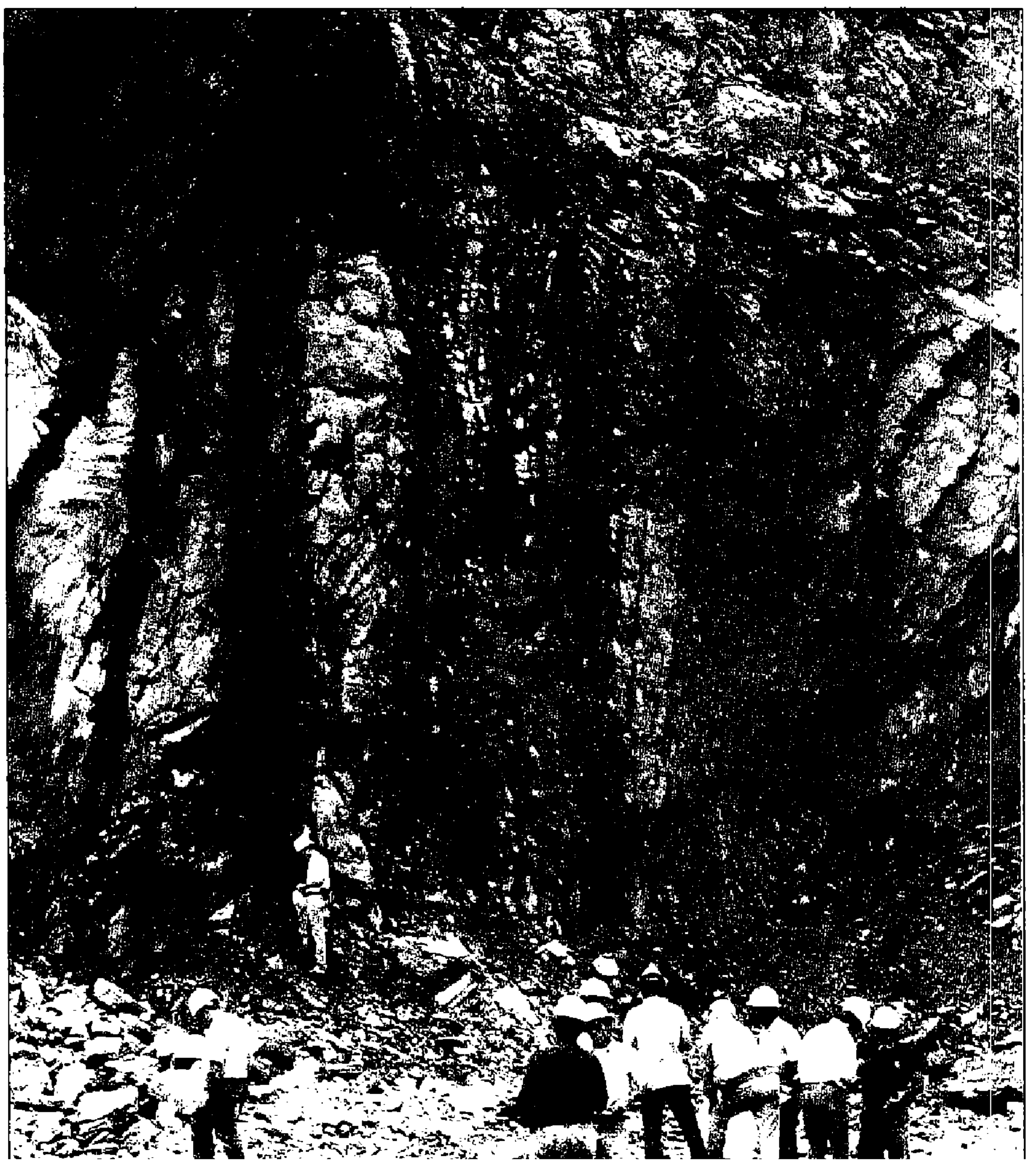
OKLAHOMA GEOLOGY

Oklahoma Geological Survey Vol. 52, No. 2 April 1992



On the cover—

Bigfork Chert at Stringtown Quarry

The Bigfork Chert (Middle and Upper Ordovician) exposed in the quarry at Stringtown, Atoka County, Oklahoma. Beds are essentially vertical; intense fracturing, complex rock cleavage, and intraformational folding are also apparent in this view. The quarry is interesting, not only for its exposure of the strata and structures, but also because solid petroleum occurs locally on fracture planes, and oil also seeps locally from the fractures. Most of the staining of the rock exposures is the result of water seepage. These strata are equivalent to the Viola Limestone to the west and north.

The Bigfork Chert has produced minor quantities of oil at the Atoka Townsite S.E. field ~12 mi to the south, and produced gas from 1960 to 1987 at the Potato Hills field in southern Latimer County.

The quarry was visited April 12, 1991, by participants in the Midcontinent Section field trip, for the 75th anniversary meeting of the American Association of Petroleum Geologists in Dallas, Texas. Field-trip leaders were Neil H. Suneson (third from right), Jock A. Campbell (sixth from right), both of the Oklahoma Geological Survey, and Maxwell J. Tilford, Tide-West Oil Co. (not shown). Other individuals in photo not identified.

Jock A. Campbell

Photo by George E. Ryberg
Prescott, Arizona

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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.

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GEOLOGY

C O N T E N T S

OKLAHOMA
GEOLOGICAL
SURVEY

VOL. 52, NO. 2

APRIL 1992

CRYSTALLOGRAPHIC EVIDENCE FOR GLAUBERITE IN THE TRIASSIC SHEEP PEN SANDSTONE, NORTHWEST CIMARRON COUNTY, OKLAHOMA

Patrick S. Mulvany[1]

Abstract

A very thin bed of dolostone in the Triassic Sheep Pen Sandstone, northwest Cimarron County, Oklahoma, contains whitish particles of kaolinite and barite that are pseudomorphic after glauberite: $Na_2Ca(SO_4)_2$. This mineral is known to occur in arid lacustrine and marine evaporitic depositional environments, commonly as a diagenetic or replacement product.

Introduction

The Upper Triassic Sheep Pen Sandstone crops out in northeast New Mexico, southeast Colorado, and northwest Cimarron County, Oklahoma (Fay, 1983). At one location in Cimarron County, the Sheep Pen contains a 1- to 3-cm-thick bed of light greenish gray (5GY8/1), argillaceous, aphanic dolostone (Fig. 1A,B). This dolostone is peculiar in that it contains conspicuous whitish particles (3–4% by volume) as much as 2.5 mm in size (Fig. 1B). This paper investigates the mineralogy and crystallography of these small particles.

Mineralogy

The particles are composed of soft, white kaolinite (dominant) and white to pale pink barite (subdominant). The surfaces of the particles are stained with yellowish brown limonite.

Crystallography

Large numbers of particles were recovered by digesting dolostone samples in hot 15% HCl. This treatment also removed limonite staining. Individual particles are single euhedrons or intergrowths of two or more euhedrons (Fig. 2). The euhedrons are monoclinic prismatic—2/m. Crystal forms are basal pinacoid c{001} and unit prism m{110}. Crystal habit is variable: prismatic by extension parallel to the c-axis, thickly tabular by extension parallel to the c-face, or prismatic with all six sides approximately equal in size (pseudorhombohedral). Kaolinite and barite are not known to exhibit this crystallography.

Sixty individual interfacial angles were measured. This was accomplished by using a photographic slide projector to create greatly enlarged silhouettes of care-

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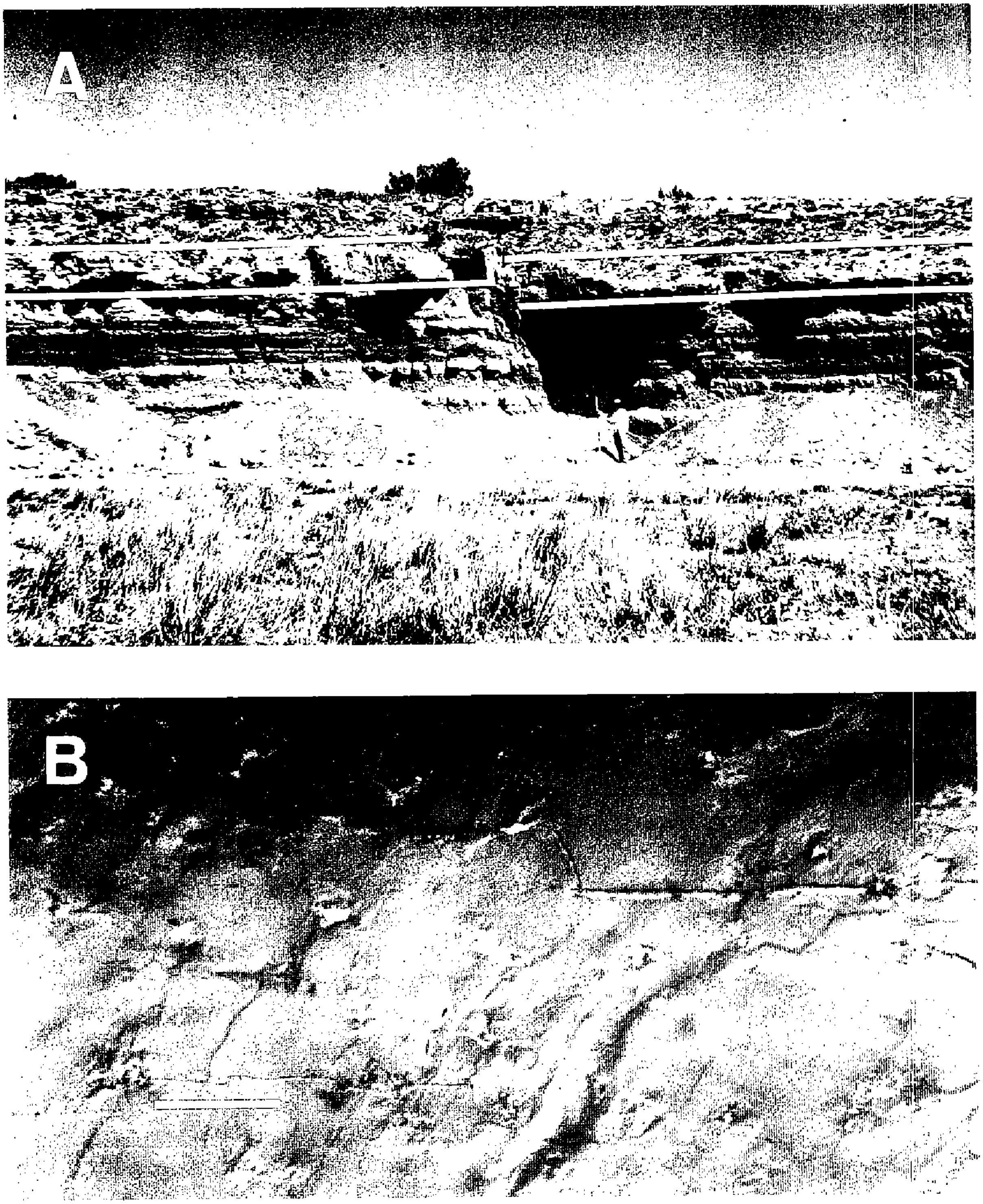

Figure 1. *A*—Small quarry viewed from south, SW¼NW¼ sec. 28, T. 6 N., R. 1 ECM, Cimarron County, Oklahoma. Lower white line is conformable contact between Sheep Pen Sandstone and underlying Sloan Canyon Formation. Very thin bed of dolostone crops out along upper white line, 1.2 m above base of Sheep Pen. Minor faulting has resulted in ~0.6 m of vertical separation. *B*—Upper surface of Sheep Pen dolostone bed showing conspicuous whitish particles. White bar scale is 1 cm long.

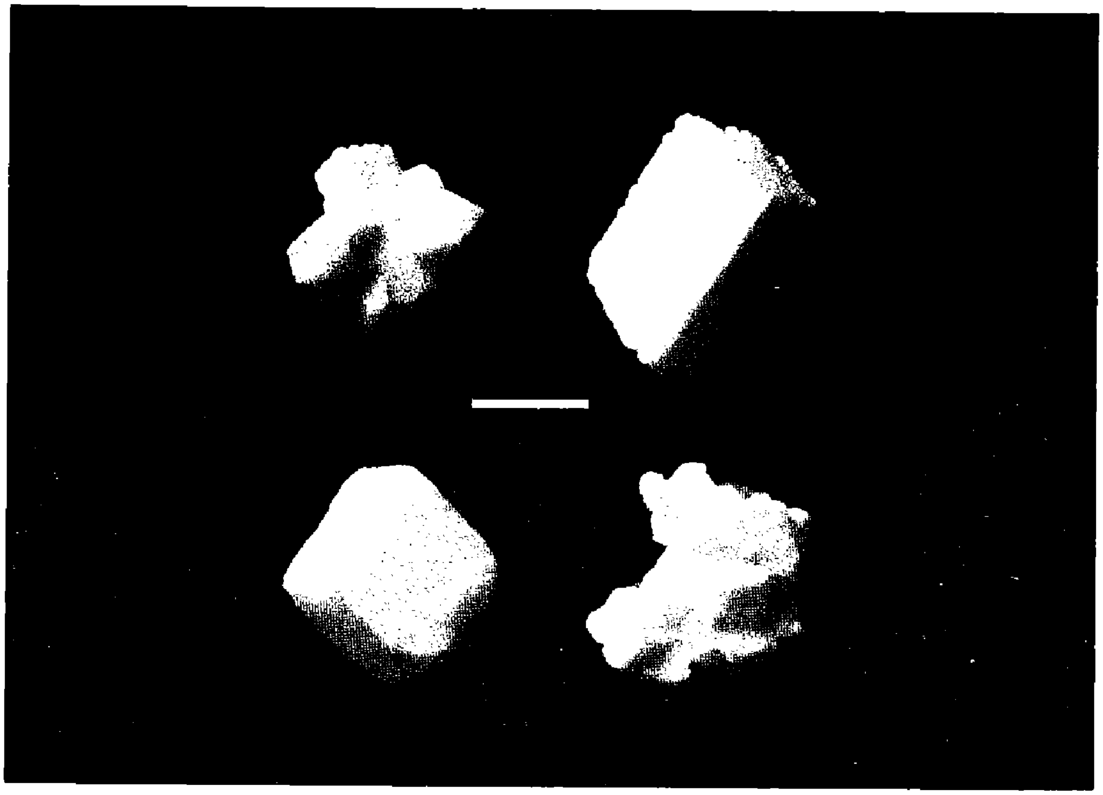

Figure 2. Particles of kaolinite and barite from the Sheep Pen dolostone are monoclinic euhedrons, singular or in intergrowths. White bar scale is 1 mm long.

fully oriented euhedrons affixed to glass slides. Obtuse interfacial angle measurements were converted to their supplementary acute counterparts. The frequency distribution of acute interfacial angles is bimodal (Fig. 3). The mean acute cm and mm interfacial angles are 75.6° and 83.1°, respectively. Standard deviations for cm and mm are 1.8° and 1.5°, respectively.

Discussion

In crystal form and habit, the euhedrons are similar to glauberite crystals, $Na_2Ca(SO_4)_2$, found in the salt deposits at Vic, France, and in Spain (Egleston, 1872, p. 84 and pl. 13, fig. 13). The salt deposits at Vic, and elsewhere in the Lorraine region of France, are assigned to the Triassic System. Interestingly, the glauberite in the Lorraine is colored red with ferric iron (Egleston, 1872, p. 84; Dana, 1951, p. 432).

For glauberite, the acute cm and mm interfacial angles are 75.5° and 83.0°, respectively (Calsow, 1930, p. 3703). The χ-square goodness-of-fit test can be employed to investigate two separate null hypotheses: (1) the cm interfacial angle measurements for Sheep Pen euhedrons are normally distributed with $\mu = 75.5°$ and $\sigma = 1.8°$ and (2) the mm interfacial angle measurements are normally distributed with $\mu = 83.0°$ and $\sigma = 1.5°$. Accordingly, $\chi^2 = 0.24$ for cm, and $\chi^2 = 0.28$ for mm. The null hypotheses cannot be rejected at the 0.75 significance level ($\chi^2.75,4 = 1.92$ for cm, and $\chi^2.75,2 = 0.58$ for mm).

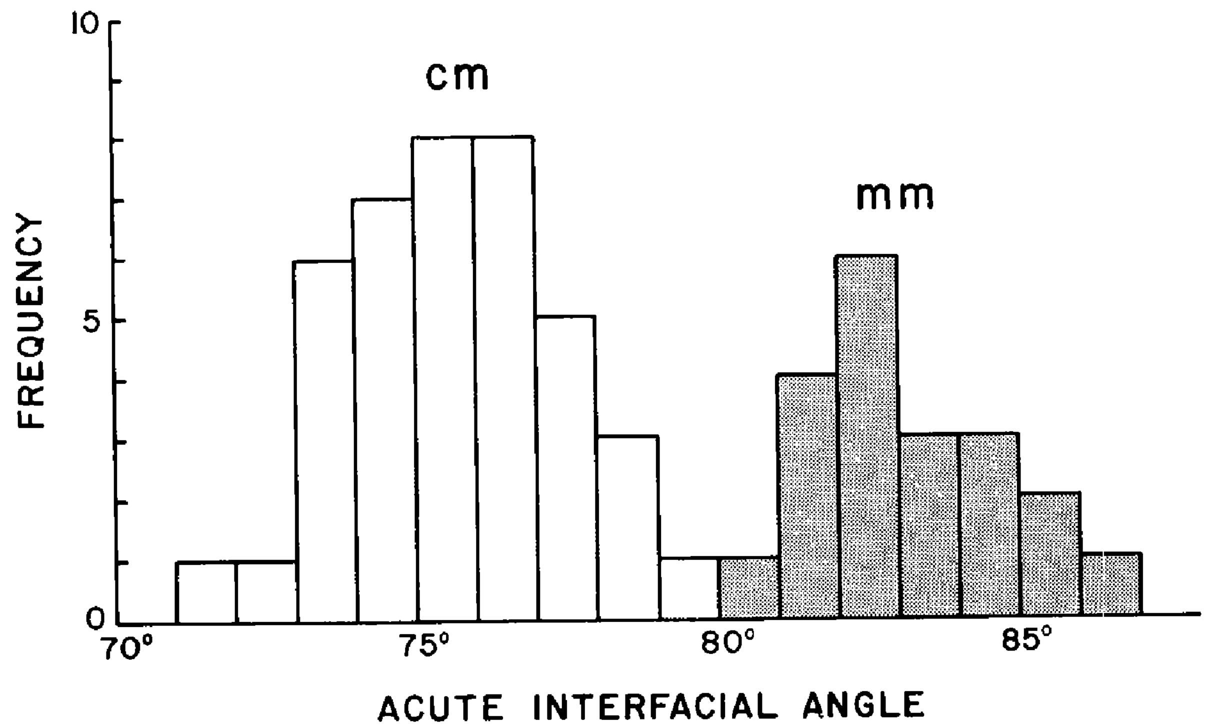

Figure 3. Frequency distribution of measured acute interfacial angles for Sheep Pen euhedrons.

Conclusions

Based on crystallographic evidence, it is concluded that the particles of kaolinite and barite in the very thin bed of Sheep Pen dolostone are pseudomorphic after glauberite. Knowledge of the former presence of this evaporite mineral should be useful in depositional environment studies of the Sheep Pen.

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OKLAHOMA EARTHQUAKES, 1991

James E. Lawson, Jr.[1]**, *Kenneth V. Luza***[2]**,**
Raymon L. Brown[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 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 1897 through 1991, more than 888 earthquakes have been located in Oklahoma.

Instrumentation

A statewide network of 12 seismograph stations was used to locate 45 earthquakes in Oklahoma for 1991 (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 five 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 two Geotech RDAS (Remote Data Acquisition System) units at either 36,000 or 1,200 24-bit samples per second. The RDAS then applies digital

[1]Oklahoma Geological Survey Observatory, Leonard. (Dan Moss is now deceased.)
[2]Oklahoma Geological Survey.

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

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 40, 60, or 10 24-bit samples per second. The samples are time-tagged by RDAS clocks locked to very low-frequency Omega Navigation/Time signal receivers. 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 1+ Unix workstation with 40 megabytes of memory, two 660-megabyte disks, and two 2.3-gigabyte Exabyte™ tape drives. All of the data from the most recent two to three days 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 dearchive directories on a 900-megabyte disk attached to a Sun 3/50 computer belonging to Lawrence Livermore National Laboratories. The dearchive directories are remote mounted, by way of the ethernet, by the Sun Sparc 1+ workstation. An Oracle™ data base on the Sun Sparc 1+ keeps track of every second of data on the permanent archive tapes, the last two or three days' data on disk, and data in the dearchive directories.

Data analysis is done by Teledyne-Geotech and Science Applications International Corp. software on the Sparc 1+ workstation.

The digital system signals are from six sensors in the Observatory vault (international station abbreviation TUL); from three sensors in a borehole on the Observatory property (station LNO); and from single sensors located at Rose Lookout (RLO) in Mayes County,

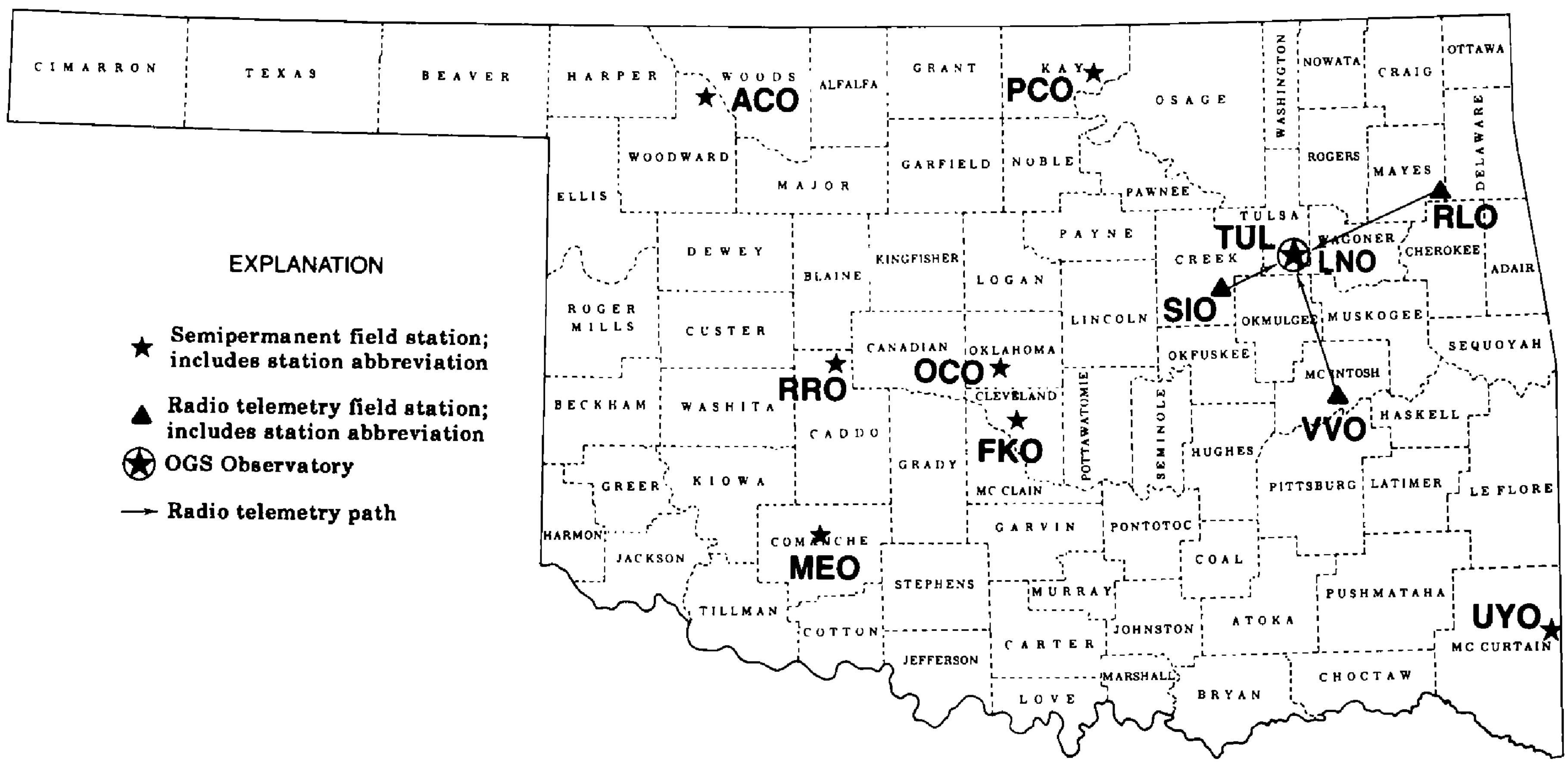

Figure 1. Active seismographs in Oklahoma.

at the Bald Hill Ranch near Vivian (VVO) in McIntosh County, and at the Jackson Ranch near Slick (SIO) in Creek County.

TUL has three (vertical, north–south, east–west) Geotech GS-13 seismometers which produce 40-sample-per-second short-period channels. Three Geotech BB-13 seismometers produce 10-sample-per-second broadband channels; three one-sample-per-second long-period channels are derived by the workstation from the broadband channels. The broadband channels are seldom used in the study of Oklahoma earthquakes; the long-period channels are never used. The short-period signals are particularly useful in calculating the direction of arrival of waves by digital calculation of polarization.

The LNO station has a Geotech 20171A seismometer in a 4.5-m-deep borehole and two Geotech 23900 (a deep-hole version of the 20171A) seismometers at 432- and 748-m depth in a borehole that is 1 m away from the 4.5-m-deep hole. The LNO equipment is provided and partially supported by Lawrence Livermore National Labortories. The three LNO channels are digitized by a second RDAS near the borehole and recorded and archived at 60 samples per second. This allows recording of higher frequency waves than is possible with the 40-sample-per-second data. The higher frequencies are particularly prominent in nearby (Oklahoma and adjacent areas) earthquakes. At frequencies above 10 Hz, the high-frequency background noise produced by wind and cultural activity is almost absent at the 748-m-deep sensor. It is particularly important for recording signals from smaller Oklahoma earthquakes, which are very difficult to see on seismograms from near-surface seismometers.

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. The operation of RLO, VVO, and SIO are partially supported by the Nuclear Regulatory Commission.

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. There are no LNO paper records. 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 at the OGS Observatory, there are seven volunteer-operated seismographs. Each consists at a Sprengnether 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). 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, upon request.

Data Reduction and Archiving

Seismic traces from the TUL vault vertical seismometer (TUL sz), the deepest borehole short-period vertical seismometer of station LNO (LNO/sz1) and one radiotelemetry site (usually VVO) are displayed on a 19-in. monitor on the Sun Sparc 1+. The traces are band passed through 0.4–4.0-Hz digital filters and are displayed in 90-min segments. A fourth, long-period vertical trace is displayed, but it records only waves from distant earthquakes. The 90-min traces are fuzzy lines with spikes showing signals above the noise. Distant earthquakes of magnitude ≥5.0 are usually identifiable by the shape of the spike and the following long-period surface waves. Other spikes represent local or regional earthquakes or surface-mine blasts. There are from 10 to 30 recordable surface-mine blasts each weekday, two to five on Saturday, and one or two on Sunday.

The monitor display is zoomed on a 60-sec segment surrounding each spike, and the event is identified by its appearance. If it is a P-wave from a distant earthquake, the display is zoomed to 15 sec and the arrival time, frequency, amplitude, and polarization (direction) are measured, calculated, and recorded for transmission to international data centers.

If a spike is identified as a possible near or regional earthquake, nine traces are displayed on the monitor (TUL sz, sn, se; LNO sz1, sz2, sz3; RLO sz; VVO sz; SIO sz). They are then filtered and unfiltered repeatedly to enhance and identify the phases. One set of filters, developed at NORESS (Norwegian Experimental Seismic System) is described by Mykkeltveit and others (1990). Using the time interval between phases, the distance can be detemined; the direction is determined from polarization (using the TUL vault vertical, north–south, and east–west signals). The distance and direction give an approximate location, which is then improved by incorporating arrival times from remote sites RLO, VVO, and SIO. At this point, a short press release is issued from the OGS offices at Norman. Paper seismograms are also searched for regional and local earthquakes. At times, a small earthquake may initially be spotted on only the digital system or only on paper seismograms.

The next stage is dearchiving digital data from the nine short-period signals (listed in the preceding paragraph). These are put in a permanent named disk file and indexed in the on-line Oracle™ data base.

Each quarter, paper seismograms from all volunteer stations and from Observatory seismograms are carefully searched for local earthquakes. Arrival times are measured and added to those already determined from the digital system. As many as two or three additional earthquakes may be found. These are dearchived from Exabyte™ tapes for digital system analysis.

Arrival times, signal durations, and various signal amplitudes are entered into a location program running on a Hewlett-Packard 9825T computer. After each location is finalized, it is entered into an Oklahoma earthquake catalog maintained by Hewlett-Packard 9825T and linked 9835A computers. This catalog is used to produce lists (by date, by county, by latitude–longitude rectangle, and several other choices), and to produce maps with a six-color Hewlett-Packard 7975A plotter.

Earthquake Distribution

All Oklahoma earthquakes recorded on seismograms from three or more stations are located. In 1991, 45 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, Garvin County earthquake (event no. 883) and McClain County earthquake (event no. 889), are probably restricted to a few tens of square kilometers away from the epicentral location. Each earthquake produced intensity-MM II effects. However, no damage was reported.

At 11:00 p.m. on January 24, 1991, a magnitude 2.8 (MDUR) earthquake occurred 7 km north of Perry. The earthquake was felt as far south as Stillwater, Oklahoma, and as far west as the Noble/Garfield county line. Intensity-MM V effects were reported in the vicinity of the epicenter. No damage was reported.

Earthquake-magnitude values range from a low of 0.8 (m3Hz) in Pittsburg County to a high of 2.8 (MDUR) in Noble County. Almost half, 21 earthquakes, occurred in Garvin, McClain, and Grady Counties, one of the most active areas in the State since 1979. Four earthquakes were located in Pontotoc County; Noble, Seminole, and Pittsburg Counties experienced two 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. Table 2 contains 1991 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; Lawson and others, 1991).

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 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 11–222 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 Lg waves, near 3 Hz in frequency, measured in nanometers;

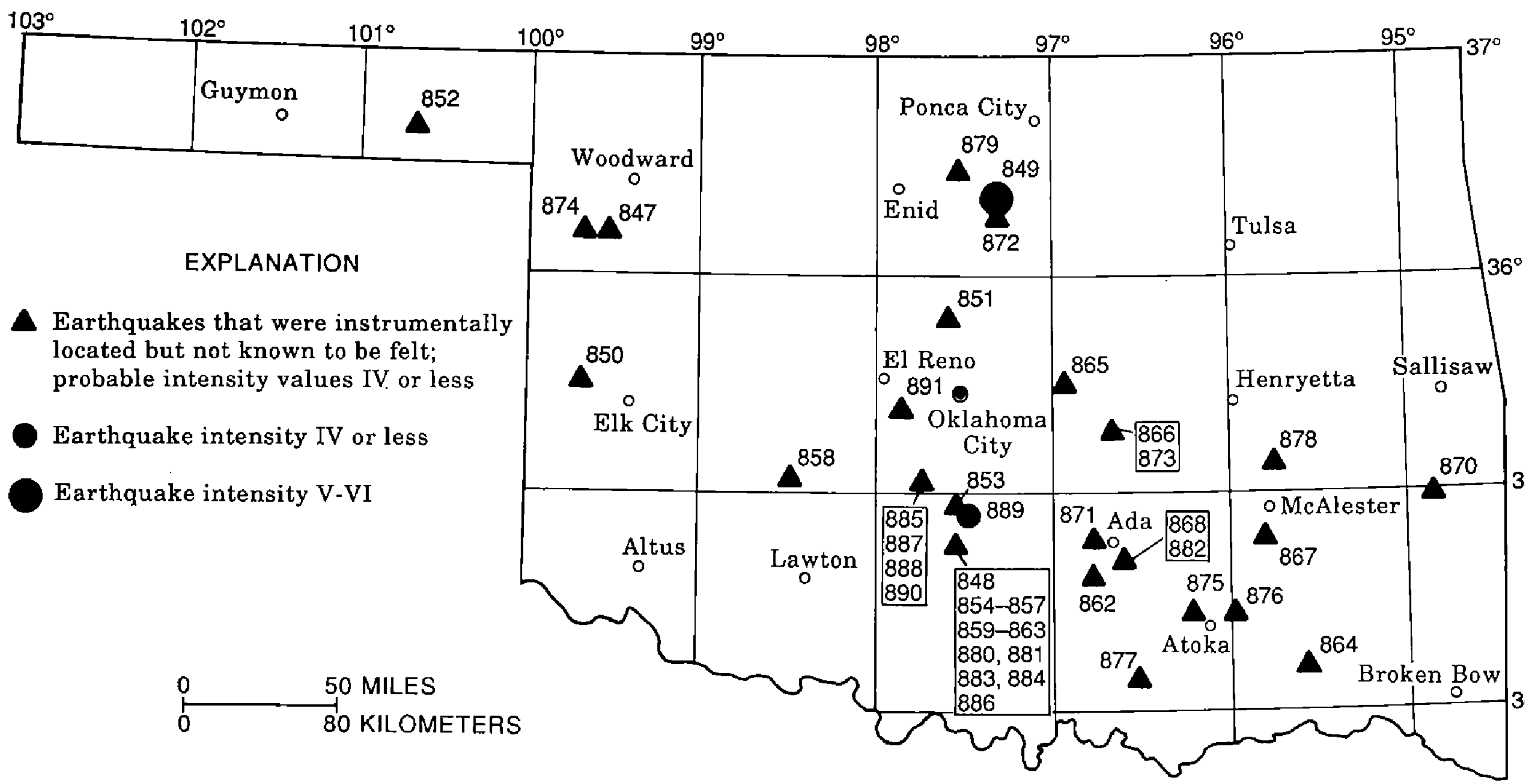

Figure 2. Distribution of Oklahoma earthquakes for 1991. Numbers correspond to event numbers in Table 2.

TABLE 2. — OKLAHOMA EARTHQUAKE CATALOG FOR 1991

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]
847	JAN 9	074559.01	Woodward				1.6	36.167	99.505	5.0R
848	JAN 14	010106.06	Garvin		1.6	1.7	2.2	34.746	97.460	5.0R
849	JAN 24	050027.65	Noble	5			2.8	36.352	97.271	5.0R
850	MAR 14	084903.03	Roger Mills				2.0	35.511	99.644	5.0R
851	MAR 15	104537.45	Logan		1.8	1.2	1.7	35.885	97.605	5.0R
852	MAR 15	141730.33	Beaver				2.4	36.659	100.603	5.0R
853	MAR 22	064957.64	McClain		1.7		1.9	34.968	97.513	5.0R
854	APR 21	071321.75	Garvin			1.6	1.6	34.713	97.585	5.0R
855	APR 21	160904.09	Garvin			2.0	2.0	34.748	97.620	5.0R
856	APR 21	165545.39	Garvin			2.5	2.4	34.812	97.635	5.0R
857	APR 22	151650.40	Garvin				2.0	34.714	97.605	5.0R
858	APR 22	164504.76	Caddo				2.0	35.098	98.442	5.0R
859	APR 22	170413.97	Garvin				2.2	34.768	97.585	5.0R
860	APR 22	172727.92	Garvin				2.1	34.741	97.585	5.0R
861	APR 22	180854.05	Garvin				2.3	34.799	97.632	5.0R
862	APR 22	181118.46	Garvin		2.2	1.8	2.4	34.760	97.585	5.0R
863	APR 22	225122.20	Garvin		2.3	2.2	1.9	34.762	97.633	5.0R
864	MAY 5	120727.40	Pushmataha			1.7	1.4	34.168	95.550	5.0R
865	MAY 5	215445.70	Lincoln		2.1		2.6	35.627	96.897	5.0R
866	MAY 6	041330.75	Seminole			1.3	1.7	35.293	96.698	5.0R
867	MAY 9	100550.07	Pittsburg		1.3	1.1	1.1	34.910	95.866	5.0R
868	MAY 10	043756.45	Pontotoc		1.7	1.2	1.1	34.683	96.635	5.0R
869	MAY 28	190512.25	Pontotoc				1.7	34.605	96.808	5.0R
870	MAY 31	231154.37	Le Flore		1.9	2.0	1.7	35.006	94.884	5.0R
871	JUN 30	081105.64	Pontotoc		1.8	1.5	1.8	34.785	96.777	5.0R
872	JUL 5	203110.25	Noble		2.3		2.1	36.256	97.264	5.0R
873	JUL 9	083845.17	Seminole		1.3	1.1	1.4	35.347	96.687	5.0R
874	JUL 11	062450.71	Ellis		1.7	1.8	2.0	36.165	99.648	5.0R
875	JUL 20	095345.70	Coal		2.0		1.7	34.435	96.189	5.0R
876	JUL 20	111752.01	Atoka		2.5	2.3	2.2	34.477	95.956	5.0R
877	JUL 25	102414.65	Johnston		1.7	1.3	1.5	34.118	96.487	5.0R
878	AUG 7	104015.79	Pittsburg		1.0	0.8	1.0	35.142	95.665	5.0R
879	AUG 8	183801.77	Garfield		2.6	1.9	2.5	36.423	97.475	5.0R
880	SEP 25	175921.16	Garvin		2.4	2.1	2.1	34.744	97.553	5.0R
881	OCT 3	065544.77	Garvin		2.6	2.4	2.2	34.741	97.667	5.0R
882	OCT 25	013126.93	Pontotoc		1.8	1.6	1.4	34.640	96.589	5.0R
883	DEC 9	160714.51	Garvin	2	2.3		2.1	34.768	97.592	5.0R
884	DEC 9	170601.39	Garvin		2.4	2.0	2.1	34.752	97.585	5.0R
885	DEC 9	171422.14	Grady		2.0	1.5	1.9	34.971	97.717	5.0R
886	DEC 9	173857.16	Garvin				1.8	34.752	97.600	5.0R
887	DEC 9	175934.23	Grady		2.6	2.4	2.3	34.893	97.702	5.0R
888	DEC 9	201158.45	Grady		1.9	1.9	1.8	34.905	97.702	5.0R
889	DEC 10	120029.64	McClain	2	2.3	1.8	2.1	34.868	97.448	5.0R
890	DEC 12	031521.33	Grady		1.4		1.9	34.924	97.706	5.0R
891	DEC 28	044559.82	Canadian		1.4		1.8	35.393	97.850	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, 1991

Event no.	Date and origin time (UTC)[a]		Nearest city	County	Intensity MM[b]
849	JAN 24	050027.65	Perry	Noble	V
883	DEC 9	160714.51	S Lindsay	Garvin	II
889	DEC 10	120029.64	Story	McClain	II

[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.

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 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, 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, with partial funding by the Nuclear Regulatory Commission. 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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NEW OGS PUBLICATIONS

GEOLOGIC MAPS OF THE LEFLORE SE AND GOWEN QUADRANGLES, LE FLORE AND LATIMER COUNTIES. Scale 1:24,000. Xerox 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; and the Leflore, Talihina, and Blackjack Ridge Quadrangles were released in 1991.

The Leflore SE Quadrangle (by LeRoy A. Hemish and Neil H. Suneson) and the Gowen Quadrangle (by LeRoy A. Hemish) are now available as black-and-white, author-prepared xerox copies, 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.

AAPG ANNUAL CONVENTION
Calgary, Alberta, June 21–24, 1992

Welcome back to Calgary!

It's not very often that we have the opportunity to greet the AAPG convention in this fashion. In fact, this is only the third time that we in Calgary have had the privilege of hosting the AAPG—1972, 1982, and now again in 1992!

We are particularly proud this year, as Calgarians, and more especially as Canadians, since 1992 is the 150th Anniversary of the Geological Survey of Canada. All the members of our societies—CSPG, AAPG, and SEPM—join with us in saluting the GSC in this auspicious commemorative year.

The convention's unifying theme this year, "Environments of Exploration," has been carefully chosen to allow for and highlight a wide variety of programs. The environment has emerged as a high-profile concern of our societies' members. This is directly reflected in the recent formation of the CSPG's Environment Geology Division and the upcoming inauguration of the AAPG's own Environmental Geology Division at the AAPG House of Delegates' meeting in Calgary on June 21, 1992.

Your organizing committee has planned some of the tried-and-true elements of past conventions, taken note of the successful new ideas from Dallas, added some innovative ideas of our own, and blended it all with aspects unique to Calgary. One of the technical sessions will be an exciting classic-style debate on the nature and origins of the Cretaceous–Tertiary Boundary. Several of the field trips, short courses, and poster sessions will take advantage of the industry-pioneering ERCB Core Research Centre.

With "the mountains" on our doorstep you will rarely have a better opportunity to see, in situ, the rocks that drive our business. The technical field trips program will take full advantage of the oversized lab we call the Rockies. But there will be much more, too: tar sands, outcrops, and a mine, dinosaur museum, hazardous waste disposal site, Arctic geology, and several field trips that will appeal to both the scientist and the tourist in all of us. You can go "upmarket" to visit the Columbia Icefields, be more frugal on the Royal Tyrrell Museum and Kananaskis Country tours, or get back to the rocks on a somewhat more strenuous, but classic, Burgess Shale outcrop trip.

We look forward to seeing as many of you as possible in June of 1992!

George Eynon
General Chairman

Gerry Macey
General Vice-Chairman

AAPG Annual Convention Agenda

Technical Program

June 22

AAPG Canada I—Exploring in the Mesozoic of Western Canada
SEPM Carbonate Platform Development, Facies, and Cyclicity
AAPG Origin, Development, and Characteristics of Sequences of Variable Scales
SEPM Clastic Diagenesis
AAPG Subandean Basins of South America
AAPG Canada II—Paleozoic Stratigraphy and Prospects—Western Canada
SEPM Evolution of Pore Systems in Carbonate Rocks with Progressive Burial
AAPG Hydrogeology in Petroleum Exploration
SEPM Recognition and Facies of Valley Fills
AAPG Catastrophism vs. Gradualism at the Cretaceous–Tertiary Boundary
AAPG Paleoceanography and Environments of Exploration of the Indian Ocean Basins and Margins

June 23

AAPG Astrogeology, Third Symposium: Siljan Ring Summary and Magellan Results
AAPG Environmental Issues and Opportunities
AAPG Reservoir Heterogeneities and Fracture Systems I
AAPG Tight Gas and Sour Gas Reservoirs
SEPM Devonian Carbonate Sequence Analysis
SEPM Shelf and Shoreline Sandstones
EMD Hydrocarbons from Coal
AAPG "I'm Not So Sure I Believe That" Research Symposium
AAPG Petroleum Exploration in Environmentally Sensitive Areas
AAPG Exploring in Fold and Thrust Belts I
SEPM Reef Initiation and Development
AAPG Pressure Seals and Abnormally Pressured Reservoirs
AAPG Petroleum Geology of Selected Basins in the Russian and Contiguous Republics
Division of Professional Affairs Technical Session: Geological Concept to Corporate Bottom Line

June 24

SEPM Research Symposium: Stratigraphic Sequences in Foreland Basins
AAPG Reservoir Heterogeneities and Fracture Systems II
AAPG New Applications of Organic Geochemistry to Exploration
AAPG Prospect Generation from Sequence Analysis

SEPM Major Controls on Fluvial Sedimentology and Stratigraphy
AAPG New and Emerging Exploration Areas
AAPG Geological Aspects of Horizontal Drilling
AAPG Exploring in Fold and Thrust Belts II
AAPG Sequence Stratigraphy—Applications and Models
SEPM Slope to Basin Sedimentation
AAPG Sub-Devonian Plays of North America

Short Courses

AAPG Applied Subsurface Mapping, *June 16–20*
AAPG Geological Applications of Capillary Pressure, *June 20*
EMD Detection of Subtle Basement Structures and Related Hydrocarbon Plays, *June 20*
AAPG Sedimentology and Sequence Stratigraphy of Reefs and Carbonate Platforms, *June 20–21*
SEPM Devonian–Early Mississippian Carbonates of the Western Canada Sedimentary Basin: A Sequence Stratigraphic Framework, *June 20–21*
SEPM Application of Ichnology to Petroleum Exploration—A Core Workshop, *June 21*
AAPG Creating, Managing, and Evaluating Multidisciplinary Teams, *June 21*
EMD Coal Bed Methane: Depositional, Hydrologic, and Petrologic Controls on Reservoir Characteristics of Coal Beds, *June 21*
CSPG Subsurface Dissolution Porosity in Carbonates—Recognition, Causes, and Implications, *June 21*
CSPG Global Patterns of Petroleum Occurrence and Exploration Strategies in Frontier Basins, *June 21*
CSPG Geostatistics for Reservoir Characterization and Management, *June 21*
CSPG Surface Exploration for Oil and Gas: Advances of the '80s, Prospects for the '90s, *June 21*
CSPG Hydrogeology and Waste Management, *June 21*
CSPG Depositional, Diagenetic, and Reservoir Parameters of the Upper Devonian Nisku Shelf, Alberta and Montana—A Core Workshop, *June 25*
CSPG Triassic Reservoir Facies and Exploration Trends, Western Canada Sedimentary Basin, *June 25–26*

Field Trips

CSPG Estuarine Valley-Fill and Coastal Deposits in Tide and Wave-Dominated Settings, Bay of Fundy and Eastern Shore, Nova Scotia, Canada, *June 15–21*
SEPM Depositional Environments and Paleontology of the Judith River and Horseshoe Canyon Formation (Late Cretaceous), Southern Alberta, *June 18–20*
SEPM Fairholme (Upper Devonian) Carbonate Platform-to-Basin Transition, Kananaskis–Banff Area, Southwestern Alberta, *June 18–20*

CSPG Triassic Stratigraphy and Sedimentary Environments of the Williston Lake Area and Adjacent Subsurface Plains, Northeastern British Columbia, *June 18–21*

CSPG Petroleum, Coal, and Environmental Geology—The Central Alberta Basin, *June 19–20*

CSPG Anatomy of the Laramide Foredeep and the Structural Style of the Adjacent Foreland Thrust Belt in Southern Alberta, *June 19–21*

CSPG Structural Geology and Stratigraphy of the Rocky Mountain Foothills and Front Ranges, Crowsnest Pass, Alberta to Sun River Canyon, Montana, *June 19–21*

CSPG Late Cretaceous Clastics—Outcrops and Core, *June 19–21*

EMD Coal, Oil, and Gas Deposits of West Central Alberta, *June 19–21*

CSPG Structural Geology in Rocky Mountain Foothills and Front Ranges, Kananaskis Country, Alberta, *June 20*

CSPG Sedimentology, Structural, and Exploration History of the Mississippian at Moose Mountain, Southwestern Alberta Foothills, *June 20*

SEPM Paleontology of the Burgess Shale/Mount Stephen Trilobite Beds, Yoho National Park, British Columbia, *June 20* or *June 25*

CSPG Sedimentology and Sequence Stratigraphy of the Upper Cretaceous Bearpaw–Horseshoe Canyon Transition, Drumheller, Alberta, *June 20–21*

CSPG The Late Precambrian Yellowhead Carbonate Platform, Jasper, Alberta: Continuous Outcrop from Platform to Basin at the Scale of Seismic Lines, *June 25–26*

CSPG Southern Canadian Foothills—Hydrocarbon Habit and Integrated Resource Planning, *June 25–26*

CSPG Sequence Stratigraphy, Siliciclastic Sedimentology, and Development Geology of the Cardium Formation, *June 25–27*

CSPG Carboniferous Stratigraphy, Tectonics, and Basin Development, Southwestern Alberta, *June 25–27*

CSPG The Upper Devonian Cripple Creek Margin: Internal Geometry and Stratigraphic Evolution, *June 25–28*

EMD The McMurry Formation: Reservoir Heterogeneities Exposed in Outcrop, *June 25–28*

SEPM Upper Devonian Platform Reefs and Inter-Platform Basins, Canmore to Jasper, Alberta, *June 25–28*

CSPG Carbonate Bank-to-Basin Transitions, Frasnian, Cline Channel, Alberta, *June 25–29*

CSPG Stratigraphy and Sedimentology of Strata in the Vicinity of MacKenzie Delta, Northwest Territories and Northern Yukon Territories, *June 25–29*

CSPG Cretaceous Channel Fill in Outcrop, Great Falls, Montana, *June 25–29*

For further information about the annual meeting, contact AAPG, Convention Dept., P.O. Box 979, Tulsa, OK 74104; (918) 584-2555, fax 918-584-0469. The preregistration deadline is May 15.

UPCOMING MEETINGS

7th International Symposium on Water-Rock Interaction, July 13–22, 1992, Park City, Utah. Information: Yousif Kharaka, Secretary-General, U.S. Geological Survey, MS 427, 345 Middlefield Road, Menlo Park, CA 94025; (415) 329-4535, fax 415-329-5110.

International Committee for Coal Petrology, 44th Meeting, July 20–24, 1992, University Park, Pennsylvania. Information: Alan Davis, Penn State University, 205 Research Bldg. E, University Park, PA 16802; (814) 865-6544, fax 814-865-3573.

Society for Organic Petrology, Annual Meeting, July 23–24, 1992, University Park, Pennsylvania. Information: Jim Hower, Center for Applied Energy Research, 3572 Iron Works Pike, Lexington, KY 40511; (606) 257-0261; fax 606-257-0302.

Northeastern Science Foundation/History of Earth Sciences Society, Meeting on the History of Geology, July 29–August 1, 1992, Troy, New York. Information: Gerald M. Friedman, Northeastern Science Foundation, P.O. Box 746, Troy, NY 12181; (518) 273-3247, fax 518-273-3249.

NOTES ON NEW PUBLICATIONS

Stratigraphic Traps I

Edward A. Beaumont and Norman H. Foster edited this 295-page volume in the AAPG Atlas of Oil and Gas Fields series. It contains studies of fields that have traps that are either purely stratigraphic or that combine stratigraphic and structural elements. Also featured is the exploration history of each field in the study.

The volume describes seven traps that are nearly purely stratigraphic traps, including the Berlin field, located in the Anadarko basin, Oklahoma. The Berlin field's trap is an updip pinchout of the distal end of a fan delta sandstone into marine shales. The updip pinchout resulted from reversal of regional dip. Five other fields included in this volume feature traps where structure plays a more important role in determining the location of the trap. Among these fields is the Hitchland field, located in the Anadarko basin, Texas, which has traps that are a combination of an anticlinal nose with porosity pinchouts across the anticlinal nose.

Order from: American Association of Petroleum Geologists Bookstore, P.O. Box 979, Tulsa, OK 74101; phone (918) 584-2555. The price is $24 plus $5.75 for postage.

Stratigraphic Traps II

Edited by Norman H. Foster and Edward A. Beaumont, this 360-page volume in the AAPG Atlas of Oil and Gas Fields series contains studies of fields with traps that are mainly stratigraphic in nature. Structure plays a role in the traps of several fields, but overall, it is clear that the main trapping features with the group of fields in this volume are stratigraphic. The history of each field's exploration and development is also described.

This volume describes 13 fields, including four fields located in the Anadarko basin in Kansas and Oklahoma: the Bindley field and the Lexington field, in Kansas, both have carbonate reservoirs; the Lexington field also has sandstone reservoirs. The East Clinton field, in Oklahoma, and the Stockholm Southwest field, in Kansas, have only sandstone reservoirs. Unconformities play a role in the traps of the Bindley and Lexington fields. The Stockholm Southwest field contains traps with reservoirs and traps related to deposition from channelized flow. East Clinton is predominantly a subaerial valley-fill trap.

Order from: American Association of Petroleum Geologists Bookstore, P.O. Box 979, Tulsa, OK 74101; phone (918) 584-2555. The price is $24 plus $5.75 for postage.

Structural Traps II—Traps Associated with Tectonic Faulting

Edited by Edward A. Beaumont and Norman H. Foster, this 267-page volume in the AAPG Atlas of Oil and Gas Fields series contains studies of fields that exist because of the presence of tectonic faulting. The traps responsible for the fields described in this volume are related either directly or indirectly to a fault block. Of the nine fields included, two are of particular interest to Oklahoma geologists: (1) The Mobeetie field, located in the Anadarko basin, Texas, is the result of a trap indirectly related to a fault block. The anticline associated with the trap formed by differential compaction over a basement fault block. (2) The Red Oak field, located in the Arkoma basin, Oklahoma, comprises traps both in a fault block and in an overlying anticline formed by differential compaction over the same fault block. The fault blocks associated with these fields formed mainly under tensional stresses. Also described in each field study is the history of its exploration and development.

Order from: American Association of Petroleum Geologists Bookstore, P.O. Box 979, Tulsa, OK 74101; phone (918) 584-2555. The price is $24 plus $5.75 for postage.

Geology in Coal Resource Utilization

Sponsored by the Energy Minerals Division of AAPG, this book provides the coal industry with information on how geology and geologic concepts can be applied to the many facets of coal resource location, extraction, and utilization. Edited by Douglas C. Peters, the 581-page volume was designed to give coal-industry managers an idea of the applications and limitations of coal geology and related fields. Case histories are included from which specific techniques can be derived. Chapters address the major coal geology subfields of exploration and reserve definition, reserve estimation, coalbed methane, underground coal gasification, mining, coal quality, and environmental impacts.

Order from: TechBooks, 4012 Williamsburg Court, Fairfax, VA 22032; phone (800) 767-1518. The price is $100, postpaid within the U.S.

OKLAHOMA ABSTRACTS

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

Tectonic Evolution of the Anadarko Basin Region, Oklahoma

WILLIAM J. PERRY, JR., U.S. Geological Survey, Federal Center, Denver, CO 80225

The Anadarko basin occupies the northern flank of the late Proterozoic (?) to early Paleozoic southern Oklahoma aulacogen. The basin began to form as an independent structural feature in Late Mississippian time, when the Texas promontory of the southern continental margin of Paleozoic North America first reacted to early stages of plate collision with Gondwana or an intervening microplate. Late Mississippian to Early Pennsylvanian structural inversion of the core of the southern Oklahoma aulacogen into the Wichita thrust-bounded uplift involved thrust loading of the region to the north, which became the Anadarko basin. Late Pennsylvanian transpression, oblique to the preexisting structural grain, modified the basin and formed numerous thrust-cored, en echelon anticlines within the southeastern part of the Anadarko basin. Many of these structures are erosionally beheaded, flanked by synorogenic sedimentary rocks, and unconformably overlain by undeformed Permian rocks. Latest Pennsylvanian strike-slip faulting in the Arbuckle Mountains is enigmatic and apparently not of great magnitude. The basin continued to subside in Middle Permian time, probably in response to compaction of older rocks, and has been essentially dormant since late Paleozoic time.

Reprinted as published in U.S. Geological Survey Bulletin 1866-A, 1989, p. A1.

Statistical Analysis of Compositional Data from Desmoinesian Sandstones in Oklahoma

THADDEUS S. DYMAN, U.S. Geological Survey, Federal Center, Denver, CO 80225

Desmoinesian sandstones from the northern Oklahoma platform and the Anadarko, Arkoma, and Ardmore basins record a complex interaction between mid-Pennsylvanian source-area tectonism and cyclic sedimentation patterns associated with numerous transgressions and regressions. Framework-grain summaries for 50 thin sections from sandstones of the Krebs, Cabaniss, and Marmaton Groups and their surface and subsurface equivalents were subjected to multivariate statistical analyses to establish regional compositional trends for provenance analysis.

R-mode cluster and correspondence analyses were used to determine the contributing effect (total variance) of key framework grains. Fragments of monocystalline and polycrystalline quartz, potassium and plagioclase feldspar, chert, and metamorphic, limestone and mudstone-sandstone rock fragments contribute most to the variation in the grain population. Q-mode cluster and correspondence analyses were used to identify four petrofacies and establish the range of compositional variation in Desmoinesian sandstones. Petrofacies I is rich in monocrystalline quartz (78–98 percent); mica and rock fragments are rare. Petrofacies II is also rich in monocrystalline quartz (60–84 percent) and averages 12 percent total rock fragments. Petrofacies III and IV are compositionally heterogeneous and contain variable amounts of monocrystalline and polycrystalline quartz, potassium feldspar, mica and chert, and metamorphic and sedimentary rock fragments.

Quantitative analyses indicate that Desmoinesian sandstones were derived from sedimentary, igneous, and metamorphic source areas. Petrofacies I and II sandstones occur predominantly in the lower Desmoinesian and are widely distributed, although they are most abundant in eastern and central Oklahoma; sandstones from petrofacies III and IV are widely distributed and occur primarily in the middle and upper Desmoinesian. The range of compositional variation and the distribution of petrofacies are related to paleotectonics and basin development, sediment recycling, and varying depositional environments.

Reprinted as published in the U.S. Geological Survey Bulletin 1866-B, 1989, p. B1.

Log-Derived Regional Source-Rock Characteristics of the Woodford Shale, Anadarko Basin, Oklahoma

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The Woodford Shale is an organic-rich, highly compacted, "black" shale of Late Devonian and Early Mississippian age that is widely regarded as a major hydrocarbon source rock in the Anadarko basin of Oklahoma. The Woodford is divided here, on the basis of log character, into three informal stratigraphic units: the lower, middle, and upper members of the Woodford Shale. Higher kerogen content of the middle member is the physical basis for this subdivision. Because source-rock properties of each member differ, geochemical and other data are best considered in view of internal Woodford stratigraphy.

Isopachs of the Woodford and its three members reveal a positive structural feature, parallel with and about 75 miles (120 kilometers north of the Wichita Mountains front, that divided the Woodford into northeast and southwest depocenters and was a hinge line separating areas of regional basement flexure during Woodford time. Lower and middle members of the Woodford thicken to the southwest into the now-eroded central trough of the southern Oklahoma aulacogen. The upper member thickens to the northeast toward Kansas, reflecting initial development of the Sedgwick basin of south-central Kansas.

Total organic carbon (TOC, in weight percent) is calculated here from log-derived formation density (ρ_b, g/cm^3) using the equation: TOC = (156.956/ρ_b)−58.272. TOC of the lower, middle, and upper members of the Woodford Shale averages 3.2, 5.5, and 2.7 weight percent, respectively. TOC does not correlate with formation thickness, but does decrease with increasing thermal maturity in response to the progressive generation and expulsion of hydrocarbons.

The total amount of organic carbon in the Woodford Shale of the study area is evenly divided between the lower, middle, and upper members. Of the 73 trillion kilograms of organic carbon mapped here, some 54 trillion kilograms are in thermally mature areas characterized by vitrinite reflectance (R_o) greater than 0.6 percent. Most of the hydrocarbons sourced by the Woodford Shale of the study area were generated from the lower and middle members, in that these two members contain 74 percent of the thermally mature organic carbon.

Reprinted as published in U.S. Geological Survey Bulletin 1866-D, 1990, p. D1.

In Situ Stress Analysis of Wellbore Breakouts from Oklahoma and the Texas Panhandle

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Orientations of crustal stresses are inferred from stress-induced breakouts (wellbore enlargements) in the eastern part of the Anadarko basin in central Oklahoma, the Marietta basin in south-central Oklahoma, and the Bravo dome area of the central Texas Panhandle. Inferred directions of maximum horizontal principal stress (SH_{max}) are east–northeast for the eastern Anadarko basin and northeast for the Marietta basin and the Bravo dome area.

The relative magnitudes of the three principal stresses (S_1, S_2, S_3) are known for the Bravo dome area from existing hydraulic-fracturing measurements, and a normal-faulting stress regime ($S_v > SH_{max} > SH_{min}$) is implied. For the eastern Anadarko basin and the Marietta basin, the magnitudes of the principal stresses are not known. Possible left-lateral oblique slip on the Meers fault during the Quaternary implies that strike-slip ($SH_{max} > S_v > SH_{min}$) and reverse ($SH_{max} > SH_{min} > S_v$) faulting has occurred in south-central Oklahoma. Thus, the study region may be a transition zone between extensional stress in the Texas Panhandle and compressional stress in Oklahoma.

Breakout data from the eastern Anadarko basin yield a single consistent SH_{max} orientation, whereas data from the Marietta basin and the Bravo dome area yield bimodal-orthogonal distributions believed to consist of northwest-oriented breakouts and northeast-oriented fracture-related wellbore enlargements. This northeast (orthogonal) trend in data from the Marietta basin and the Bravo Dome area is probably related to drilling-induced hydraulic fracturing of the wellbore or to preexisting natural fractures or joint sets intersecting the wellbore. On dipmeter log records, breakouts and fracture-related enlargements have similar elliptical cross sections. Orthogonally oriented breakout and fracture-related wellbore enlargements are therefore differentiated by comparing their long-axis orientations with directions of known or inferred horizontal stress.

The mean orientations of either the breakout of fracture-related orthogonal trends in the Marietta basin and the Bravo dome area data sets are not as well constrained as the mean orientation of breakout data for the eastern Anadarko basin. Poorly constrained mean orientations give the appearance of data scatter or dispersion among wellbore enlargement orientations within the northwest and northeast bimodal-orthogonal trends. Drill holes in the Marietta basin and Bravo dome area are located primarily between northwest-striking subparallel faults. Mean data orientations calculated for either orthogonal trend for individual well data sets appear to rotate counterclockwise across these two fault-bounded study areas. Stress trajectory rotation between subparallel faults within the Marietta basin and the Bravo dome study areas may account for the data scatter.

Although breakouts and fracture-related enlargements formed in all parts of the thick sequences of sedimentary rocks logged, they are primarily in limestone, shale, and dolomitic rock, probably because of the abundance of these rock types.

Reprinted as published in U.S. Geological Survey Bulletin 1866-F, 1990, p. F1.

Petrology and Depositional Facies of Siliciclastic Rocks of the Middle Ordovician Simpson Group, Mazur Well, Southeastern Anadarko Basin, Oklahoma

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The Mazur well in the southeastern Anadarko basin of Oklahoma penetrates the McLish (oldest), Tulip Creek, and Bromide Formations of the upper part of Middle Ordovician Simpson Group. Lithofacies and petrographic analysis of 650 ft of core indicates deposition in a rapidly subsiding aulacogen. Lithofacies associations suggest that the deposits accumulated in cycles that consist of mudstone-siltstone-limestone in the lower part of the lithofacies sequence and quartzarenite in the upper part. The lithofacies sequence in the lower part of the cycles is interpreted as deposits of subtidal to intertidal environments. The lithofacies sequences in the upper part of the cycles are deposits of tidal channels.

The sandstones are made up of generally rounded and well-sorted to moderately sorted quartz grains and exhibit highly quartzose characteristics. They consist of framework grains and cement and lack detrital matrix. The framework grains are composed of monocrystalline and polycrystalline quartz (as much as 99 percent); feldspar (as much as 4 percent) including orthoclase, microcline, and perthite; and rock fragments (as much as 12 percent) consisting of chert, micaceous rock fragments, siltstone, shale, limestone, glauconite, collophane, and skeletal fossil fragments. Cements include silica, carbonate, and clay. The silica cement consists of quartz overgrowths, and the carbonate cement comprises calcite, ferroan calcite, ferroan dolomite, and ankerite. The mineralogical and textural maturity of the sandstones suggests deposition in tidal-influenced environments in which winnowing by waxing and waning tidal currents promoted clean, mature sediments.

Reprinted as published in U.S. Geological Survey Bulletin 1866-E, 1989, p. E1.

Thermal Maturation of Eastern Anadarko Basin, Oklahoma

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Vitrinite reflectance (Rm) measurements on samples from wells along a line extending for 125 mi (200 km) from the northern shelf area of the Anadarko basin near the Kansas State line south to the deep part of the basin show that the level of thermal maturity of sedimentary organic matter in the samples was set after maximum burial.

Burial history reconstruction curves show the tectonic evolution of this area: minimal subsidence occurred in the northern part of the basin in the Early Paleozoic, and moderate to rapid subsidence occurred throughout most of the remaining part of the basin from the Middle Ordovician to Permian. Temperatures determined from reflectance values are high as compared to those generally accepted for the onset of hydrocarbon generation and also to those obtained from other similar studies in the basin. Regression analysis yields a reflectance gradient of 0.109 percent Rm/1,000 ft (300 m) along the profile. Isoreflectance lines show the depth to the 0.6- and 1.3-percent Rm levels, the window of oil generation. The isoreflectance lines can be used to estimate the level of thermal maturity above or below them.

Reprinted as published in U.S. Geological Survey Bulletin 1866-C, 1989, p. C1.

Composition, Clay Mineralogy, and Diagenesis of the Simpson Group (Middle Ordovician), Grady County, Oklahoma

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Mineralogic and petrologic analyses were performed on more than 110 core samples of the Middle Ordovician Simpson Group in the Sunray DX, Parker No. 1, Mazur well, Grady County, Oklahoma. Core was recovered from present depths in the Anadarko basin of about 15,900–17,200 ft and includes (in descending order) all or parts of the Bromide, Tulip Creek, McLish, Oil Creek, and Joins Formations of the Simpson Group.

The whole-rock mineral composition of the samples is mainly related to varying lithology and degree of carbonate cementation. Most shale is clay rich and quartz poor, averaging about 85 percent clay minerals, 7 percent quartz, and 3 percent feldspar, by weight, as determined using X-ray powder diffraction. The high clay/quartz ratios suggest that much of the shale may have formed from either reworked, altered volcanic ash or that silica was expelled from shale by diagenetic processes during burial. Most sandstone is quartz-arenite and some subfeldspathic arenite; quartz graywacke is also present. Little late silica cement is found in adjacent sandstones; however, early quartz overgrowth cement is ubiquitous in most sandstones. Excess silica from the alteration of glass to clay or expelled from shale during diagenesis and then transported undip in solution may have been a source for early silica cement in shallower sandstones.

Discrete illite and interstratified illite/smectite having low (<15 percent) expandability (R≥1) are the main clay minerals. Iron-rich, authigenic chlorite cement is locally concentrated in some sandstones. Illite and illite/smectite commonly make up more than 90 relative weight percent of the clay minerals in sandstone and more than 95 relative weight percent of those in shale and carbonate rocks.

Scanning electron microscopy reveals that much of the illite is diagenetic and is present as tabular fibers in pores or as pseudomorphic intergrowths after smectite. Illite is also present as overgrowths evident as sericitic cement in thin section examination. Most chlorite in sandstones is authigenic and is present as pore-lining cement or as pseudomorphic replacement after kaolinite. A clay-mineral assemblage consisting of illite, ordered illite/smectite (R≥1), and chlorite and without smectite and kaolinite suggests that burial temperatures exceeded 150°C. This interpretation is supported by burial- and thermal-history reconstructions for the Mazur well.

Carbonate cements are abundant throughout the entire Simpson sequence. Early iron-poor calcite cement is commonly replaced by iron-rich calcite, dolomite, or ankerite. Rhombic dolomite in sandstone and in carbonate rocks commonly has overgrowths of ferroan dolomite or ankerite. Cementation and (or) replacement by ankerite is later than calcite or iron-free dolomite and is generally less selective. Dolomite and ankerite cements commonly replace detrital clay and calcite. Spatial and textural relations suggest that the conversion of smectite to illite contributed, in part, to the formation of dolomite and ankerite cements.

Secondary porosity, formed mainly from the dissolution of intergranular carbonate cements, is best developed in sandstones from the Oil Creek and Tulip Creek Formations. Maximum porosity measured from point-count analysis is 11 percent.

Reprinted as published in U.S. Geological Survey Bulletin 1866-H, 1991, p. H1.

Stockholm Southwest Field

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The Stockholm southwest (SW) field, discovered by Texas Oil and Gas Production in March 1979, is located in southwest Wallace and northwest Greeley Counties, Kansas, and eastern Cheyenne County, Colorado. It consists of 87 original oil wells which have produced 5.5 million bbl of oil. As of the middle of 1989, it was producing almost 1,200 bbl of oil/day from 66 active wells.

Regionally, the Stockholm SW field is situated on a stable Paleozoic platform which extended north from the Anadarko basin. During early late Morrowan time, there was a significant regression of the Anadarko sea. The subsequent Stockholm fluvial system created an erosional valley which was later back-filled with fluvial and estuarine sediments during transgressions of the Anadarko sea. Regionally, the upper Morrow section is approximately 85 ft (26.2 m) thick, whereas it is approximately 150 ft (46.2 m) thick in the Stockholm Valley. This striking thick can be mapped seismically. Subsequent valley systems subparallelled the preexisting Stockholm Valley system, depositing the overlying Johannes sandstone, which is a secondary pay at Stockholm SW.

Since the discovery of Stockholm SW field, subsequent exploration activity has extended the productive trend five townships in a north–south direction along the Colorado/Kansas border. This activity has led to the discovery of eight new oil fields. Conservative engineering estimates indicate approximately 170 million bbl of oil in place in the entire trend.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 75, p. 1397, August, 1991.

Regional Subsurface Analysis of the Western Anadarko Basin, Western Oklahoma and Texas Panhandle, Employing Computer-Generated Maps and Cross Sections

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Current computer technology and commercial data sources provide explorationists with important regional perspectives in mature productive areas. Previously, without the computer, comprehensive regional analyses were costly and time consuming and, when accomplished, effectively delayed prospect generation. Regional maps generated by the computer on a wide variety of stratigraphic horizons and intervals often furnish insights which are valuable to exploration efforts.

A large portion of the western Anadarko basin, approximately 16,000 mi^2, was analyzed with a commercial database containing over 28,000 well records and approximately 250,000 correlated tops in this area. These formation tops along with commercially available digital land grid and exploration software were utilized to generate a comprehensive suite of structure, contour, isopachous, and isochore maps. An analysis with these maps provides an extensive and detailed look at the western Anadarko basin and reveals stratigraphic and structural relationships which help generate prospect leads. These relationships are usually not recognizable by county-wide or smaller area studies.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 75, p. 1396, August 1991.

Geochemical Surface Anomaly Distribution Above Active Hydrocarbon Source Beds: Anadarko Deep Example

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Surface geochemical surveys were run on all available county roads across the deep part of the Anadarko basin in Caddo, Custer, and Washita Counties, Oklahoma. In the Anadarko Deep there are three major mature petroleum source horizons: Woodford, Springer–Morrow, and Middle–Upper Pennsylvanian marine shales. In most of the area surveyed, the Woodford is post mature. However, the Springer–Morrow and Middle–Upper Pennsyvlanian horizons are currently in the oil and/or thermal gas-generating windows.

Surface gamma-ray surveys were run over 1,708 mi in T8–9N, R13–19W to see if there were areas of discrete detectable microseep alteration (anomalies) or whether the entire generating area would be without anomalous contrast. Data were analyzed and anomalies were noted. The anomalies were then plotted against the position of major structural elements and drilling results.

Discrete areas of anomalies were noted, many coincident with established production. More importantly, large areas were seen to be without anomalies. It is most probable that the detectable microseeps at the surface are associated with gathered concentrations of hydrocarbons at depth since the entire area was not found to be anomalous.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 75, p. 1395, August 1991.

Mississippian Facies Relationships, Eastern Anadarko Basin, Oklahoma

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Mississippian strata in the eastern Anadarko basin record a gradual deepening of the basin. Late and post-Mississippian tectonism (Wichita and Arbuckle orogenies) fragmented the single large basin into the series of paired basins and uplifts recognized in the southern half of Oklahoma today.

Lower Mississippian isopach and facies trends (Sycamore and Caney Formations) indicate that basinal strike in the study area (southeastern Anadarko basin) was predominantly east–west. Depositional environment interpretations made for Lower Mississippian strata suggest that the basin was partially sediment starved and exhibited a low shelf-to-basin gradient. Upper Mississippian isopach and facies trends suggest that basinal strike within the study area shifted from dominantly east–west to dominantly northwest–southeast due to Late Mississippian and Early Pennsylvanian uplift along the Nemaha ridge.

Within the study area, the Chester Formation, composed of gray to dove-gray shales with interbedded limestones deposited on a carbonate shelf, thins depositionally into the basin and is thinnest at its facies boundary with the Springer Group and the upper portion of the Caney Formation. As basin subsidence rates accelerated, the southern edge of the Chester carbonate shelf was progressively drowned, causing a backstepping of the Chester Formation calcareous shale and carbonate facies. Springer Group sands and black shales transgressed northward over the drowned Chester Formation shelf.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 75, p. 1398, August 1991.

Exploring the Wichita Mountain Front—With New Parameters

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Understanding the short south flank of the Anadarko basin has been limited by a lack of well control and extremely poor seismic data in this complex trend. This flank lies immediately south of the synclinal axis of the Anadarko basin and has been uplifted nearly 40,000 ft in a space of 5 to 10 mi. Variously called the Wichita Mountain front or the buried Wichita–Amarillo mountains, this trend separates the deep Anadarko basin from the Hardeman or Palo Duro basin to the south. With tensional forces during the Acadian and Wichitan orogenies, then compressional movement in the Late Pennsylvanian (the Arbuckle orogeny), this 250-mi trend traverses more than half of southwestern Oklahoma. It extends from the Arbuckle Mountains westward into the Texas Panhandle and is noted for its early shallow oil and gas fields in its uppermost blocks. For the past 25 years deeper drilling, especially in Beckham County, Oklahoma, and Wheeler County, Texas, has found huge quantities of gas in the lower Paleozoic carbonates. These limestones and dolomites in the Hunton and Arbuckle are becoming attractive targets because of the recent activity at Cottonwood Creek, Susie Pi-Hoodle (Alden area), and the new Park Avenue well south of Cordell. In February 1991 an extensive 460-mi survey of 28 seismic lines was completed—shooting with the intent to image the intermediate fault blocks that bring those carbonates up from 40,000 ft of burial to the surface along the Wichita Mountain front. For the first time, detailed high-resolution data has been obtained in previously poor-to-questionable record areas. Including a series of dip lines from West Mayfield to Lawton that show the structural style and types of hydrocarbon traps that are attracting large exploration dollars, this talk will also discuss the new parameters needed to obtain high-quality data.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 75, p. 1398, August 1991.

Dynamics of High Level A-Type Sheet Granite Crystallization

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Cambrian rifting produced the bimodal gabbro-granite-rhyolite of the Wichita Mountains Igneous Province, Oklahoma. Layered gabbros formed an extensive substrate (≈3–4 km) for an ≈1.4 km thick overlying rhyolite volcanic pile. Intrusive into the base of the volcanics are a series of thin (≈0.5 km) but laterally extensive (20–55 km), high SiO_2 (71.0–77.6 wt. %) Hb–Bl–Mt alkali-feldspar leucogranite sheets of the Wichita Granite Group (WGG). The WGG has typical A-Type characteristics (e.g., magmatic Fl) including a "within plate" trace element signature. The WGG crystallized from high T, relatively "dry" magmas. Measured Zr concentrations suggest temperatures in excess of 900°C. Abundant granophyre, miaroles, and intrusion into coeval volcanics indicate emplacement pressures as low as the 10^2 bar range. Comparison with the 1 kb T-xH_2O phase relationships of the A-Type

Watergums granite (Clemens et al., 1986) suggest crystallization extended from a liquidus T of ≈900–975°C with an initial xH_2O <2.8 wt. %, down to a solidus T of <730°C and a xH_2O ≈4.2 wt. %.

Several textural, mineralogic and chemical granite varieties are present within individual sheets. Coarser-grained (≈1 cm) seriate and finer-grained granophyric microgranite predominate. Porphyritic and pegmatitic granite are rarer. Fine-grained granite commonly occurs as stoped blocks in coarse grained granite and may represent a more differentiated margin of the sheets. Abundant miaroles at the base of stoped blocks indicate upward volatile migration during crystallization. Segregation of residual melt formed late stage aplite dikes. Modal layering of mafic minerals is observed and can exhibit "crossbedding." Internal magmatic contacts, defined by changes in grain size or modal abundance of quartz, also produce a subtle layering within broadly, texturally homogeneous granite sheets. Within individual sheets distinct mineralogic domains (e.g., Hb–Mt–Sp; Bi–Mt–Fl) also exist. Hb and Bi commonly exhibit antipathetic modal variation and in some domains both phases are replaced by Mt–Fl a trend consistent with increasing fluorine fugacity and oxidation state during crystallization.

The laterally extensive nature of individual granite sheets, settling of granite/rhyolite blocks and crossbedded segregations of mafic minerals show that the WGG crystallized from relatively fluid melts. We suggest that high fluorine activities implied for these magmas significantly lowered the viscosity of these magmas. This feature coupled with the extended temperature range for crystallization enhanced the effectiveness of processes such as gravitational settling, flow sorting, volatile migration and magma chamber recharge in producing textural and limited chemical variability within high level sheet-like granite magmas that otherwise should have rapidly quenched upon intrusion.

Reprinted as published in the Geological Society of America *Abstracts with Programs, 1991*, v. 23, no. 5, p. A328.

Three Dimensional Fluid Flow and MVT Ore Genesis in the Midcontinent Basins of North America

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Recent hydrogeologic studies suggest that most MVT-type ore deposits form soon after tectonic compression and uplift of foreland basins and the onset of gravity-driven flow as shown by Garven and Freeze (1984). Similar hydrogeologic events appear to have played a major role also in the migration and entrapment of some of the world's largest oil pools. Attractive features of this hydrologic model include the relatively large volumes of fluid transport, elevation of groundwater temperature in discharge areas due to forced heat convection, and apparent timing to tectonic events in foreland basins adjacent to areas of stratabound mineralization. There are questions, however, regarding the hydrology and geochemistry of ore precipitation, the availability of salt, the generation of basinal brines, and the role of three-dimensional flows that still need to be resolved.

A new effort is underway to better characterize the three-dimensional patterns of brine migration, heat transport, and ore formation at both the basin and district scales. This is especially needed for assessing the paleohydrogeology in the Midcontinent of North America where a number of orogenic events controlled the evolution of regional flow systems and ore formation throughout the Phanerozoic. Deformation and uplift of the Appalachian forelands resulted in westerly brine migration which was followed by northwesterly and finally northerly flow patterns as the Ouachita and Wichita mountains were uplifted in the late Paleozoic. The Appalachian and Ouachita flow systems waned in the Mesozoic with erosion, and emergence of the Rocky Mountains created new easterly directed flow but this system appears to have been too weak to have played an important role in ore mineralization. The evolution of these flow systems is being quantified hydrologically with three-dimensional modeling and work in progress will be discussed. Detailed district-scale simulations illustrate with remarkable realism the effects of permeability and structural features on district-scale flow and patterns of mineralizations.

Reprinted as published in the Geological Society of America *Abstracts with Programs, 1991*, v. 23, no. 5, p. A20.

Layered Proterozoic Rocks and a Proterozoic Angular Unconformity Beneath the U.S. Midcontinent on COCORP and Reprocessed Industry Seismic Reflection Data

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A thick sequence of Proterozoic layered rocks is observed on COCORP deep reflection data to lie hidden beneath the Phanerozoic cover of the U.S. midcontinent. Increasingly available industrial seismic reflection data sets throughout this region, reprocessed in conjunction with the COCORP data, continue to map these layered rocks and delineate their distribution and structure.

Presently observed on COCORP data beneath southern Illinois and Indiana, and southwest Oklahoma and adjacent Texas, this Proterozoic layered assemblage as a whole varies from 1 to 3 times the thickness of the entire overlying Phanerozoic section. Beneath southern Illinois and Indiana the layered assemblage is imaged on COCORP data for close to 200 km in an E–W direction. Reprocessed industrial reflection data reveal that the assemblage also continues a considerable distance to the north in Illinois, and potential field data and proprietary industry reflection data suggest an even broader distribution.

These Proterozoic layered rocks occur within the region of the Middle Proterozoic "Granite–Rhyolite province" of the U.S. midcontinent, an area within which scattered wells to basement commonly encounter 1.3–1.5 Ga undeformed granite and/or compositionally similar rhyolite. Therefore, these layered rocks may comprise a thick admixture of silicic volcanic and volcaniclastic rocks between scattered volcanic-intrusive centers such as the St. Francis Mountains of SE Missouri (perhaps also injected by mafic sills). On the COCORP data and especially on reprocessed industry reflection data from this region, a significant angular unconformity is locally observed at the base of this Proterozoic layered assemblage. This angular unconformity also may define the base of the 1.3–1.5 Ga Granite–Rhyolite Province, and may give an indication of the substantial volume of lower crustal material that was mobilized during middle Proterozoic time by anatectic melting. It appears, however, that basement-penetrating drill holes in these regions commonly are located above anomalous basement highs or at potential field anomalies, and thus may over-sample granite and rhyolite. Therefore, it is likely that the rocks of the layered assemblage are distinctly under-sampled and may contain a largely unknown sedimentary sequence of regional extent. Continuing efforts include expanding the reprocessing of industry seismic data throughout the region to further map the structure and evolution of this Proterozoic sequence.

Reprinted as published in the Geological Society of America *Abstracts with Programs, 1991*, v. 23, no. 5, p. A315.

Tidal Influence Within Pennsylvanian Sandstones

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Within Pennsylvanian-age strata of the Illinois basin, large-scale, linear sand bodies have been previously interpreted as fluvial and deltaic in origin. Nonetheless, analyses of the fine-scale sedimentology and bed forms within such sandstones and the associated shales indicate that tidal processes greatly influenced the depositional environments within such lithofacies. Recent work on Mid-Continent Pennsylvanian-age sandstones indicates the occurrence of similar depositional environments.

Based upon the pervasive tidal influence observed within such strata, environmental analogs other than fluvial and deltaic bear consideration. In general, tidally influenced estuarine models seem particularly appropriate. Within such settings, the changeover from a fluvially dominated deposystem to tidally influenced estuary occurs during transgressive phases. Despite the tidal influence that can be interpreted from the sedimentology, the strata contain few, if any, marine indicators because of the low salinities that occurred during deposition. In addition, high rates of sedimentation result in a high degree of preservation of organic materials derived from terrestrial sources.

Ongoing work in the Mid-Continent indicates that Morrowan, Atokan, Desmoinesian, Missourian, and Virgilian sands share a number of similarities with the tidally influenced environments delineated in the Illinois basin studies. Thus a tidal/estuarine interpretation might be a generalizable model for many Pennsylvanian sandstones. In addition, enhanced understanding of the siliciclastic parts of Mid-Continent cyclothems provides a more useful framework for documentation of carbonate/siliciclastic interrelationships. Oscillations of carbonate/siliciclastic environments may be more readily explainable by climatic cycles rather than by traditionally popular depth-related facies models.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 75, p. 1392, August 1991.

Formation Evaluation in Pressure-Depleted Reservoirs

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Wells drilled within the Mid-Continent frequently penetrate reservoirs that have undergone significant pressure loss due to offset production. Recognition of this pressure depletion, through wireline and mud-log interpretation, is crucial to proper completion (or plugging) decisions and evaluation of reservoir continuity between wells. Reservoirs exhibiting symptoms of low pressure can still be capable of commercial production but sometimes require alteration of standard drilling and completion procedures.

Locally excessive hydrostatic overbalance causes penetration rates to slow significantly in a depleted zone, with expected drilling breaks absent or reversed. Slow drilling in turn causes mud-log gas increases, which are a function of hydrocarbon-bearing rock volume drilled per unit of time, to be small or absent. The depth of origin of cuttings is commonly misinterpreted, and objective sandstones are frequently logged as absent due to lack of a normal drilling break. Chromatographic composition of gas readings remains essentially unchanged, allowing evaluation of fluid types and contacts, although the small gas concentrations can strain instrument resolution limits. Lost circulation due to excessive overbalance is a common problem in exhausted reservoirs, resulting in drilling difficulties, loss of cutting and mud-log gas data, and subsequent completion problems. Unlike the mud-log data, which routinely paint a dismal picture of reservoir potential, wireline log effects are less consistent and can generate unwarranted optimism. Low-pressure zones are commonly characterized by excessive mud cake, and exaggerated neutron-density gas effect because of the low fluid density, and an altered resistivity invasion profile.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 75, p. 1398–1399, August 1991.

Bore Hole Temperatures and the Climate Record in the Midcontinent of North America

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Regression analysis of climate data in the midcontinent of North America shows that climate change in the past century correlates with latitude. Warming has been greater in northerly latitudes (43–55°N), lesser-to-no change has occurred at latitudes 36–43°N, and cooling has occurred at latitudes 30–36°N. Temperature-depth profiles in 100–200 m deep bore holes in the north-central U.S. contain a record of this climate change also showing that the ground-surface temperature has increased during the past century. The increase in ground temperature also correlates with latitude showing a 2.4°C increase between 46–49°N, a 1.0–1.5°C increase between

43–46°N and negligible change between 40–43°N. Agreement between these two different data sets suggests that ground temperature profiles obtained in heat flow and geothermal studies contain meaningful information on climate change.

We tested this hypothesis with data from bore holes located close to weather stations, and have applied both analytical and numerical models in the analysis. The temperature increase deduced from bore holes exceeds that calculated by linear-regression of the climatic data. This implies that linear regression is inadequate for analysis of climatic data and that the step and ramp models used for analysis of subsurface temperature data are also inadequate. To explore this problem further, we analyzed climatic data using numerical models of temperature-depth relations in which climate data force subsurface temperatures over time. We display the results as color images of temperature and depth over time. Near the surface, interannual variability generates oscillatory patterns, but at depths below the level of penetration of the annual pulse, longer period warming trends raise the isotherms and cooling trends lower the isotherms. This type of analysis is superior to any statistical treatment of the climate data because it does not rely on an assumed probability model.

Reprinted as published in the Geological Society of America *Abstracts with Programs, 1991*, v. 23, no. 5, p. A341.

Reservoir Characterization with Limited Information

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It is now possible to estimate the external geometry and the internal reservoir heterogeneity of potential producing zones from a single well. Information from logs and samples often is sufficient to make a unique interpretation of the depositional origin of the potential producing zone. Most wells drilled in the Mid-Continent test specific structural or stratigraphic prospects based upon limited subsurface information. Even without core, seismic, and dipmeter information, multivariant analysis of logs and samples is sufficient for comparison to Holocene depositional patterns.

Recognition of the origin of the reservoir interval allows comparison to similar producing reservoirs. Production experience can be used to design both completion and field development programs. Patterns of directional permeability, geometry of flow units, sweep potential, and primary and secondary recovery potential can be estimated. This allows decisions to be made on well spacing, perforation interval, and frac design.

The analysis of all available information can make the difference in completing a successful well and in confirming the play concept. A common failure is that an early effort is not made in synthesizing information to make the correct decisions.

The expert system illustrated provides the framework for data analysis and the nature of information that can be used for determining relative probabilities for specific reservoir characteristics.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 75, p. 1399, August 1991.

Inorganic Gases in Natural Gas as an Indicator of Subcrustal Events in Southeastern Colorado

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Helium, nitrogen, and argon are small, chemically unreactive molecules which can diffuse through a gas-field cap rock relatively rapidly compared to hydrocarbons. To maintain the concentration of these species over geologic time spans, the rate of influx of these gases must at least equal their diffusional loss rate.

Nitrogen in natural gas is generally believed to result from the thermal degradation of nitrogen-bearing organic compounds. Helium and argon are usually thought to be of crustal radiogenic origin. An alternate source of all three gases may be subcrustal outgassing.

Anomalously high concentrations of He, Ar, and N_2 occur in the natural gases of southeastern Colorado. The diffusional flux of He and Ar from gas fields and the generation rate of these through radioactive decay indicate insufficient concentrations of uranium, thorium, and potassium exist within the normal compositional range of the earth's crust. For nitrogen, there is insufficient organic carbon in the sedimentary column to generate the observed volumes of N_2 unless the thermal degradation of organics is a recent event. Anomalous concentrations of He, Ar, and N_2 suggest the presence of a subcrustal outgassing and thermal event under southeastern Colorado.

The occurrence of a subcrustal event could correlate with the anomalously high heat flow in eastern Colorado, the recent (less than 5 Ma) epeirogenic uplift of the Great Plains, the thickest continental crust in the Mid-Continent, and recent nearby vulcanism.

Reprinted as published in the American Association of Petroleum Geologists *Bulletin*, v. 75, p. 1397, August 1991.

Surface Faulting and Earthquake Recurrence in "Stable" Continental Interiors—Examples from Australia and North America

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Earthquakes in "stable" continental interiors (SCI) are rare relative to those along plate margins, but they can potentially cause widespread damage because of low regional attenuation and because the human population is usually ill prepared to cope with severe ground motion. Past earthquake-hazard assessments of SCI have relied on statistical analyses of seismicity because geologic data on the behavior of seismogenic faults were virtually nonexistent. Worldwide, only 10 historical SCI earthquakes have formed surface ruptures—five have occurred in Australia since 1968 and the first occurred in North America in 1989. In addition to these historical events, written reports and verbal accounts identify as many as eight prehistoric fault scarps in Australia. In the SCI of the United States, known prehistoric scarps exist on the Meers and Criner faults, Oklahoma, and possible latest Quaternary surface faulting is reported at Harlan County Lake, Nebraska. Considering the increasing number of such reports in recent years, a systematic search of SCI will likely show that prehistoric ruptures are more common [than] previously thought.

Our geological studies of the scarps from the 1988 Tennant Creek and 1986 Marryat Creek earthquakes in Australia, and the prehistoric scarp on the Meers fault, Oklahoma, show that the recurrence intervals for surface rupturing on these faults are several tens of thousands of years or more. At Tennant Creek, thermoluminescence dating of eolian sand indicates that the penultimate faulting event occurred more than 60,000 yr ago. At Marryat Creek, the lack of topography associated with the scarp and the moderately developed soil exposed in two trenches indicate that the recurrence of surface-rupturing events is measured in at least tens of thousands of years. On the Meers fault, middle Holocene and middle Pleistocene deposits are vertically offset similar amounts, which implies a long-term average recurrence interval of more than 100,000 yr. In each case, the Recent earthquakes reactivated ancestral faults that formed in Proterozoic (Tennant and Marryat Creeks) or early Paleozoic (Meers) time.

Earthquake hazard assessments of SCI are hindered by an incomplete inventory of fault scarps, poor knowledge of the behavior of seismogenic faults, and the aseismic character of some seismogenic faults. If recurrence intervals of tens of thousands of years or more typify SCI faults, then, on a human time scale, the hazard posed by a single fault is small; but if many faults are present, then the hazard could be greater. Better hazard assessments in SCI might result from statistically computing a composite recurrence interval for all faults in a region and using this interval to evaluate the probability of a specific site being affected by a damaging earthquake.

Reprinted as published in the Geological Society of America *Abstracts with Programs, 1991*, v. 23, no. 5, p. A431.

Genetic Implications of Regional and Temporal Trends in Ore Fluid Geochemistry of Mississippi Valley-Type Deposits in the Ozark Region

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Fluids extracted from aqueous fluid inclusions in epigenetic gangue and ore minerals record the migration of huge volumes of highly saline fluids throughout the stratigraphic section of the Ozark region. The extracted fluids share many similarities regionally, but there are significant temporal differences which define two geochemically distinct end-member ore-forming fluids that we refer to as the Viburnum Trend main stage or Viburnum Trend type and the Tri-State type.

Viburnum Trend-type fluids are enriched in potassium and are associated only with deposits close the the basal Lamotte Sandstone. The main-stage octahedral galena ore of the Viburnum Trend and much of the Old Lead Belt ore is thought to be derived from this type of ore fluid. Galena deposited by Viburnum Trend-type fluids contains less radiogenic lead than galena deposited by Tri-State-type fluids. Sulfides deposited by Viburnum Trend-type fluids also contain isotopically heavier sulfur and significant amounts of copper, cobalt, nickel, and silver.

Tri-State-type fluids have a low potassium content when compared with Viburnum Trend-type fluids and are characteristic of deposits where ore-forming fluids migrated through large volumes of carbonate rock. These fluids are thought to have formed the ore deposits of the Tri-State, Northern Arkansas, and Central Missouri districts, the cubic galena-stage ore of the Tri-State, Northern Arkansas, and Central Missouri districts, the cubic galena-stage ore of the Viburnum Trend, and the many trace occurrences of sphalerite throughout the Ozark region. Galena deposited by Tri-State-type fluids has more radiogenic lead and the sulfides have isotopically lighter sulfur than sulfides deposited by Viburnum Trend-type fluids. A systematic south to north increase of potassium in the Tri-State-type fluids suggests that they migrated from a southerly source such as the Arkoma basin.

Possible explanations for the origins of these two end-member fluids include: (1) a single parent brine evolved into two distinct fluids due to reactions with geochemically distinct aquifers during migration, (2) the two distinct fluids reflect normal fluid evolution within a single source basin of a bittern and of later halite dissolution, and (3) the Viburnum Trend and Tri-State-type brines migrated to southeast Missouri from two different source basins. Our data does not preclude any of these possibilities; however, the geochemical similarity of the Viburnum Trend end-member fluid to a bittern may be accounted for by water-rock modifications of the brine during migration. Other evidence strongly supports a southerly source for the ore-forming brines thus limiting possible sources for the Viburnum Trend-type fluid to the Arkoma and/or Black Warrior basins of the Ouachita foreland trough. Viburnum Trend-type fluid flow was probably funneled northward through basal sandstones within the Reelfoot rift and water-rock modifications occurring there may have resulted in its unique geochemistry.

Reprinted as published in *Economic Geology*, v. 85, p. 842, July 1990.

Catastrophic Release of Heat and Fluid Flow in the Continental Crust

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Heat may be released catastrophically from the continental crust by the onset of free convection in orogenic zones. Orogeny itself could create the conditions necessary for free convection by increasing the permeability of the crust. In the specific case of a continental collision zone, the conditions favoring free convection may move progressively into continental interiors, perhaps leading to repeated episodes of convection and related thermal events. Simple models and assumptions suggest that individual episodes of convective circulation and heat release persist for periods of time of the order of 10^6 yr or less. The rate and magnitude of energy release depend upon the initial thermal state and permeability of the crust and the depth of fluid circulation. Estimates made from typical parameters indicate that the total thermal energy released from the crust is approximately equivalent to an increase of background heat flow from about 60 to 200 mW/m^2 for a period of 10^6 yr. A significant amount of this heat can be transported into the interior of a continent by a gravity-driven flow system if a continuous aquifer of sufficient permeability is present. The hypothesis could explain several phenomena attributed to tectonically driven fluids associated with the Alleghenian–Ouachita orogeny. These include the formation of Mississippi Valley-type lead–zinc deposits, widespread potassic alteration, and remagnetizations. Although speculative, the hypothesis is consistent with our current state of knowledge concerning the extent of fluid circulation in the continental crust.

Reprinted as published in *Geology*, v. 20, p. 83, January 1992.