG melt composition.

Both fluorite and titanite are present in the starting composition, and an antipathetic modal variation of fluorite and titanite has previously been noted in the MSG. Only titanite is observed in experiments with <1.2 wt.% F in melt, whereas only fluorite (euhedral or spherical forms) is found at higher F concentrations, following the reaction Ttn + 2F = Flu + Qz + Ti component, with the Ti component hosted by production of Ilm, Mag, or Bt. By limiting titanite stability, F may affect the REE budget in A-type magmas.

Hydrous phases are present at H_2O-undersaturated conditions. Relict amphibole without overgrowth is present at 1.2 wt.% H_2O in melt. Runs at 200 MPa, with as little as 2.4 wt.% H_2O and 0.6 wt.% F in the melt, precipitated amphibole as small, skeletal crystals and overgrowths on relict grains. An increase in H_2O at constant F results in crystallization of amphibole and the resorption of biotite. An increase in F at constant H_2O results in the crystallization of biotite at the expense of amphibole. Therefore, early crystallization of amphibole/biotite in A-type granites does not a priori indicate intrinsically high P_{H_2O}.

Experiments reproduce phase relations commonly observed in A-type granites at F and H_2O contents consistent with typical whole-rock analyses, thus large gains or losses of volatile components are not necessarily required to explain such petrogenesis.

Reprinted as published in the Geological Society of America *1995 Abstracts with Programs*, v. 27, no. 6, p. A-431–A-432.

Mineralogical Variation Within the Compositionally Homogeneous Mount Scott Granite

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The Cambrian A-type Mount Scott Granite, of the Wichita Mountains, Oklahoma, is a sheet pluton, ~0.5 km thick with ~220 km^2 of areal exposure. Whole-rock analyses indicate the pluton is compositionally homogeneous with respect to major and trace elements. Mineralogically, the rock is comprised of the same primary components: alkali-feldspar phenocrysts (8–12%) set in a matrix of alkali feldspar (48–54%) and quartz (30%), with a minor amount of plagioclase (1.7–3.3%). Plagioclase occurs both as small crystals and as rims around some phenocrysts (rapakivi texture). The rock also contains a small amount of largely glomerocrystic ferroedenitic hornblende, biotite, hematite, magnetite, and ilmentite. Accessory phases include titanite, flourite, zircon, apatite, and allanite. Secondary minerals include sericite, flourite (although most grains are primary), and chlorite. Chlorite results from alteration of biotite (and not hornblende): many chlorite grains have biotite morphologies, small fragments of biotite, and are adjacent to unaltered hornblende.

Surprisingly, despite compositional homogeneity, a textural and mineralogical variation is observed in the Mount Scott Granite. Its matrix contains a variable amount of granophyre: samples range from 0 to ~70%. The mineralogical variation corresponds with this textural variation. Samples with no granophyre (see table) contain more plagioclase (both grains and rims), hornblende, and titanite, and less oxide, biotite, chlorite, and fluorite than those with ~70% granophyre. Grains are smaller and glomerocrysts are more widely distributed in 70% granophyre samples.

Mode Table

gran	0%	70%
plag	3.3	1.7
hbl	3.0	2.2
bt	0.0	0.1
ox	1.2	2.1
ttn	0.3	0.1
flu	0.0	0.1
chl	0.2	0.1

How can this mineralogical variation result in a compositionally homogeneous rock? One likely cause is a variation in melt volatile concentration, specifically H_2O and F. Such variation is difficult to evaluate by direct analysis; there have been many opportunities for fluid/rock interaction. However, the mineralogical variation has been investigated experimentally. At 850°C, 200 MPa, varying the H_2O (dry to H_2O saturated) and F (0.15–3.0 wt.%) has yielded a decrease in amphibole stability and increase in biotite stability with increasing H_2O and F. Likewise, fluorite is only stable at higher F and H_2O concentrations (>~2.5, 1.0 wt.% in melt, respectively), whereas titanite is stable at lower concentrations. Thus, experiments indicate that melts that formed granophyre-rich samples contained H_2O excessive of 2.5 wt.% and F excessive of 1 wt.%.

Reprinted as published in the Geological Society of America *1996 Abstracts with Programs*, v. 28, no. 7, p. A-42.

Structure of Continental Rifts: Role of Older Features and Magmatism

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Recent geological and geophysical studies in several continental rifts have begun to shed light on the details of the processes which govern the structural evolution of these important exploration targets. In Kenya and Tanzania, the classic East African rift has been the object of several investigations which reveal that its location follows the boundary (suture?) between the Tanzanian craton (Archean) and Mozambiquan belt (Proterozoic). The Baikal rift also follows a similar boundary, and the Midcontinent rift of North America appears to do the same. Rifts themselves often act as zones of weakness which are reactivated by younger tectonic regimes. The classic North American example of this effect is the Eocambrian Southern Oklahoma aulacogen which was deformed to create the Anadarko basin and Wichita uplift in the late Paleozoic. The Central basin platform has a similar history although the original rift formed at ~1,100 Ma. Integration of geophysical data with petrologic and geochemical data from several rift zones has also provided a new picture of the nature and extent of magmatic modification of the crust. An interesting contradiction is that Phanerozoic rifts, except the Afar region, show little evidence for major magmatic modification of the crust whereas, at least in North America, many Precambrian rifts are associated with very large mafic bodies in the crust. The Kenya rift displays evidence for modification of the lower crust in a two-phase magmatic history, but upper crustal magmatic features are limited to local intrusions associated with volcanoes. In this rift, complex basement structure plays a much more important role than previously realized, and the geophysical signatures of basement structure and magmatism are easy to confuse. If this is also the case in other rifts, additional rift basins remain to be discovered.

Reprinted as published in the American Association of Petroleum Geologists *1996 Annual Convention Official Program*, v. 5, p. A73–A74.

Nature of the Mesoproterozoic "Granite-Rhyolite" Province

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The Granite-Rhyolite Province underlies much of the midcontinent of North America and ranges in age from 1.5 to 1.3 Ga old. This province is usually described as being composed of undeformed high silica rhyolites and related epizonal granitic plutons, of an "anorogenic" origin. Igneous rocks of intermediate and mafic compositions are described as being absent or rare. Using a sample suite from a wide geographic range (Michigan to Colorado) and reports from the literature, it becomes apparent that there is a wide range of compositions of igneous rocks in this province. These variations can be seen in the petrography, chemistry, and isotopic composition of the igneous rocks.

Igneous rocks that make up this province range from true granites to gabbros. This variability can be seen in the geochemistry of rocks from the study suite, with SiO_2 ranging from 54–72 wt.%, Zr/Yb ratios ranging from 4–36, and (La/Yb)n ranging from 6–36. Geochemically, the rocks have strong A-type affinities. Almost all samples have negative Eu anomalies and have modest LREE enrichments. Initial Pb isotopic compositions are also quite variable. All of the geochemical data suggest a source region that was heterogeneous in composition and age.

Although the majority of recovered and observed rocks are silicic, it is important to note the presence of intermediate and mafic intrusive and extrusive rocks. Models proposed for the origin of igneous rocks of this province must include mechanisms for the production of the wide range of rock types and compositions.

Reprinted as published in the Geological Society of America *1996 Abstracts with Programs*, v. 28, no. 7, p. A-375.

Detrital Zircon Tie Between Upper Triassic Chinle-Equivalent Strata in Nevada and the Dockum Group of Texas

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Sandstone from the Upper Triassic Santa Rosa Sandstone (Dockum Group) from northwestern Texas yields a detrital zircon suite nearly identical to that found in the Upper Triassic Osobb Formation (Auld Lang Syne Group) of western Nevada. Ages of the zircon population include 270 Ma (n=1), 390 Ma (n=1), 515–525 Ma (n=8), ~1010 Ma (n=4), 1425 Ma (n=2) and 2725 Ma (n=1). With the exception of the Archaean grain, this age distribution is matched exactly by the population in the Osobb Formation, and closely resembles the zircon suite in the Chinle Formation at Currie, Nevada. The Santa Rosa Sandstone was clearly derived in large part from the eroded Cambrian core of the Amarillo-Wichita Uplift, as evidenced by abundant 515–525 Ma zircons. Other possible sources include Permian tuff in strata that underlie the Santa Rose Sandstone, and Grenvillian and 1400–1450 Ma plutons that are common across the southern part of the continent. The Devonian zircon may have been derived from the Appalachian alluvial wedge, or from Devonian boulders in Ouachita flysch-molasse deposits. The zircon ages support previous interpretations that a major Chinle-Dockum river system developed across southern North America in Late Triassic time, flowing from southeast to northwest. We suggest that Cambrian zircons derived from sources in southern Oklahoma and northern Texas were carried by a trunk river across northern New Mexico and Arizona, and southern Utah, to eastern Nevada (Currie Chinle Formation), and thence through a delta onto the Triassic continental shelf (Osobb Formation).

Reprinted as published in the Geological Society of America *1995 Abstracts with Programs*, v. 27, no. 6, p. A-62.

Late Mesozoic to Early Cenozoic Denudation of the Wichita Mountains, Oklahoma, Based on Apatite Fission-Track Dating

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The Wichita Mountains (WM) are associated with a series of basement-involved uplifts and related basins within foreland of the Ouachita orogen. The exhumation timing of the WM is a matter of debate. Originally, erosional surfaces found on the granitic rocks of the WM have been interpreted as Permian age wave cut benches. New interpretations suggest that the granite platforms are Pliocene pediment surfaces.

We report new apatite fission-track (AFT) analyses for Mount Scott granite (100–145 Ma), Bally Mountain rhyolite (134–165 Ma) and Mount Sheridan gabbro (205–215 Ma). Mean track lengths range from 10–12μm, which indicates significant partial annealing. The WM were uplifted in the Late Paleozoic during the Ouachita Orogeny and eroded. During Mesozoic time, these rocks were probably covered with shale and limestone. As a result of burial to 1–2 km depth, the temperature of the rocks was elevated to 60°–90°C into a partial annealing zone and the track lengths were shortened. Begining in the Late Cretaceous to Eocene time, the Mesozoic rocks were uplifted and eroded. Denudation continues through Present time with brief episodic periods of tectonic stability. The sedimentary record of deposition and climatic changes in the Gulf Coast, the High Plains, and the Southern Rocky Mountains can be tied to the Late Mesozoic to Early Cretaceous denudation history of the WM constrained by the AFT results.

Reprinted as published in the Geological Society of America *1995 Abstracts with Programs*, v. 27, no. 6, p. A-126–A-127.

The Slick Hills of Southwestern Oklahoma: Their Significance in Understanding Pennsylvanian Tectonics in the Southern Part of the Laurentian Craton

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The Slick Hills of southwestern Oklahoma are the exposed portion of the Frontal fault zone, a region of intense Pennsylvanian-age deformation that is located between the contemporary Wichita uplift (to the south) and the Anadarko basin. During the Lower Palaeozoic the area formed part of the Southern Oklahoma aulacogen, a zone of crustal weakness trending 120°–300°. A thick and structurally anisotropic sequence of thinly bedded rocks (mostly carbonates) was deposited on a thick suite of Cambrian igneous rocks, some of which are thickly layered. Subsequent Pennsylvanian deformation dismembered the aulacogen. The structural styles developed reflect variation in isotropy between igneous basement (both within and without the aulacogen) and sedimentary cover. In essence the cover incrementally detached itself along numerous horizons of slippage recording progressive phases of deformation, while strain in the more massive basement rocks was resolved by large discrete faults. However large amplitude folding took place in areas where the basement was layered. Significant detachment of the sedimentary cover from the basement was not possible because the unconformity between the two is highly irregular—a range of buried hills with a relief of at least 1,000 ft (~300 m). Within the carbonate section, the principal indicators of compressive strain are parallel-style semichevron folds, reverse faults and pressure-solution cleavage. Brittle fractures, oriented at high angles to the aulacogen margins, generally postdate the compressive features. The most reasonable interpretation of the various strain indicators is that they record a principal compressive stress oriented approximately NE–SW. This stress imparted a compressional fabric with a small left lateral component of strike slip to rocks within the inherited aulacogen boundaries. This stress direction is difficult to reconcile with more or less contemporary orogenic deformation in the Ouachita Mountains of southeastern Oklahoma. In the latter area, large scale shortening in a generally SE–NW direction took place. It may be more fruitful to contemplate deformation in the Slick Hills and the entire aulacogen area as a product of the final incorporation of the Laurentian plate within Pangaea.

Reprinted as published in the Geological Society of America *1995 Abstracts with Programs*, v. 27, no. 6, p. A-460.

Geological and Geophysical Studies of the Bally Mountain Area, Western Slick Hills, Southwest Oklahoma

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The Slick Hills of southern Oklahoma are the exposed portion of the WNW–ESE trending Frontal fault zone, previously interpreted as an area of transpressive Pennsylvanian deformation separating the Wichita uplift and Anadarko basin in southwestern Oklahoma. The Slick Hills are recently exhumed relief of Permian age, exposing deformed Cambro-Ordovician carbonates and underlying late Cambrian igneous basement, beneath a veneer of relatively undeformed Permian sedimentary rocks. The northern and southern boundaries of the Frontal fault zone are the Mountain View and Meers faults respectively. Both faults have enormous stratigraphic displacements to the northeast (up to 22,000 and 10,000 ft, respectively). The Blue Creek Canyon fault, an oblique left lateral high angle reverse fault, separates the Slick Hills into eastern and western portions. The stratigraphic downthrow of the fault, from about 1,500–8,000 ft to the southwest, means that the structure acts as an oblique back-thrust within the zone. Here we report the results of a combined geophysical and geological study in the area of Bally Mountain, in the western part of the area. The area of study, which includes surface exposures of both igneous basement and Lower Palaeozoic cover, encompasses the Blue Creek Canyon fault. The results of our study are presented as gravity and vertical intensity magnetic anomaly maps, as a reconnaissance structure map on an air photograph base at a scale of 1:2,400, and as cross sections. Data collected in the field include the orientations of numerous fold axes, bedding surfaces, fractures, stylolites, veins, and faults. Field-collected fracture data are compared with lineament data derived from air photographs.

The structures exposed on the Bally Mountain area are essentially similar in both style and orientation to those found elsewhere in the Slick Hills. The most obvious features are parallel folds, reflecting the basic anisotropy of the thinly bedded Lower

Palaeozoic carbonates. Most folds are upright, exhibiting semi-chevron profiles. Space problems in the folds are accommodated by extensive bedding-parallel faulting as well as pressure solution cleavage. Fracture patterns reflect local fracturing, related to fold bends, as well as a regional pattern of extension fractures oriented about 040–050. In a regional context, most compressive structures in the Slick Hills trend N40°–N60°W. These N40°–N60°W trends have been interpreted as a response to a regional N50°E compressive stress. The strata exposed in the Bally Mountain area appear to have deformed under a similar stress regime. The Blue Creek Canyon fault has a displacement of ~8,000 ft in the area. A pronounced linear anomaly on the northeast side of the fault may represent a small basic intrusion.

Reprinted as published in the Geological Society of America *1995 Abstracts with Programs*, v. 27, no. 6, p. A-389.

An Integrated Macintosh Geological Workstation: Structural Geology in the Slick Hills of Oklahoma

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Off-the-shelf and custom software, and flexible data interchange formats make it possible to carry out integrated geological data analysis with minimal expenditure, implementing a multi-application geological information and analysis system. In this thesis the analysis was subdivided into four major tasks, all of which made use of vertical data integration pathways. Detailed structural analysis of a portion of Bally Mountain, in the Slick Hills of Oklahoma, demonstrates the utility of such an approach.

The analysis was subdivided into four distinct tasks. In all portions Deneba Canvas, a raster/vector CAD-type application, was used as the assembly point for graphics. The fracture analysis and preliminary study involved digitizing air photographs at 1″=660 ft on a flat bed scanner into Adobe Photoshop and importing these raster images into Canvas, where fractures were vectorized on the rastermap image. For statistical fracture analysis, digitized images were rectified from quadrangle data and fractures were digitized using MapPICT (a custom digitizing application) and exported into Rockware's Rosy; images and rose diagrams were exported for Canvas. As an aid to the field study and structural analysis, digitized air photos were used and strike and dip information was fed into Rockware's Stereo and all resulting graphics were imported into Canvas. Finally regional information in map form was digitized and imported into Canvas where GIS-type overlays were made of scanned raster and vector data. Some final image preparation was also conducted in Adobe Illustrator.

Reprinted as published in the Geological Society of America *1995 Abstracts with Programs*, v. 27, no. 6, p. A-195.

Lithologic Mapping of the Arbuckle Group Formation in the Slick Hills of Southwestern Oklahoma, Utilizing Remote Sensing/Geographic Information Systems

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Lithologic tonal patterns trending northwest/southeast were observed in Landsat TM data over the Slick Hills of southwestern Oklahoma. The Slick Hills are primarily

Cambrian-Ordovician carbonates (upper Timbered Hills Group, Arbuckle Group) which were deposited on the Upper Cambrian Reagan Sandstone. These sedimentary rocks lie unconformably on the Cambrian Carlton Rhyolite Group. Different band combinations and image processing techniques were analyzed to produce an image that exhibited the most visible lithologic tonal patterns. To aid in interpretation, a GIS lithologic data layer was placed over the image to help correlate the tonal patterns within the Arbuckle Group formations. The following factors were considered to explain the tonal patterns in the Landsat TM image: lithologic composition, vegetation reflectance and surface roughness.

Lithologic correlation is based on spectral curve variations due to different mineral compositions (i.e., rock types). Using a spectral radiometer, spectral curves were produced by measuring samples of the Arbuckle Group formations. Analysis of the spectral curves indicated little compositional difference between formations.

The vegetation spectral response recorded on TM band 4 was analyzed to determine the influence it would have on the image. If vegetation did occur along different lithologic units, it would then show up as banding on the image. There was no visible differentiation detected on the image produced by TM band 4.

To determine if the tonal patterns were caused by surface roughness (rock texture), the bedding planes of the Arbuckle Group formations were examined. Detailed analysis revealed that tonal patterns were caused by alternating thin and thick bedding planes within the Arbuckle Group. A highpass (directional) filter was applied to the image to enhance surface roughness. The filtered image showed linear trends that corresponded with the tonal patterns in the Landsat TM image. To verify the tonal patterns were caused by surface roughness, DN values from the Landsat TM data were examined. Spectral DN numbers were extracted and calibrated from the Landsat TM data, by obtaining pixel values from four of the Arbuckle Group formations. Analysis of this data indicated widely spaced beds have a higher reflectance value than closely spaced beds. This is consistent with the evidence that indicated surface roughness (i.e., bedding thickness) caused the lithologic tonal patterns in the imagery.

Reprinted as published in the Geological Society of America *1995 Abstracts with Programs*, v. 27, no. 6, p. A-112.

Initiation of the Arbuckle Platform in the Slick Hills, Oklahoma

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Late Cambrian (Franconian) transgression involved (i) transgression, (ii) the transgressed surface, (iii) eustatic sea level changes, and (iv) tectonic adjustments. Basal Reagan and Honey Creek Formations (the Timbered Hills Group) pass into the Fort Sill Formation (Arbuckle Group). The Reagan is constructed of alluvium, tidal sandbars and green shale heterolithics; topmost Reagan is glauconitic. The Honey Creek consists of cyclic alternations of quartz sandstones and detrital grainstones. Abundant lime mud defines the base of the Arbuckle Group. The lower Fort Sill displays shallowing-upward cycles; the top of the formation (locally dolomitized) displays massive algal boundstones. The succeeding Signal Mountain Formation is dominated by "below wave base" facies. The transgression inundated a hilly rhyolitic land surface; the resulting archipelago persisted until the end of Fort Sill deposition. Clear waters around islands were colonized by carbonate organisms. Facies variation is related to topography; lee- and windward carbonate facies are preserved. Eustatic variations are recorded by meter-scale cycles in the Honey Creek and Fort Sill Formations. The sequence shows two grand cycle boundaries, one low in the Honey Creek (associated with slight angular unconformity due to compaction around rhyolite terrain). The other constitutes the Fort Sill/Signal Mountain boundary. Tectonic definition of the Southern Oklahoma aulacogen is recorded by aberrant variations in the size and type of siliciclastic grains, facies changes that record increasing water depth and increase in the thickness of grand cycle packages.

Reprinted as published in the American Association of Petroleum Geologists *1997 Annual Convention Official Program*, v. 6, p. A29.

Folding Style and Deformation Mechanisms in Arbuckle Group Carbonates, Slick Hills, Oklahoma

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This study documents brittle flexural slip as the dominant mechanism in the Limestone Hills, southern Oklahoma. The field area is in southwestern Oklahoma on the southern flank of the Southern Oklahoma Aulacogen. Pennsylvanian left-lateral transgressive deformation resulted in a series of doubly plunging parallel folds. The folding mechanism appears to be flexural slip with into-the-hinge thrusting. Localized slip along bedding planes is evident with slickensides perpendicular to the local hinge line. Orientation data taken along individual layers show hinge migration of individual layers. Oriented samples were collected from all hinge domains and along limbs of the folds. Ultra-thin thin sections, cut perpendicular to and parallel with the local fold hinges, document deformation mechanisms in the area. The rocks in the area are highly fractured and the dominant deformation mechanism appears to be brittle, suggesting a significant influence on reservoir quality in similarly deformed rocks. Although twinning of calcite shows ductile deformation, the presence of micro-twins with visible offset along microcracks support brittle deformation. The presence of grain size reduction of individual grains along microfractures also supports brittle deformation. However, the presence of sigmoidally shaped tension gashes along the fold limbs supports some ductile deformation of the area. Grain size reduction without a loss of cohesion is also present indicating pressure solution in samples taken along the limbs of the folds. Work to date shows a change in deformation mechanisms from ductile to brittle as flexural slip folding progressed, suggesting that the deformation mechanism is a significant control of the folding process.

Reprinted as published in the American Association of Petroleum Geologists *1997 Annual Convention Official Program*, v. 6, p. A72.