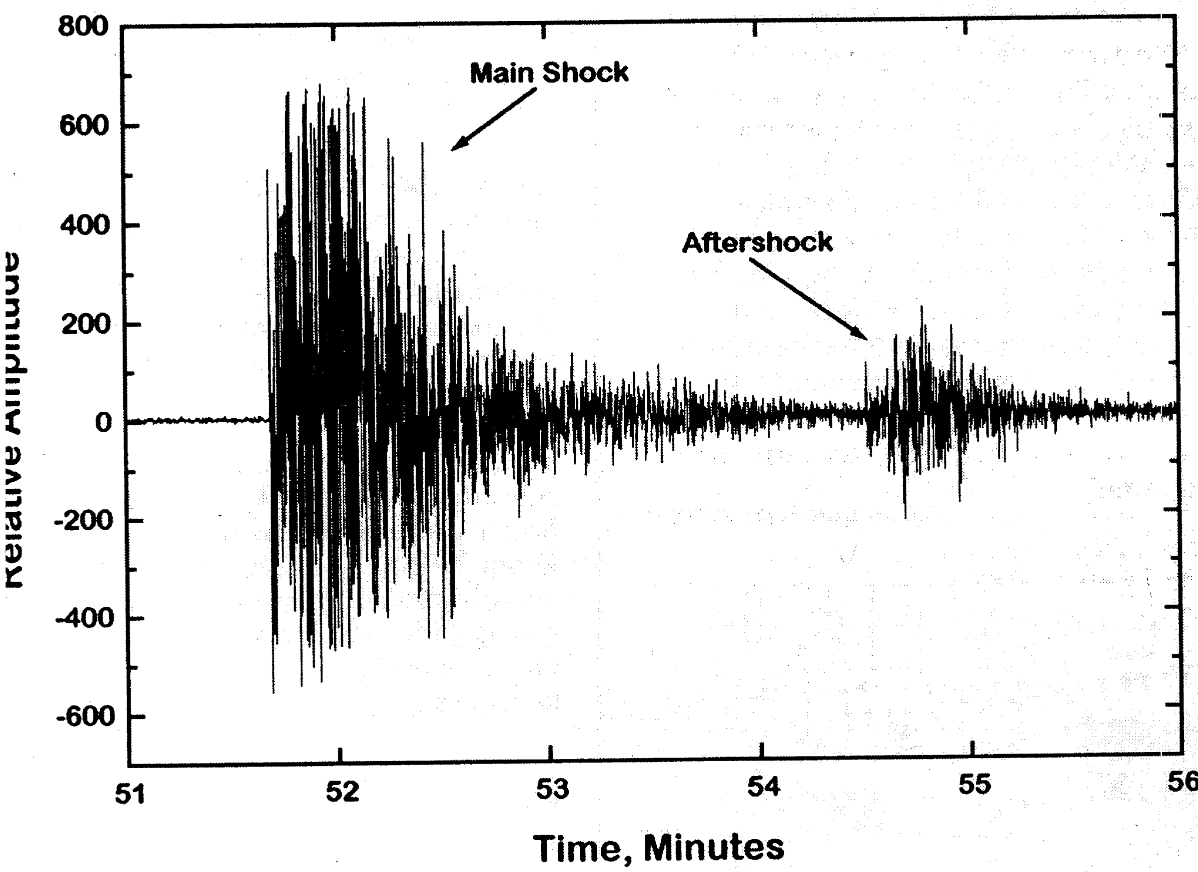
OKLAHOMA GEOLOGY

April, 1995



Vol. 55, No. 2

On The Cover —

Antioch Earthquake Recorded by the OGS Digital Seismic System

A magnitude-4.2 earthquake shook central Oklahoma at 9:52 a.m. CST on January 18, 1995. This earthquake was followed by a small after-shock about 3 minutes later. The epicenter was tentatively located near Antioch, ~12 mi west of Pauls Valley, Garvin County, Oklahoma (Fig. 1). The Oklahoma Geological Survey's seismograph stations, as well as numerous stations throughout the United States and Canada, recorded the quake. The digital recording (on the cover) of the Garvin County earthquake and after-shock was made by station FNO (jointly operated at Norman by the Oklahoma Geological Survey and the School of Geology and Geophysics at the University of Oklahoma).

The earthquake was reported felt in southeast Tulsa, Oklahoma City, and Mustang, Oklahoma. Some residents near the epicenter reported pictures falling from walls and dishes falling out of storage cabinets. No major damage was reported.

Since 1978, numerous earthquakes have occurred within a 25-mi-wide by 38-mi-long fault zone that extends between Norman and Pauls Valley, Oklahoma. Of the ~50 earthquakes that occur in Oklahoma annually, almost half are located within this fault zone.

(continued on page 84)

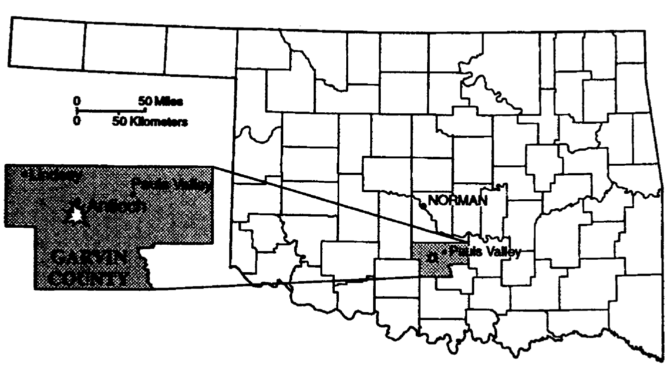


Figure 1. Approximate location of the Garvin County earthquake, near Antioch, January 18, 1995.

OKLAHOMA GEOLOGICAL SURVEY

CHARLES J. MANKIN
Director

KENNETH S. JOHNSON
Associate Director

OKLAHOMA GEOLOGY NOTES

Editor
Christie Cooper

Editorial Assistant
Tracy Peeters

Cartography
T. Wayne Furr, *Manager*
James H. Anderson
Charlotte Lloyd

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

This publication, printed by the Oklahoma Geological Survey, Norman, Oklahoma, is issued by the Oklahoma Geological Survey as authorized by Title 70, Oklahoma Statutes 1981, Section 3310, and Title 74, Oklahoma Statutes 1981, Sections 231–238. 1,500 copies have been prepared for distribution at a cost of $1,180 to the taxpayers of the State of Oklahoma. Copies have been deposited with the Publications Clearinghouse of the Oklahoma Department of Libraries.

OKLAHOMA GEOLOGY

Notes

C O N T E N T S

VOL. 55, NO. 2

Effects of Bias in the Oklahoma Earthquake Catalog

John E. DeLaughter[1]

Abstract

Bias in an earthquake catalog may be caused by masking events with noise or by adding events. Phasor plots and rose diagrams are two independent statistical tests for the presence of bias in a catalog. In some cases, they may indicate the cause of bias. Bias, due to masking, is shown to be present in the Oklahoma earthquake catalog for low magnitude events. An apparent bias, due to added events, may be present for large magnitude events, but the apparent bias may be due to a statistical artifact.

Introduction

For the purposes of this paper, bias in an earthquake catalog is defined as a variation from a statistically random distribution of earthquake occurrence times for any magnitude level. This definition closely follows that of Rydelek and Sacks (1989). It should be noted that the presence of statistical bias in a catalog cannot be taken as an absolute proof of unexpected behavior. Instead, it should be used as a diagnostic tool to identify potential problems in interpretation of a catalog.

The causes of biasing can be divided loosely into two sets: (1) those that bias by removing, or masking, events and (2) those that bias by adding events. Masking occurs when, in an otherwise standard distribution of earthquakes with respect to time, some source of noise prevents the detection of earthquakes below some magnitude for some period during the day. This type of bias makes it appear that there are fewer earthquakes than would be expected for a given time period.

Examples of biasing by masking of earthquake events are common. Cultural noise (e.g., traffic) and wind noise create a mask that hides events. Masking is most severe for events of low magnitudes; it has little effect on larger events. In Oklahoma, recording stations are placed in rural areas as much as possible in order to minimize problems due to cultural noise (J. E. Lawson, personal communication, 1995).

Biasing of a catalog by added events is recognized less widely, but it, too, can be a problem. Mine blasts and seismic exploration can add events that must be removed from a catalog. In Oklahoma, quarry blasts are detected by a distinct train of 1 Hz surface waves (Luza and Lawson, 1979), while seismic exploration is generally recognized by its semiperiodic character and the absence of S-waves. Large storms also are possible sources of added events (Shurbet and Keller, 1972), as are tidal forces (Ryall and others, 1968; Churchin and Pennington, 1987; Rydelek and others, 1988, 1991; Hartzell and Heaton, 1989).

More problematic causes of added-event bias in an earthquake catalog are non-self-similar behavior (e.g., aftershocks and volcanic eruptions) and induced activity (e.g., hydraulic fracturing of wells), which also can add extra events over some time period. They require sophisticated methods of identification as they have many characteris-

[1]Northwestern University, Evanston, Illinois.

tics in common with primary (i.e., non-aftershock) earthquakes.

Rydelek and Sacks (1989) have developed a method for detecting bias based on the principle of the random walk. They begin by assuming a Poisson distribution of occurrence times (i.e., that earthquakes occur rarely, independently, and with no time preference). This assumption is good for most earthquakes; however, aftershocks must be removed from the data set as they are not independent of the primary event.

Rydelek and Sacks (1989) construct a phasor plot of a walk by treating each earthquake as a step in the direction of the hour it occurred, based on a 24-hour clock; each step is a unit vector, or phasor. (The occurrence time is the phase of the earthquake for this type of analysis.) Thus, for a sequence of earthquakes at 1:00 a.m., 6:00 p.m., noon, and 5:00 p.m., the resultant walk would step to 15°, 270°, 180°, and 255°. Figure 1A shows the results of a typical random walk.

The probability of a walk exceeding a given radius on a phasor plot may be calculated, or conversely, the radius of walk for any given probability level may be found. In the latter method, the radius of walk is proportional to the square root of the number of events. Thus, the confidence level may be

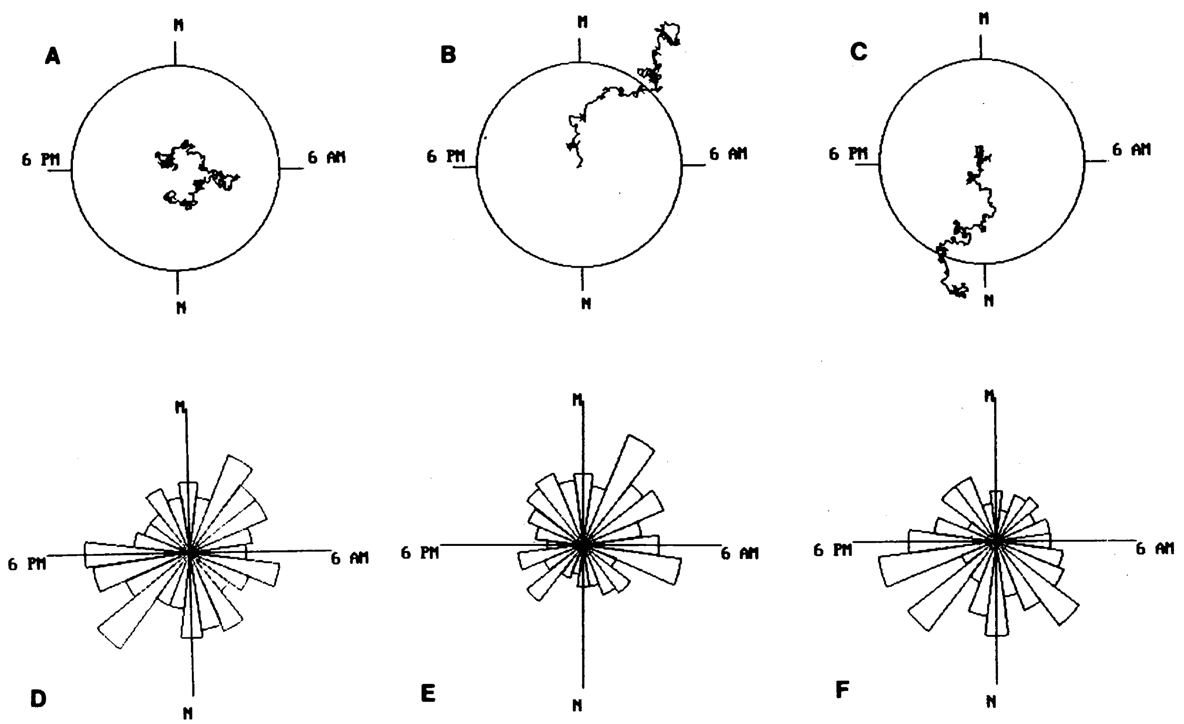


Figure 1. Phasor plots and rose diagrams. A phasor plot is made by plotting each earthquake as a step towards the time of its occurrence. If the series is biased, then the plot will "walk out" of the circle. A circle with a greater radius indicates a greater confidence level for a phasor plot; in other words, the larger the circle, the more confident we are that the series is biased when the phasor plot walks out. In these figures, the confidence level is 95%. (*A*) An unbiased phasor plot remains near the center. (*B*) A phasor plot biased by masking daytime events walks out near midnight. (*C*) A phasor plot biased by adding daytime events walks out near noon. (*D*) The rose diagram for A. All petals are approximately the same length. (*E*) The rose diagram for B. The daytime petals are shorter than the nighttime petals. (*F*) The rose diagram for C. The daytime petals are longer than the nighttime petals.

drawn as a circle about the origin, with a larger circle corresponding to a higher confidence level. This extremely sensitive test is capable of detecting, with 95% confidence, a bias of an extra 12 events in a sample of 120. (In other words, if each of one hundred catalogs of 120 events held 12 biased events, the bias should be detected in 95 of the catalogs.) Figure 1B shows the phasor plot of a simulated catalog (DeLaughter, 1993) that has been biased by masking of daytime events. Figure 1C shows the phasor plot of the same catalog when biased by adding events to the daytime.

As may be seen from Figure 1B,C, phasor plots can detect bias, but not the cause of bias. The cause may be inferred from the direction in which the plot gradually "walks out," but a vector sum of biasing events may create an artificial result, or the biasing events may cancel each other completely. Also, any single test for bias may show the presence of bias in cases where no bias actually exists; therefore, a second test is desirable.

The second diagnostic that can be performed is chi-square analysis, graphically displayed as a diagram (essentially a circular histogram) (Hartzell and Heaton, 1989). The number of earthquakes occurring at some hour is summed and compared to a uniform distribution by a chi-square test. For 120 events, the least number expected in any hour is 1, and the greatest is 9. The mean number expected in any segment, also called the expected value, is 5. Figure 1D shows the unbiased rose diagram corresponding to the phasor plot of Figure 1A. Figure 1E shows the bimodal distribution typical of bias due to masked events. Added events are expected to create a tightly grouped region of excess events (Fig. 1F). Thus, the relative lengths of the petals in the rose diagram generally give some indication of the cause of bias in the phasor walk.

Study Description and Results

There have been many analyses of the Oklahoma earthquake catalog (Luza and others, 1978; Luza and Lawson, 1979, 1981; Burchett and others, 1985), but none has included a statistically reliable examination of the amount of bias in the catalog. This study used phasor plots and rose diagrams to test the catalog for bias. With the exception of one subset (mean magnitude >2.3 M), all analyses were done at the 95% confidence level. Locations and magnitudes of earthquakes from the Oklahoma earthquake catalog for the years 1977–1991 formed the data set for the study. Central Standard Time was used for earthquake occurrence times throughout this study.

The data set was tested first for the presence of aftershocks, which had to be removed from the catalog before phasor plots and rose diagrams could be used. As the catalog showed a large deviation from Poisson behavior, it was assumed that aftershocks were present (DeLaughter, 1993). For this study, any earthquake within 20 km radius and 24 hours of a prior event was assumed to be an aftershock and was removed from the data set. These parameters closely approximate those determined by other methods for regions with similar seismic histories (Bath, 1973; Gardener and Knopoff, 1974).

Next, the catalog was divided into four subsets, based on mean magnitude (M). The mean magnitude for each event is the arithmetic mean of the magnitudes given in the original data set. The original magnitudes (m) in the Oklahoma earthquake catalog are reported in three magnitude scales based on duration (mDUR), 3 Hz amplitude (m3Hz), and 1 Hz amplitude (mbLg) (see "Oklahoma Earthquakes, 1994," p. 51, this issue). Admittedly, this mean magnitude is ad hoc; however, it is necessary as no single measure of magnitude was used for the entire data set. Fortunately, all three magnitudes are relatively close, so the mean magnitude is very close to the individual magnitude.

The first subset consists of 0.7–1.75 M earthquakes. There are 159 primary events in this group. The phasor plot walks out of the circle at 1:00 a.m., and the rose diagram shows much greater values from 6:00 p.m. to 6:00 a.m. (Fig. 2). Unlikely high values occur at 9:00, 10:00, and 11:00 p.m., and at 2:00 and 5:00 a.m.; unlikely low values occur at 10:00 a.m. and 2:00 p.m.

Winds are at a maximum from approximately 9:00 a.m. to 7:00 p.m. in Oklahoma (Pacific Northwest Laboratory, 1981). In addition, traffic flow is an order of magnitude greater from 7:00 a.m. to 8:00 p.m. than it is during the remaining hours of the day, based on an analysis of Oklahoma traffic patterns found in the data of the Oklahoma Department of Transportation (1990). Therefore, I suggest that at this mean magnitude there is a masking bias due to wind and cultural noise.

The second subset is of earthquakes with 1.75–2.0 M. There are 143 primary events in this range. The phasor plot of these earthquakes also walks out near midnight (Fig. 3A). At these larger magnitudes, the mean magnitude of an earthquake is more likely to be above the noise level, and there should be a lower level of biasing than in the first subset. The rose diagram (Fig. 3B) shows that, while daytime values are still low, they are closer to the expected values. For 143 events in 24 hours, the expected value of events is 6. Evidence for daytime noise bias is not as strong at this mean magnitude as at the lowest mean magnitude. However, there are unlikely high values at 7:00 and 10:00 p.m., and at 1:00 and 4:00 a.m.

The third subset is of 2.0–2.23 M earthquakes. The phasor plot does not walk out, and the rose diagram has no anomalous values (Fig. 4). Both the phasor plot and rose diagram indicate that the catalog is unbiased with respect to time for this mean magnitude range.

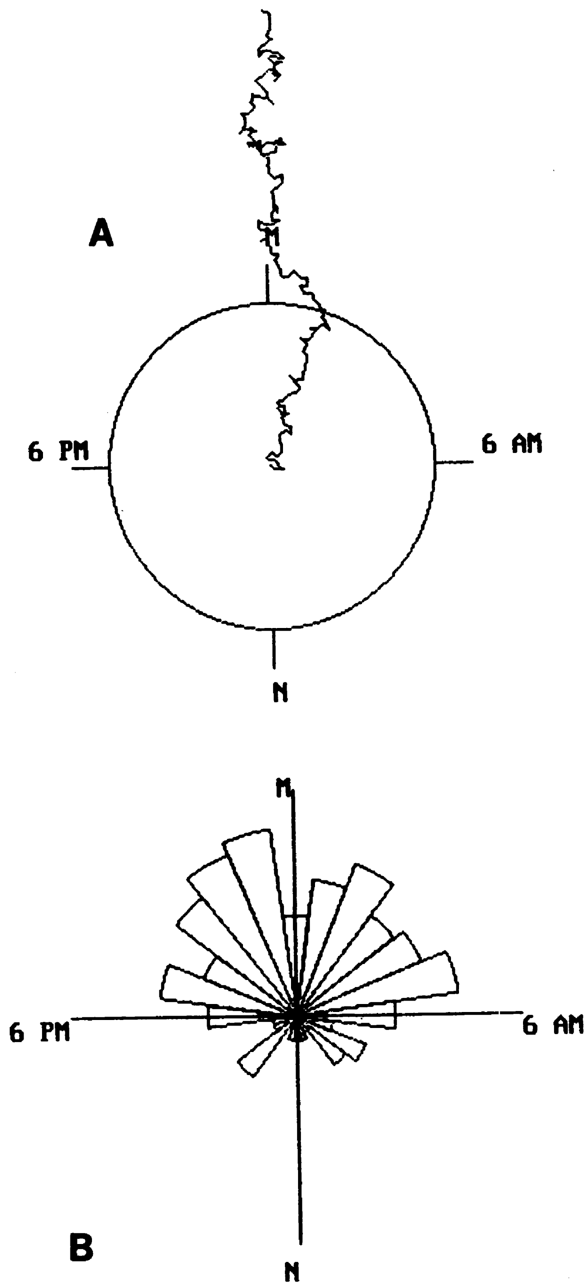


Figure 2. Phasor plot and rose diagram for 0.7–1.75 M earthquakes. These events show strong evidence of noise bias during the daytime: (*A*) the phasor walks out near 1:00 a.m., and (*B*) the nighttime petals are much longer than daytime petals. The circle represents the radius for the 95% confidence level.

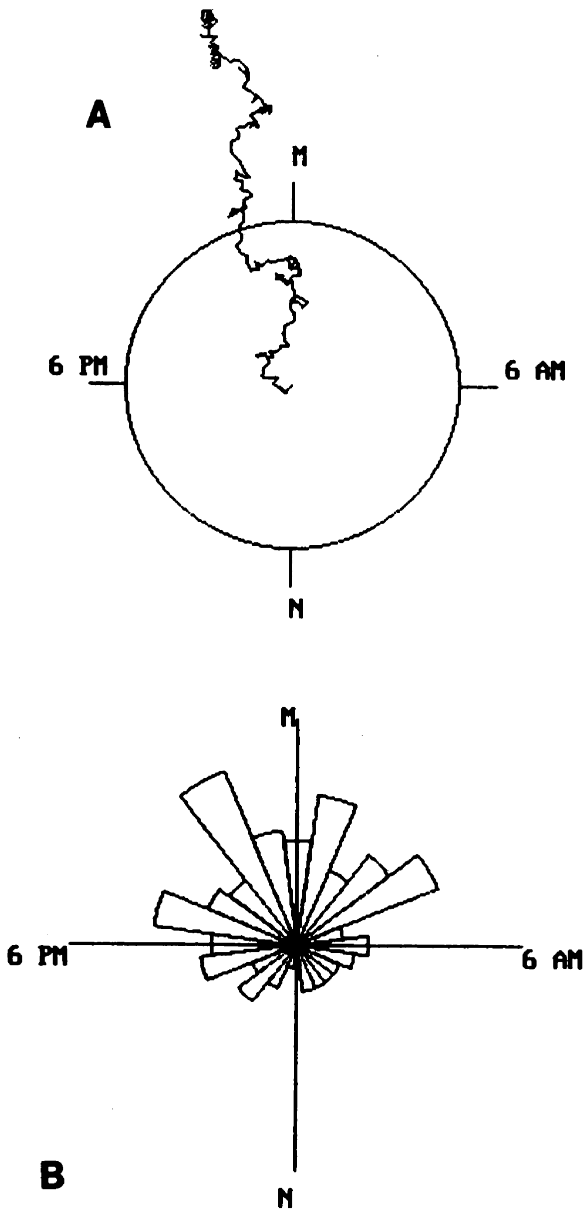


Figure 3. Phasor plot and rose diagram for 1.75–2.0 M earthquakes. (*A*) The phasor plot again walks out near midnight, and (*B*) the rose diagram still shows longer nighttime petals, but the evidence for daytime noise bias is not as great as in Fig. 2. The circle represents the radius for the 95% confidence level.

The final subset of earthquakes includes all primary events with mean magnitude >2.23 M. There are 121 events in this category. The phasor plot does not walk out at the 95% confidence level, but does at the 90% confidence level, which indicates the possibility of a weak bias (Fig. 5A,B). The rose diagram (at 95% confidence level) is even more compelling (Fig. 5C). There are unlikely high values at noon and 8:00 p.m., and unlikely lows at midnight and 3:00 a.m. The rose diagram as a whole shows a bias toward the afternoon.

The bias could be due to masked or added events, or it could be a statistical

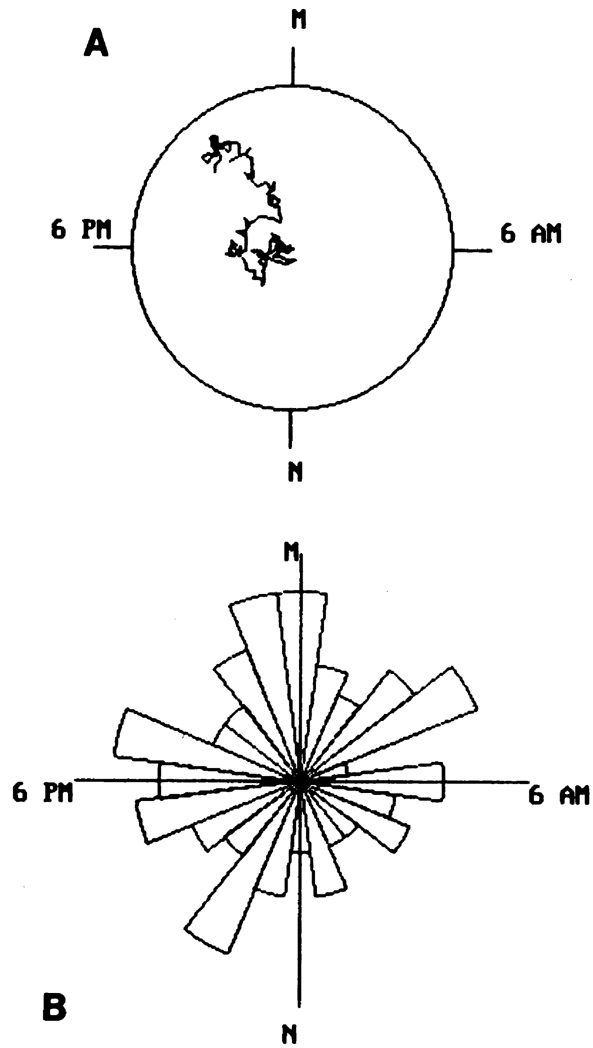


Figure 4. Phasor plot and rose diagram for 2.0–2.23 M earthquakes. (*A*) The phasor plot does not walk out, and (*B*) the rose diagram has no unlikely values. The catalog probably is unbiased for this magnitude range. The circle represents the radius for the 95% confidence level.

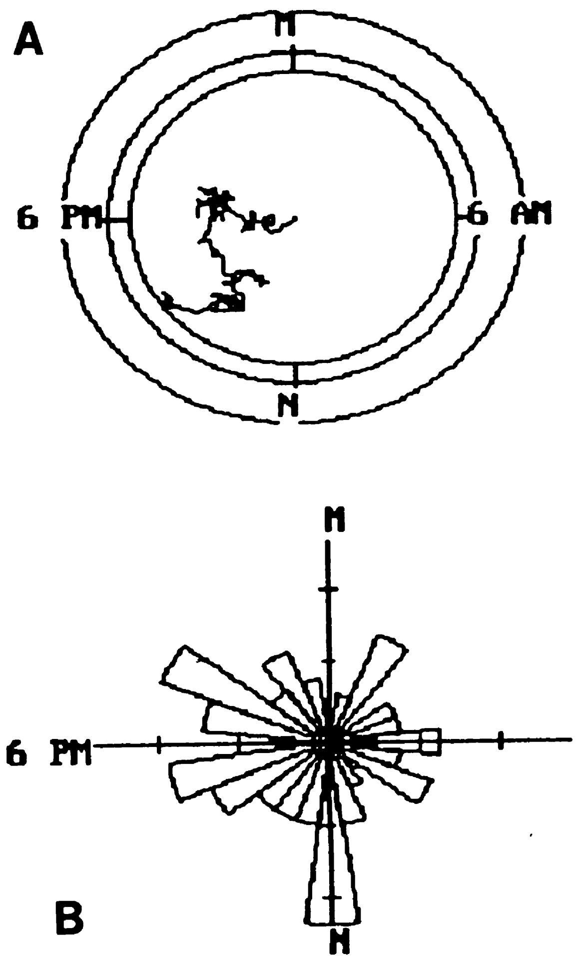


Figure 5. Phasor plot and rose diagram for 2.23–3.7 M earthquakes. The phasor plot (*A*) does not walk out at the 95% confidence level (middle circle), but does at the 90% confidence level (inner circle). The rose diagram (*B*) shows an afternoon bias at the 95% confidence level.

artifact. Since the timing of this bias is opposite to that at low mean magnitudes, masking can be eliminated as a cause. There is some corroborating evidence for an induced bias: in 1981, Luza and Lawson noted that hydraulic fracturing of a well coincided with a large cluster of microseisms. It is possible also that some aftershocks were left in the data set, due to the crudeness of the method used to remove them. They could bias the catalog even in a case where no real bias is present. If aftershocks remain in the data set, why should they be biased toward the afternoon?

Tidal forces have been suggested by many authors as a potential mechanism for inducing earthquakes; however, tidal accelerations at the time of the earthquakes in question do not appear to be either unusually large or small (DeLaughter, 1993). Oil-field activity is another possible explanation, but, again, no corroborating evidence (e.g., location or timing of events) has been found (DeLaughter, 1993). We conclude, therefore, that the apparent bias at the highest mean magnitudes is probably due to a statistical artifact rather than to a real effect.

Conclusions

At low mean magnitude levels (<2.0 M), the Oklahoma earthquake catalog apparently is biased by some combination of wind and cultural noise. Based on the timing of the bias, it is likely that cultural noise predominates. The effects of this bias are greatest at low magnitudes.

At moderate mean magnitudes (2.0–2.23 M), the catalog appears to be unbiased. The phasor plot does not walk out, and the rose diagram shows no unlikely values. These results agree well with those of Luza and others (1982), which indicated reliable detection and location of earthquakes for all of Oklahoma for 2.1 m3Hz and above. Their estimate of 50% location for 1.5 m3Hz events also agrees with the results of this study.

At large mean magnitude (>2.23 M), this study shows that there may be a bias due to added events. No physical cause has been shown to be responsible for this bias, however, and it is probable that it is due to unidentified aftershocks in the data set.

Acknowledgments

This research would not have been possible without the kind donation of earthquake data from Dr. Kenneth V. Luza at the Oklahoma Geological Survey and well data from Geological Information Systems. Also, I must thank Dr. Jud Ahern, who read the many drafts of this article, for his time and advice.

References Cited

Bath, Marcus, 1973, Introduction to seismology: Birkhäuser Verlag, Basel and Stuttgart, 395 p.

Burchett, R. R.; Luza, K. V.; Van Eck, O. J.; and Wilson, F. W., 1985, Seismicity and tectonic relationships of the Nemaha uplift and Midcontinent geophysical anomaly (final project summary): Oklahoma Geological Survey Special Publication 85-2, 33 p.

Churchin, J. M.; and Pennington, W. D., 1987, Tidal triggering of intermediate and deep focus earthquakes: Journal of Geophysical Research, v. 92, no. B13, p. 13957–13967.

DeLaughter, J. E., 1993, Detection of bias in the Oklahoma earthquake catalog: methods and interpretation: University of Oklahoma unpublished M.S. thesis, 64 p.

Gardener, J.; and Knopoff, L., 1974, Is the sequence of earthquakes in southern California, with aftershocks removed, Poisson?: Seismological Society of America Bulletin, v. 64, p. 1363–1367.

Hartzell, S.; and Heaton, T., 1989, The fortnightly tide and the tidal triggering of earthquakes: Seismological Society of America Bulletin, v. 79, p. 1282–1286.

Luza, K. V.; and Lawson, J. E., Jr., 1979, Seismicity and tectonic relationships of the Nemaha uplift in Oklahoma, part II: U.S. Nuclear Regulatory Commission NUREG/CR-0875, 81 p.

_____ 1981, Seismicity and tectonic relationships of the Nemaha uplift in Oklahoma, part III: Oklahoma Geological Survey Special Publication 81-3, 70 p.

_____ 1982, Seismicity and tectonic relationships of the Nemaha uplift in Oklahoma, part IV: Oklahoma Geological Survey Special Publication 82-1, 52 p.

Luza, K. V.; Dubois, R. L.; Lawson, J. E., Jr.; Foster, P.; and Koff, L., 1978, Seismicity and tectonic relationships of the Nemaha uplift in Oklahoma: U.S. Nuclear Regulatory Commission NUREG/CR-0050, 67 p.

Oklahoma Department of Transportation, 1990, Oklahoma traffic characteristics, 1990; a factual analysis of traffic volumes and vehicle classification data: Oklahoma Department of Transportation, Planning Division, Oklahoma City, 333 p.

Pacific Northwest Laboratory, 1981, Wind energy resource atlas; volume 7—the south-central region: Pacific Northwest Laboratory, Richland, Washington, 228 p.

Ryall, A.; Van Wormer, J. D.; and Jones, A. E., 1968, Triggering of microearthquakes by earth tides and other features of the Truckee, California, earthquake sequence of September 1966: Seismological Society of America Bulletin, v. 58, p. 215–248.

Rydelek, P. A.; and Sacks, I. S., 1989, Testing the completeness of earthquake catalogs and the hypothesis of self-similarity: Nature, v. 337, p. 251–253.

Rydelek, P. A.; Davis, P. M.; and Koyanagi, R. Y., 1988, Tidal triggering of earthquake swarms at Kilauea Volcano, Hawaii: Journal of Geophysical Research, v. 93, no. B5, p. 4401–4411.

Rydelek, P. A.; Sacks, I. S.; and Scarpa, R., 1991, On tidal triggering of earthquakes at Camp Flegri, Italy: Geophysics Journal International, v. 109, p. 125–137.

Shurbet, D. H.; and Keller, G. R., 1972, Generation of microseisms by atmospheric coupling: Texas Journal of Science, v. 23, p. 471–478.

OKLAHOMA EARTHQUAKES, 1994

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

Introduction

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

Earthquakes tend to occur in belts or zones. For example, narrow belts of earthquake epicenters coincide with oceanic ridges where plates separate, such as in the mid-Atlantic and east Pacific Oceans. Earthquakes also occur where plates collide and/or slide past each other. Although most earthquakes originate at plate boundaries, a small percentage occur within plates. The New Madrid earthquakes of 1811–12 are examples of large and destructive intraplate earthquakes in the United States.

The New Madrid earthquakes of 1811 and 1812 are probably the earliest historical earthquake tremors felt in Oklahoma (Arkansas Territory) by residents in southeastern Oklahoma settlements. The earliest documented earthquake in Okla-

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

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

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

homa 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, Gutenberg-Richter) earthquake was felt in Austin, Texas, as well as Des Moines, Iowa, and covered a felt area of ~362,000 km^2 (Docekal, 1970; Kalb, 1964; von Hake, 1976). From 1897 through 1994, 1,130 earthquakes have been located in Oklahoma.

Instrumentation

A statewide network of 11 seismograph stations was used to locate 113 earthquakes in Oklahoma for 1994 (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 anti-alias filtering to eliminate frequencies too high for the final sampling rate. After one to three digital filter and resampling stages, the RDAS produces 60, 40, 20, or 10 24-bit samples per second. The samples are time-tagged by RDAS clocks locked to 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 2+ Unix workstation with 64 megabytes of memory, two 660-megabyte disks, two 2.1-gigabyte disks, and two 2.5 gigabyte Exabyte™ tape drives. All of the data from the most recent two weeks are retained on disk. Each day, data from the preceding day (167 million bytes) are automatically archived onto Exabyte™ tape. All Oklahoma earthquakes, and other selected events, are placed in named de-archive directories. An Oracle™ data base on the Sun Sparc 2+ 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 de-archive directories. Data analysis is done by Teledyne-Geotech and Science Applications International Corp. software on the Sparc 2+ workstation.

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

TUL has three (vertical, north–south, east–west) Geotech GS-13 seismometers which produce 40-sample-per-second short-period signals. A three-component broadband Geotech KS54000-0103 seismometer in a 120-m-deep borehole produces seven digital data channels. Three are broadband signals from seismic signals in vertical, north–south, and east–west directions. From the broadband signals the Sparc 2+ workstation derives three long-period signals. A seventh signal, the vertical earth tides, is recorded from the vertical mass displacement signal from the KS54000-0103. The broadband signals are archived at 10 samples per second, and

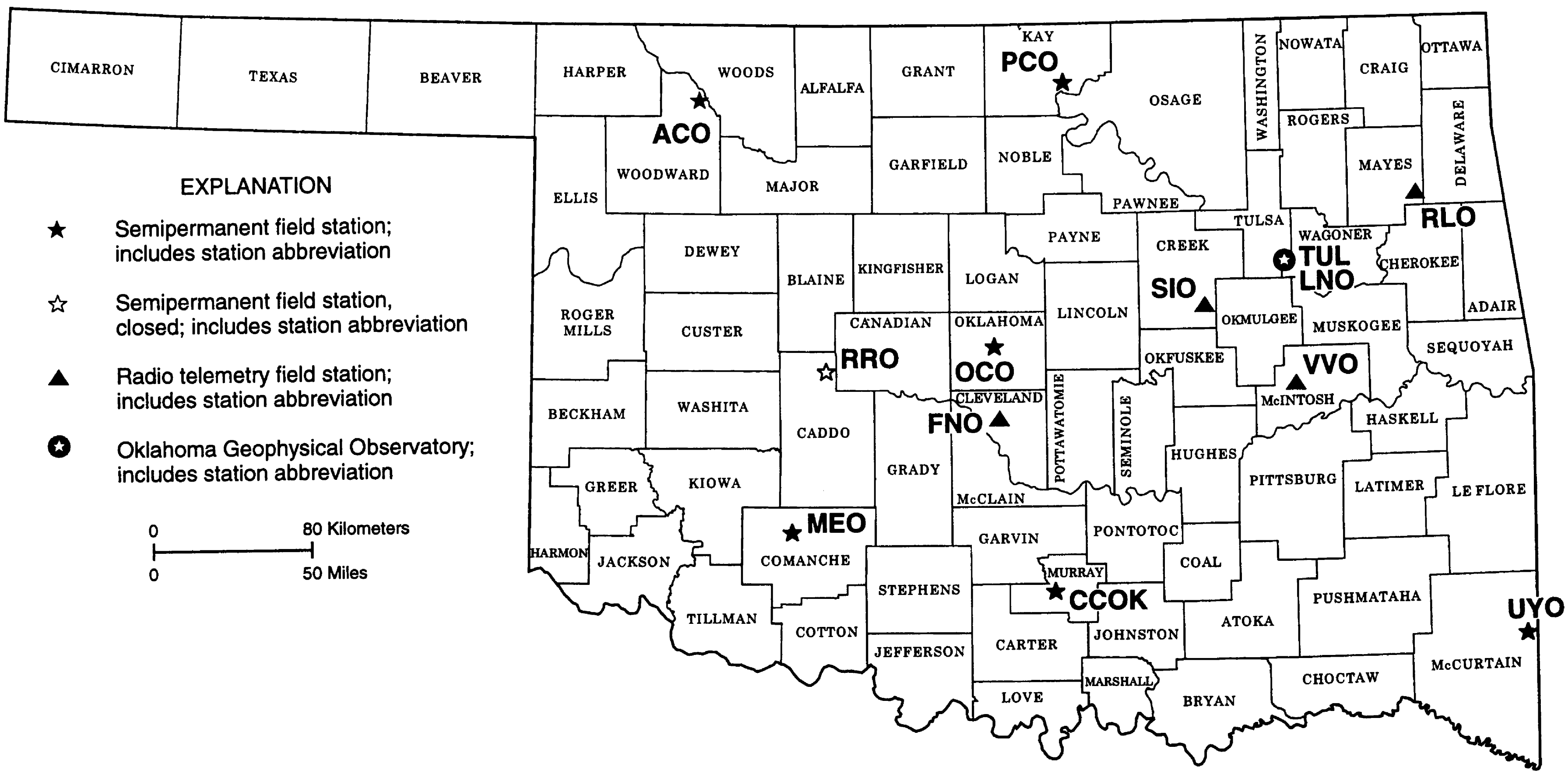


Figure 1. Active seismographs in Oklahoma.

the long-period and vertical-earth-tide signals are recorded at one sample per second. On November 10, 1994, the broadband sample rate was increased from 10 samples per second to 20 samples per second. This increase was for two purposes. One was to allow the broadband borehole seismometer to record higher frequencies (≤8 Hz) characteristic of Oklahoma earthquakes. The other was to make the signals compatible for the GSETT-3 (Group of Scientific Experts Technical Test-3), which begins in 1995. GSETT-3 is a prototype international seismic-monitoring system to detect underground nuclear tests. Data segments will be copied automatically and sent to the International Data Center by Internet without affecting the recording and analysis of Oklahoma earthquakes.

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

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 depths 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 Laboratories. The three LNO signals 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.

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

In the Leonard vault, seven additional seismometers produce analog (wiggly-line) recordings on paper-drum recorders. Eleven such recordings are produced, five of which are the proper frequencies to record some aspect of nearby earthquakes. One paper recording is produced from each of RLO, VVO, and SIO. 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 recorded at the OGS Observatory, seismograms are recorded by six volunteer-operated seismographs. Each consists of a Geotech S-13 short-period vertical-motion-sensing seismometer in a shallow tank vault, or in an abandoned mine shaft (station MEO) or large-diameter, hand-dug, shallow water well (station UYO). A new station, CCOK, opened on August 10, 1994, at Camp Classen (YMCA Camp) in Murray County. This station is operated by Jim Parry and his staff. (Red Rock Canyon station, RRO, has been closed.) The seismometer signal runs through 200–1,800 ft of cable in surface PVC conduit to the volunteer's house or other building. The volunteer has a Sprengnether MEQ-800B timing system amplifier-filter-drum recorder, which records 24 hours of seismic trace at 1 mm/min in a spiral path around the paper on the drum. The times are set by a time signal radio receiver tuned to the National Institute of Standards and Technology and high-frequency radio station WWV. The volunteers mail in the seismograms weekly (or more often, if requested).

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 radio-telemetry site (usually VVO) are displayed on a 19-in. monitor on the Sun Sparc 2+. 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 determined; 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 also are searched for regional and local earthquakes. At times, a small earthquake may be spotted initially only on the digital system or only on paper seismograms.

The next stage is de-archiving 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.

TABLE 2. — OKLAHOMA EARTHQUAKE CATALOG FOR 1994

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]
1018	JAN 11	01 18 34.50	McClain	—	2.2	2.6	2.4	34.976	97.416	5.0R
1019	JAN 16	20 06 48.31	Major	—	2.1	2.0	2.1	36.402	98.115	5.0R
1020	FEB 05	04 53 33.11	Caddo	—	2.0		1.4	34.946	98.155	5.0R
1021	FEB 06	12 28 24.08	Creek	—	1.8	1.4	1.8	35.683	96.370	5.0R
1022	FEB 24	17 11 02.42	Grady	—	1.9	1.9	2.4	35.370	98.063	5.0R
1023	FEB 24	23 42 39.48	Grady	—	2.1	2.6	2.6	34.773	97.686	5.0R
1024	FEB 25	16 38 01.35	Pontotoc	—	2.0	2.1	2.3	34.820	96.588	5.0R
1025	FEB 25	22 37 16.50	Pontotoc	—	1.2		1.8	34.880	96.628	5.0R
1026	FEB 25	23 47 58.64	Grady	—	2.0	1.8	2.2	34.771	97.680	5.0R
1027	MAR 04	22 42 54.65	Roger Mills	—	1.8			35.882	99.951	5.0R
1028	MAR 06	02 00 12.12	Roger Mills	—	1.9			35.824	99.787	5.0R
1029	MAR 11	15 31 06.13	Harper	—	2.2			36.734	99.689	5.0R
1030	MAR 24	04 53 01.75	Roger Mills	—	2.1			35.824	99.834	5.0R
1031	MAR 24	11 14 46.47	Custer	—	2.3			35.721	98.944	5.0R
1032	APR 05	09 14 47.47	Custer	—	2.0			35.547	98.819	5.0R
1033	APR 05	09 18 57.45	McClain	—	1.7	1.6	2.0	35.023	97.559	5.0R
1034	APR 14	21 50 05.13	Grady	—	2.4	2.3	2.3	34.690	97.725	5.0R
1035	APR 14	22 22 20.25	Stephens	—	1.9	2.0	2.2	34.641	97.743	5.0R
1036	APR 14	22 36 21.67	Stephens	—	2.7	2.7	2.2	34.643	97.733	5.0R
1037	APR 14	23 55 55.04	Stephens	—	1.9		1.8	34.391	97.774	5.0R
1038	APR 15	01 19 52.04	Stephens	—	2.5	2.8	2.0	34.643	97.714	5.0R
1039	APR 15	02 33 00.11	Stephens	—	2.1	1.9	1.9	34.580	97.630	5.0R
1040	APR 15	03 40 04.13	Grady	—	2.3	2.2	1.7	34.687	97.706	5.0R
1041	APR 15	03 42 52.27	Seminole	—	1.7			35.195	96.626	5.0R
1042	APR 15	03 54 19.76	Grady	—	2.0		1.3	35.055	98.012	5.0R
1043	APR 15	04 00 20.47	Blaine	—	1.9		2.1	35.690	98.600	5.0R
1044	APR 15	04 14 48.58	Blaine	—	1.6		1.9	35.844	98.628	5.0R
1045	APR 15	04 17 40.38	Carter	—	1.6		2.1	34.323	97.507	5.0R
1046	APR 15	04 20 52.14	Grady	—	2.1	1.9	2.0	34.721	97.741	5.0R
1047	APR 15	04 38 26.53	Grady	—	1.7		2.2	34.717	97.745	5.0R
1048	APR 15	04 43 45.62	Stephens	—	2.2	2.5	2.1	34.670	97.741	5.0R
1049	APR 15	05 28 33.07	Stephens	—	1.9	2.1	2.0	34.651	97.721	5.0R
1050	APR 15	06 40 10.25	Stephens	—	1.9	1.9	2.3	34.627	97.710	5.0R
1051	APR 15	08 13 59.96	Stephens	—	1.9		1.8	34.676	97.721	5.0R
1052	APR 15	10 04 41.88	Grady	—	1.8	1.6	1.8	34.709	97.878	5.0R
1053	APR 15	11 52 55.26	Grady	—	1.7		2.1	34.690	97.749	5.0R
1054	APR 15	14 27 20.12	Stephens	—			2.3	34.648	97.737	5.0R
1055	APR 15	16 37 52.73	Grady	—	2.3	2.1	1.8	34.682	97.721	5.0R
1056	APR 15	17 32 14.11	Grady	—	2.0		1.6	34.726	97.682	5.0R
1057	APR 15	19 46 14.43	Stephens	—	2.8		1.9	34.601	97.713	5.0R
1058	APR 15	22 13 18.33	Stephens	—	2.3		1.8	34.674	97.710	5.0R
1059	APR 15	23 40 45.41	Stephens	—	2.0		1.9	34.612	97.710	5.0R
1060	APR 16	01 35 56.69	Stephens	—	2.1	1.9	1.8	34.565	97.694	5.0R
1061	APR 16	04 15 45.30	Grady	—	1.6		1.9	34.731	97.731	5.0R
1062	APR 16	07 20 29.99	Stephens	—	3.1	2.9	2.7	34.663	97.713	5.0R
1063	APR 26	13 45 07.07	Garvin	—			2.1	34.823	97.655	5.0R
1064	APR 26	15 10 16.32	Grady	—	2.2	2.0	1.9	34.862	97.702	5.0R
1065	APR 26	16 41 13.13	Garvin	—	2.0	1.8	1.8	34.854	97.655	5.0R
1066	APR 27	06 00 14.53	Garvin	—	1.6		2.1	34.826	97.632	5.0R
1067	APR 29	03 28 59.63	Garfield	F		2.8	2.5	36.203	98.052	5.0R
1068	MAY 03	18 05 03.13	Carter	—	1.9		1.6	34.190	97.100	5.0R
1069	MAY 04	06 14 25.16	Garvin	—	1.6	1.6	2.2	34.737	97.655	5.0R
1070	MAY 04	07 59 27.74	Stephens	—	1.6		1.7	34.651	97.647	5.0R
1071	MAY 04	08 47 43.32	Garvin	—	1.8	1.7	1.8	34.791	97.647	5.0R
1072	MAY 04	09 05 26.84	Garvin	—	2.0	1.6	1.9	34.787	97.647	5.0R
1073	MAY 04	10 18 42.70	Canadian	—	1.7		1.6	35.448	98.061	5.0R
1074	MAY 04	16 34 46.58	Garvin	—			2.3	34.760	97.632	5.0R
1075	MAY 17	17 09 21.65	Garvin	—	2.2		2.0	34.659	97.490	5.0R

1076	MAY 17	19 53 02.74	Garvin	—			1.8	34.662	97.467	5.0R
1077	MAY 23	17 05 43.16	Canadian	—			2.2	35.565	98.102	5.0R
1078	MAY 24	01 07 34.02	McClain	—	1.6		2.2	34.881	97.635	5.0R
1079	JUN 21	03 13 53.45	Carter	—	1.4		1.5	34.451	97.448	5.0R
1080	JUL 04	07 28 28.38	Garvin	—	2.8	2.7	2.3	34.652	97.498	5.0R
1081	JUL 08	01 23 26.22	LeFlore	—	2.1	2.2	1.8	35.134	94.675	5.0R
1082	JUL 13	14 05 55.29	Pontotoc	—	2.1	1.6	1.9	34.620	96.561	5.0R
1083	JUL 19	16 44 36.36	McClain	—	2.0		1.5	34.863	97.584	5.0R
1084	JUL 20	04 37 58.89	McClain	—	1.5	1.6	1.8	35.113	97.539	5.0R
1085	AUG 03	11 45 06.63	Johnston	—	2.0		1.5	34.403	96.753	5.0R
1086	AUG 08	12 55 46.00	Beckham	—			1.8	35.159	99.960	5.0R
1087	AUG 15	02 19 32.94	McClain	—	2.4	1.8	1.9	34.935	97.268	5.0R
1088	AUG 17	01 23 59.40	Tillman	—			1.6	34.534	99.085	5.0R
1089	AUG 24	04 03 50.66	Stephens	—	1.4		1.6	34.453	97.651	5.0R
1090	AUG 25	04 45 00.47	Garvin	—	2.2	2.1	2.0	34.679	97.473	5.0R
1091	SEP 06	14 17 35.28	McClain	—	2.3	1.7	1.9	34.912	97.460	5.0R
1092	SEP 23	07 22 35.93	Grady	—	1.5		1.6	34.776	97.682	5.0R
1093	SEP 23	09 24 43.65	Grady	—			2.0	34.768	97.710	5.0R
1094	SEP 23	11 42 38.92	Grady	—			1.8	34.815	97.684	5.0R
1095	SEP 23	21 36 53.26	Grady	—			1.7	34.754	97.690	5.0R
1096	SEP 24	06 47 14.63	Grady	—	1.6		1.6	34.823	97.690	5.0R
1097	SEP 24	14 26 53.38	Grady	—			1.7	34.815	97.710	5.0R
1098	SEP 24	15 06 33.47	Grady	—	2.5	2.3	1.6	34.831	97.686	5.0R
1099	SEP 26	08 31 05.52	Carter	—	1.4		1.5	34.288	96.987	5.0R
1100	SEP 30	03 07 30.47	McClain	—	2.2	1.8	1.9	34.867	97.447	5.0R
1101	SEP 30	15 01 02.00	Murray	—			1.5	34.401	97.147	5.0R
1102	OCT 01	04 54 46.13	McClain	—	2.7	2.6	2.1	34.882	97.494	5.0R
1103	OCT 05	08 34 42.23	Pontotoc	—		1.9	2.2	34.820	96.811	5.0R
1104	OCT 13	13 51 43.61	Garvin	—	1.9		2.0	34.531	97.447	5.0R
1105	OCT 13	16 54 46.69	Garvin	—	2.6	2.5	1.9	34.679	97.471	5.0R
1106	OCT 15	20 39 47.54	Garvin	—	2.2		2.0	34.601	97.471	5.0R
1107	NOV 13	16 33 26.96	Dewey	—			2.2	35.954	99.058	5.0R
1108	NOV 15	03 42 49.01	Okfuskee	—	1.6	1.4	1.6	35.503	96.350	5.0R
1109	NOV 30	08 29 27.58	Grady	—	2.0	1.7	1.7	34.848	97.687	5.0R
1110	DEC 13	10 32 06.72	Caddo	—	1.4		2.1	34.868	98.471	5.0R
1111	DEC 20	04 12 22.08	Garvin	—			2.0	34.794	97.523	5.0R
1112	DEC 20	04 15 09.08	Garvin	—			1.8	34.805	97.519	5.0R
1113	DEC 20	04 19 39.28	Garvin	—			1.9	34.830	97.534	5.0R
1114	DEC 20	04 29 38.96	Garvin	—			2.0	34.759	97.538	5.0R
1115	DEC 20	04 49 16.15	Garvin	—			1.8	34.770	97.523	5.0R
1116	DEC 20	05 06 19.62	Garvin	—			1.8	34.792	97.503	5.0R
1117	DEC 20	05 09 03.30	Garvin	—	1.8		2.1	34.759	97.519	5.0R
1118	DEC 20	05 56 04.50	Garvin	—			2.2	34.778	97.531	5.0R
1119	DEC 20	06 00 19.43	Garvin	—	1.5		1.8	34.762	97.531	5.0R
1120	DEC 20	06 34 27.22	Garvin	—	1.5		1.7	34.794	97.531	5.0R
1121	DEC 20	17 33 08.62	Garvin	—			1.8	34.762	97.491	5.0R
1122	DEC 20	22 04 36.40	Murray	—	1.6	2.0	1.6	34.395	97.296	5.0R
1123	DEC 21	08 38 26.66	Garvin	—	2.0	1.7	1.8	34.739	97.503	5.0R
1124	DEC 22	03 34 39.81	Garvin	—	1.4		1.7	34.776	97.521	5.0R
1125	DEC 22	14 12 59.63	Garvin	—	2.0	1.7	1.9	34.692	97.468	5.0R
1126	DEC 22	14 37 26.40	Garvin	—			1.7	34.718	97.501	5.0R
1127	DEC 22	15 43 16.13	Garvin	—			2.5	34.700	97.499	5.0R
1128	DEC 23	11 41 02.36	Garvin	—	1.7	1.6	1.8	34.671	97.479	5.0R
1129	DEC 23	21 56 16.89	Garvin	—	2.5	2.2	2.0	34.671	97.463	5.0R
1130	DEC 30	08 26 44.52	Garvin	—	2.1	1.7	1.8	34.729	97.655	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.

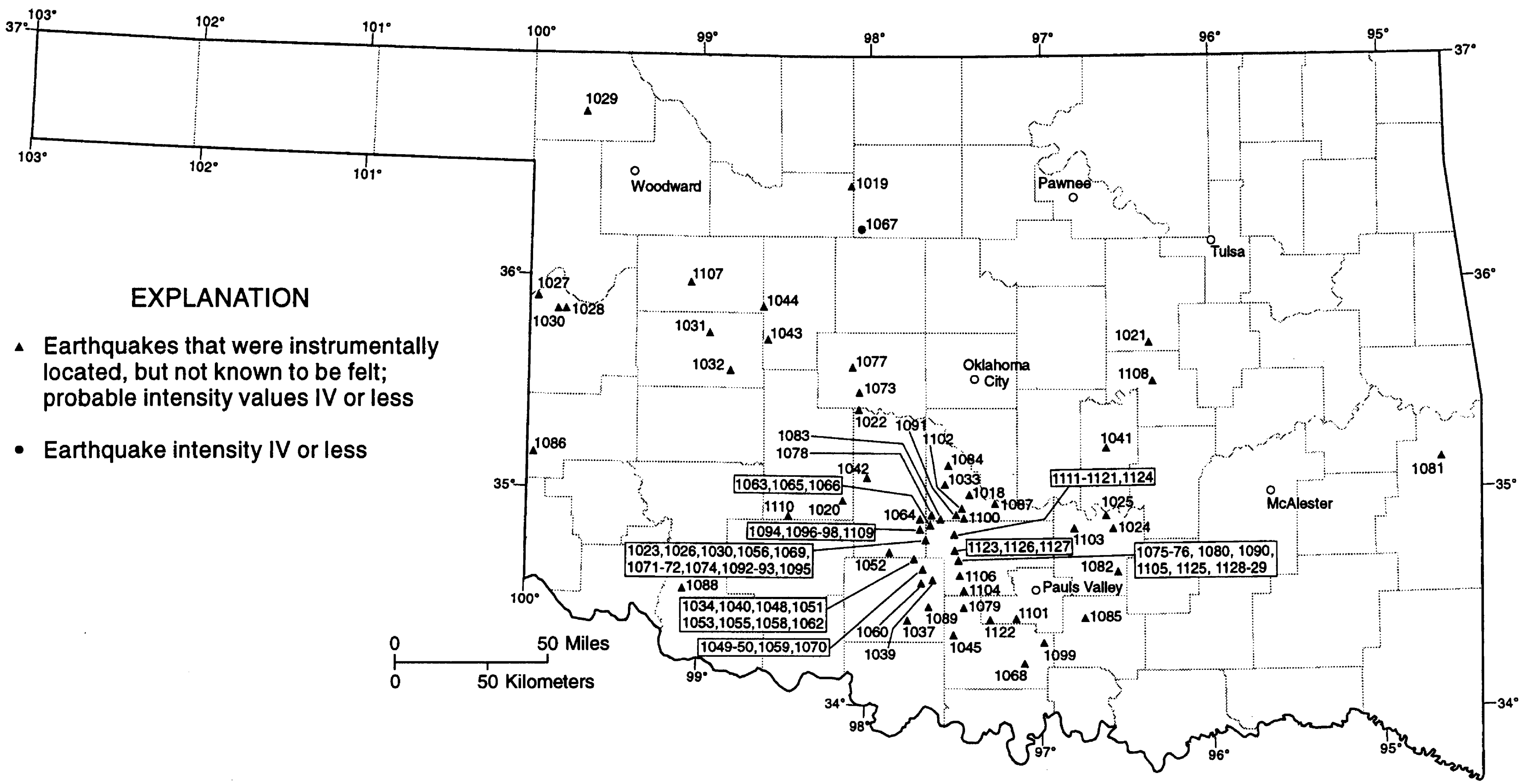


Figure 2. Distribution of Oklahoma earthquakes for 1994. Numbers correspond to event numbers in Table 2.

TABLE 3. — EARTHQUAKE THAT WAS REPORTED FELT IN OKLAHOMA, 1994

Event no.	Date and origin time (UTC)[a]		Nearest city	County	Intensity MM[b]
1067	APR 29	032859.63	26 km SW Enid	Garfield	felt

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

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

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 de-archived 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 1994, 113 Oklahoma earthquakes were located (Fig. 2; Table 2). One earthquake was 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 area for the earthquake listed in Table 3, Garfield County earthquake (event no. 1067), was probably restricted to a few tens of square kilometers away from the epicentral location. No damage was reported.

Earthquake-magnitude values range from a low of 1.2 (m3Hz) in Pontotoc County to a high of 3.1 (m3Hz) in Stephens County. An unusually high number—72—of earthquakes were located in Garvin (33), Grady (22), and Stephens (17) Counties in 1994. However, most of the earthquake activity in these counties occurred in three time intervals. From April 14 to 16, 25 earthquakes were located in northeastern Stephens County and southeastern Grady County. A second earthquake swarm occurred in southeastern Grady County between September 23 and 24. Western Garvin County experienced 18 earthquakes between December 20 and 23. Nine earthquakes were located in McClain County; Carter and Pontotoc Counties experienced four earthquakes; three earthquakes were located in Roger Mills County; Canadian, Caddo, Custer, and Murray Counties each experienced two earthquakes.

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.

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 1994 Oklahoma earthquake data displayed in a modified version of the regional earthquake catalog. Each event is sequentially numbered and arranged according to date and origin time. The numbering system is compatible with the system used by Lawson and Luza (1980–90, 1993,1994), Lawson and others (1991,1992), and for the *Earthquake Map of Oklahoma* (Lawson and Luza, 1995).

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. The magnitude of a local earthquake is determined by taking the logarithm (base 10) of the largest ground motion recorded during the arrival of a seismic-wave type and applying a standard correction for distance to the epicenter. When the magnitude value is increased one unit, the amplitude of the earthquake waves increases 10 times. There are several different scales used to report magnitude. Table 2 has three magnitude scales, which are mbLg (Nuttli), m3Hz (Nuttli), and MDUR (Lawson). Each magnitude scale was established to accommodate specific criteria, such as the distance from the epicenter, as well as the availability of certain seismic data.

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

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

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

In 1979, St. Louis University (Stauder and others, 1979) modified the formulas for m3Hz. This modification was used by the OGS Observatory beginning January 1, 1982. The modified formulas had the advantage of extending the distance range for measurement of m3Hz out to 400 km, but also had the disadvantage of increasing m3Hz by about 0.12 units compared to the previous formula. Their formulas 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:

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

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

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

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

Acknowledgments

Shirley Jackson, Ruth King, and Todd McCormick maintained the OGS Observatory at Leonard. Volunteer seismograph-station operators and landowners at various locations in Oklahoma make possible the operation of a statewide seismic network.

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

References Cited

Docekal, Jerry, 1970, Earthquakes of the stable interior, with emphasis on the Midcontinent: University of Nebraska, Lincoln, unpublished Ph.D. dissertation, v. 1, 169 p.; v. 2, 332 p.

Kalb, Bill, 1964, Earthquakes that shook Oklahoma: Orbit Magazine—The Sunday Oklahoman, Oklahoma City, September 27, p. 4–7.

Lawson, J. E., Jr., 1978, A preliminary duration magnitude scale for local and regional earthquakes recorded at Oklahoma seismograph stations: Oklahoma Geological Survey Observatory Open-File Report, 14 p.

______ 1980, Geophysical observatory establishes continuous time synchronization: Oklahoma Geology Notes, v. 40, p. 214.
Lawson, J. E., Jr.; and Luza, K. V., 1980, Oklahoma earthquakes, 1979: Oklahoma Geology Notes, v. 40, p. 95–105.
______ 1981, Oklahoma earthquakes, 1980: Oklahoma Geology Notes, v. 41, p. 140–149.
______ 1982, Oklahoma earthquakes, 1981: Oklahoma Geology Notes, v. 42, p. 126–137.
______ 1983, Oklahoma earthquakes, 1982: Oklahoma Geology Notes, v. 43, p. 24–35.
______ 1984, Oklahoma earthquakes, 1983: Oklahoma Geology Notes, v. 44, p. 32–42.
______ 1985, Oklahoma earthquakes, 1984: Oklahoma Geology Notes, v. 45, p. 52–61.
______ 1986, Oklahoma earthquakes, 1985: Oklahoma Geology Notes, v. 46, p. 44–52.
______ 1987, Oklahoma earthquakes, 1986: Oklahoma Geology Notes, v. 47, p. 65–72.
______ 1988, Oklahoma earthquakes, 1987: Oklahoma Geology Notes, v. 48, p. 54–63.
______ 1989, Oklahoma earthquakes, 1988: Oklahoma Geology Notes, v. 49, p. 40–48.
______ 1990, Oklahoma earthquakes, 1989: Oklahoma Geology Notes, v. 50, p. 68–76.
______ 1993, Oklahoma earthquakes, 1992: Oklahoma Geology Notes, v. 53, p. 51–62.
______ 1994, Oklahoma earthquakes, 1993: Oklahoma Geology Notes, v. 54, p. 57–68.
______ 1995, Earthquake map of Oklahoma (earthquakes shown through 1993): Oklahoma Geological Survey Map GM-35, scale 1:500,000.
Lawson, J. E., Jr.; Luza, K. V.; and Moss, Dan, 1991, Oklahoma earthquakes, 1990: Oklahoma Geology Notes, v. 51, p. 50–61.
Lawson, J. E., Jr.; Luza, K. V.; Brown, R. L.; and Moss, Dan, 1992, Oklahoma earthquakes, 1991: Oklahoma Geology Notes, v. 52, p. 48–59.
Luza, K. V., 1978, Regional seismic and geologic evaluations of Nemaha uplift, Oklahoma, Kansas, and Nebraska: Oklahoma Geology Notes, v. 38, p. 49–58.
Mykkeltveit, Svein; Ringdal, Frode; Kvaerna, Tormad; and Alewine, R. W., 1990, Application of regional arrays in seismic verification: Seismological Society of America Bulletin, v. 80, p. 1777–1801.
Nuttli, O. W., 1973, Seismic wave attenuation and magnitude relations for eastern North America: Journal of Geophysical Research, v. 78, p. 876–885.
Stauder, W.; Hermann, R.; Singh, S.; Reidy, D.; Perry, R.; and Morrissey, Sean-Thomas, 1979, Central Mississippi Valley Earthquake Bulletin: First Quarter 1979, no. 19, 50 p.
Stover, C. W.; Reagor, B. G.; Algermissen, S. T.; and Lawson, J. E., Jr., 1981, Seismicity map of the State of Oklahoma: U.S. Geological Survey Miscellaneous Field Studies Map MF-1352, scale 1:1,000,000.
Tarbuck, E. J.; and Lutgens, F. K., 1990, The earth—an introduction to physical geology: Merrill Publishing Co., Columbus, Ohio, 651 p.
von Hake, C. A., 1976, Earthquake history of Oklahoma: Earthquake Information Bulletin, v. 8, p. 28–30.
Wells, L. L., 1975, Young Cushing in Oklahoma Territory: Frontier Printers, Stillwater, Oklahoma, 221 p.
Wood, H. O.; and Neumann, Frank, 1931, Modified Mercalli intensity scale of 1931: Seismological Society of America Bulletin, v. 21, p. 227–283.
Zollweg, James, 1974, A preliminary study of the seismicity of the central United States, 1974: St. Louis University unpublished undergraduate report, 15 p.

Oklahoma's FDD Oil Reservoir Project Workshops Scheduled

A series of workshops to be launched in June 1995 in Norman, Oklahoma, will feature the findings of the ongoing Fluvial-Dominated Deltaic Oil Reservoir project. This project involves staff from the Oklahoma Geological Survey (OGS), the University of Oklahoma Geological Information Systems, and OU's School of Petroleum and Geological Engineering. Overall project direction is provided by Charles J. Mankin, OGS Director and State Geologist.

Primary funding for the project, which began in 1993, is provided through a grant from the Department of Energy's Bartlesville Project Office and by matching State funds. Other funding has included private contributions of software and equipment.

For purposes of this project, fluvial-dominated deltaic (FDD) reservoirs are interpreted to consist of sandstone that was deposited in a deltaic or strictly fluvial environment. Oklahoma's FDD reservoirs are Pennsylvanian in age and primarily are within the Cherokee Group. In Oklahoma, light-oil production from the nearly 1,000 fluvial-dominated deltaic reservoirs is a major component of the State's total crude oil output and provides an estimated 15% of the State's total production.

The project has identified all FDD reservoirs in the State of Oklahoma and grouped them into plays with similar exploration and development characteristics. The project team is collecting, organizing, and analyzing all available data on these reservoirs and conducting characterization and simulation studies on selected reservoirs in each play. Lead geologists on the project team are Rick Andrews, Jock Campbell, and Robert Northcutt. The project's petroleum engineer is Roy Knapp.

The next phase of the project is a technology-transfer program to help the operators of FDD reservoirs use this information to sustain the life expectancy of existing wells and increase oil recovery. The elements of the technology-transfer phase of the program include developing and publishing play folios, holding workshops to release play analyses and identify opportunities in each of the plays, and establishing a publicly accessible computer laboratory.

There will be eight workshops, focusing on the following plays:

- Morrow play—June 1, 1995
- Booch play—August 31, 1995
- Layton & Osage-Layton play—November 1995
- Prue & Skinner play—February 1996
- Cleveland and Peru plays—May 1996
- Red Fork play—August 1996
- Bartlesville play—November 1996
- Tonkawa play—February 1997

The computer lab will contain all the data files for the plays, as well as other oil and gas data files for the State, and the necessary software to analyze the information. Technical support staff will be available to assist interested operators in the evaluation of their producing properties, and professional geological and engineering outreach staff will be available to assist operators in determining appropriate improved recovery technologies for those properties. The lab will be equipped with PCs, plotters, laser printers, CD-ROM readers, and scanning and digitizing equipment. Geology-related mapping software, such as GeoGraphix, ARC/INFO, ArcView, Surfer, Atlas MapMaker for Windows and Radian CPS/PC, will be available for public use. Access to data will be through menu-driven screen applications that can be used by computer novices as well as experienced users. The lab opens June 1, 1995, and at a future date, it will be possible to access the facility from other locations through remote modems and, eventually, Internet.

The FDD project has the potential of assisting several thousand operators in Oklahoma by providing them with practical ways to improve production from existing leases and/or to reduce operating costs. Currently available technologies can improve recovery factors in these FDD reservoirs if enough information is available to determine the most appropriate course of action for the independent operator. This project will develop the needed reservoir-level information, and staff will advise interested operators about the implementation of appropriate improved-recovery technologies.

Most FDD reservoir production in Oklahoma is by small companies and independent operators who usually do not have ready access to the information and technology required to maximize exploitation of these reservoirs. Thus, production from FDD oil reservoirs in Oklahoma is at high risk because individual well production commonly is low (1–3 barrels per day) and operating costs are high. Declines in crude oil prices or increases in operating costs can cause an increase in well-abandonment rates. Without positive intervention, most of the production from Oklahoma FDD reservoirs will be abandoned by the beginning of the next century.

The FDD Reservoir Project, through its technology-transfer workshops, publications, and computer lab, has the potential to assist several thousand operators in Oklahoma by providing them practical ways to improve production from existing leases and/or to reduce operating costs. Successful implementation of appropriate improved-recovery technologies could sustain production from FDD reservoirs throughout much of the 21st century.

Morrow Play Featured in First FDD Workshop

A one-day workshop on the Morrow FDD play, located in northwestern Oklahoma, will be presented Thursday, June 1, 1995, in the Sarkeys Energy Center, Room A-235, on the OU campus, Norman.

Operators in this play have priority status to attend if registered by May 12. Registration fee is $15, which includes lunch and a copy of the play folio, *Fluvial-Dominated Deltaic (FDD) Oil Reservoirs in Oklahoma: The Morrow Play* (OGS Special Publication 95-1).

Specific dates and locations for other workshops will be announced later. For more details, or to receive registration forms, contact:

Michelle Summers
Oklahoma Geological Survey
100 E. Boyd, Room N-131
Norman, OK 73019
(405) 325-3031 *or* (800) 330-3996
FAX 405-325-7069

NEW OGS *Publication*

GEOLOGIC MAP GM-35. ***Earthquake Map of Oklahoma,*** by James E. Lawson, Jr., and Kenneth V. Luza. One sheet, folded in envelope, scale 1:500,000. Price: $6.

A complete listing of known Oklahoma earthquakes and their intensities and magnitudes, keyed to map locations, is presented in this 63½- × 38½-inch, four-color map, printed at a scale of 1:500,000 (1 inch equals ~8 miles). Earthquake epicenters are arranged into four color-coded groups according to their intensity values and the time periods in which they occurred. Each time period represents a major change in seismic instrumentation that resulted in improved earthquake detection and location accuracy; the period beginning in 1977, when a statewide network of seismograph and radio-telemetry stations was put in place, shows the greatest amount of earthquake activity. Out of 1,015 earthquakes recorded since 1897, 888 occurred between 1977 and 1993. One of the most active areas in the State is within a zone situated between Norman and Pauls Valley.

A 44-page booklet, the "Oklahoma Earthquake Catalog," accompanies the map and contains a listing of all recorded Oklahoma earthquakes, with intensities and magnitudes, through 1994. The booklet also offers information on Oklahoma's tectonic setting, seismic network, data reduction and archiving methods, distribution of earthquakes, and a glossary of terms.

From 1882 to 1994, 132 Oklahoma earthquakes were reported felt. The earliest earthquake able to be located in Oklahoma occurred near Jefferson, in Grant County, on December 2, 1897. The largest known Oklahoma earthquake occurred near El Reno, Canadian County, on April 9, 1952, and was felt as far away as Austin, Texas, and Des Moines, Iowa. Each year, approximately 50 earthquakes are located in Oklahoma; of these, only one or two (on average) are reported felt.

Currently, 11 widely separated locations in Oklahoma record ground motion. The main recording and research station, the Oklahoma Geological Survey Observatory at Leonard, near Tulsa, was built in 1961 for Jersey Production Research Co. (now Exxon). Since July 1, 1978, the Observatory has been a part of the Oklahoma Geological Survey's research program.

Authors of the map and booklet are James E. Lawson, Jr., chief geophysicist at the OGS Observatory, and Kenneth V. Luza, OGS engineering and environmental geologist. The map provides basic data to help evaluate the State's earthquake potential, which is especially useful in determining selection of sites for major construction projects.

GM-35 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 *or* (800) 330-3996; fax 405-325-7069. Add 10% to the cost of publication(s) for mail orders, with a minimum of 50¢ per order.

Notes ON NEW PUBLICATIONS

Hydrogeology of the Chickasaw National Recreation Area, Murray County, Oklahoma

Prepared in cooperation with the National Park Service, this 86-page USGS report by Ronald L. Hanson and Steven W. Cates presents an assessment of the water resources in the Chickasaw National Recreation Area and vicinity. The park was established in 1902 to preserve freshwater and mineral springs that flow into Rock Creek and its principal tributary, Travertine Creek, but over the years the discharge from the park's springs and wells has declined substantially. Because of the apparent continued decline in the spring flows and possible future stresses on the hydrologic system by ground-water pumping, this study was undertaken to compile and appraise information about the hydrogeology of the CNRA and adjoining areas. The scope of the study included an evaluation of the quantity and quality of stream flow, spring flows, and artesian well flows; it also evaluated the effect of local ground-water pumping on the hydrologic system.

Order WRI 94-4102 from: U.S. Geological Survey, Water Resources Division, 202 N.W. 66th St., Bldg. 7, Oklahoma City, OK 73116; phone (405) 843-7570, fax 405-843-7712. A limited number of copies are available free of charge.

Steady-State Simulation of Ground-Water Flow in the Blaine Aquifer, Southwestern Oklahoma and Northwestern Texas

The Blaine aquifer, which supplies water for the irrigation of ~200,000 acres in Oklahoma and northwestern Texas, is the subject of this USGS open-file report, written by D. L. Runkle and J. S. McLean. The Okahoma Water Resources Board requires information on the ability of the aquifer to sustain development. The USGS worked in cooperation with the Oklahoma Water Resources Board and the Oklahoma Geological Survey to define ground-water flow in the aquifer. As part of the study, a generalized finite-difference ground-water flow model was prepared for the Blaine aquifer and is available for use and modification. The study area includes the most productive parts of the Blaine aquifer, covering ~4,400 mi^2 in all or part of Harmon, Jackson, and Greer Counties in Oklahoma, and all or part of Hardeman, Collingsworth, and Childress Counties in Texas.

Order OF 94-387 from: U.S. Geological Survey, Water Resources Division, 202 N.W. 66th St., Bldg. 7, Oklahoma City, OK 73116; phone (405) 843-7570, fax 405-843-7712. A limited number of copies are available free of charge.

New OGS Publication List Available

The Oklahoma Geological Survey has recently updated its *List of Available Publications.* The list can be obtained free of charge by contacting the OGS Publication Sales Office at 100 E. Boyd, Room N-131, Norman, OK 73019; phone (405) 325-3031 *or* (800) 330-3996; fax 405-325-7069.

Oklahoma Rock Clubs

Ada Hardrock & Fossil Club
923 E. 34th St.
Ada, Oklahoma 74820
Meets 2nd Thursday, 7:30 p.m.
Place varies
President: Doug Kreis
(405) 436-1655

Enid Gem & Mineral Society
2614 W. Oklahoma
Enid, Oklahoma 73703
Meets 1st Thursday, 7:30 p.m.
Hoover Building
Garfield County Fairgrounds
President: George Salwaechter
(405) 237-9525

McCurtain County Gem & Mineral Club
406 S.E. Ave. "E"
Idabel, Oklahoma 74745
Meets 3rd Tuesday, 7:30 p.m.
Idabel Public Library
President: Cephis Hall
(405) 494-6612

Mount Scott Gem & Mineral Society
44 N.W. 29th St.
Lawton, Oklahoma 73505
Meets 4th Friday, 7:00 p.m.
Lawton Town Hall
5th St. and "B" Ave.
President: Richard Robinson
(405) 355-9081

N.W. Arkansas Gem & Mineral Society
Route 1, Box 288A
Colcord, Oklahoma 74338
President: John Moose
(501) 524-4027

Oklahoma Mineral & Gem Society
P.O. Box 25632
Oklahoma City, Oklahoma 73125
Meets 3rd Thursday, 7:30 p.m.
Will Rogers Garden Center
3400 N.W. 36th
President: Paul Cinnamon
(405) 751-4967

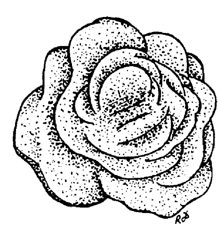
Osage Hills Gem & Mineral Society
P.O. Box 561
Bartlesville, Oklahoma 74005
Meets 3rd Thursday, 7:00 p.m.
First Presbyterian Church
5th and Dewey
President: Dave Kennedy
(918) 333-9709

Shawnee Gem & Mineral Club
10 Donna Lane
Shawnee, Oklahoma 74801
Meets 1st Tuesday, 7:30 p.m.
Northridge Church of Christ
President: Willogene Morris
(405) 386-2314

Stillwater Mineral & Gem Society
1116 S. Gray
Stillwater, Oklahoma 74074
Meets 4th Thursday
First United Methodist Church
President: John Osborne
(405) 377-4288

Tahlequah Rock & Mineral Society
P.O. Box 932
Tahlequah, Oklahoma 74465
President: Betty Ruth Adams
(918) 456-5827

Tulsa Rock & Mineral Society
P.O. Box 2292
Tulsa, Oklahoma 74101
Meets 2nd Monday, 7:00 p.m.
Tulsa Downtown Library
President: Wayne Mouser
(918) 582-8700



State rock of Oklahoma, the barite rose.

We advise calling in advance to verify meeting times.

AAPG Southwest Section Convention

Dallas / Fort Worth, Texas ★ June 3–7, 1995

Hosted by the Dallas Geological Society, the theme of this year's AAPG Southwest Section Convention is "Discoverers of New Wealth."

The program calls for papers and posters to be presented in technical sessions dealing with hydrocarbon fundamentals, petroleum geology and economics, environmental perspectives, geophysics, well-logging techniques, and surface exploration and remote sensing.

Two field trips are planned. Participants in the first trip will observe sequence stratigraphy of Dallas County; the second trip will visit the dinosaur tracks of Glen Rose, Texas.

AAPG 95
SOUTHWEST SECTION

Five short courses are offered: (1) integrated stratigraphic analysis, (2) workstation techniques, (3) evaluating carbonate reservoirs, (4) the geologist as entrepreneur, and (5) personal computers and geology.

For further information about the meeting, contact Robert W. Richter, Enserch Exploration, Inc., 4849 Greenville Ave., Suite 1200, Dallas, TX 75206; phone (214) 987-6304, fax 214-987-7706. *The preregistration deadline is April 30.*

GEM AND MINERAL

SHOW AND CONVENTION

Oklahoma City, Oklahoma, June 9–11, 1995

Sponsored by the Rocky Mountain Federation of Mineralogical Societies, Inc., and hosted by the Oklahoma Mineral and Gem Society, this year's show will be at the Oklahoma State Fair Park.

For more information, contact Dan McLennan, Show Chairman, Oklahoma Mineral and Gem Society, P.O. Box 26523, Oklahoma City, OK 73126; (405) 525-2692.

5th ARCHIE Conference, "Visualization Technology to Find and Develop More Oil and Gas," May 14–18, 1995, The Woodlands, Texas. Information: American Association of Petroleum Geologists, Education Dept., P.O. Box 979, Tulsa, OK 74101; (918) 584-2555, fax 918-584-0469.

Basement Tectonics, 12th International Conference, May 21–26, 1995, Norman, Oklahoma. Information: M. Charles Gilbert, School of Geology and Geophysics, 810 Sarkeys Energy Center, University of Oklahoma, Norman, OK 73019; (405) 325-3253, fax 405-325-3140.

SEG International Field Conference on Carbonate-Hosted Lead-Zinc Deposits, June 3–6, 1995, St. Louis, Missouri. Information: Martin Goldhaber, U.S. Geological Survey, MS 973, Box 25046, Federal Center, Denver, CO 80225; fax 303-236-3200.

35th U.S. Symposium on Rock Mechanics, June 4–7, 1995, Lake Tahoe, Nevada. Information: Jaak Daemen, Mining Engineering, MS 173, University of Nevada, Reno, NV 89557; (702) 784-4309, fax 702-784-1766.

Clay Minerals Society, Annual Meeting, June 4–8, 1995, Baltimore, Maryland. Information: Patricia Jo Eberl, Clay Minerals Society, P.O. Box 4416, Boulder, CO 80306; (303) 444-6405, fax 303-444-2260.

American Society for Surface Mining and Reclamation, Annual Meeting, June 5–8, 1995, Gillette, Wyoming. Information: Gerald E. Schuman, Program Committee, 8408 Hildreth Rd., Cheyenne, WY 82009; (307) 772-2433, fax 307-637-6124.

Mine Development, Planning, and Operations Conference, June 6–8, 1995, Pittsburgh, Pennsylvania. Information: George Roman, Maclean Hunter Publishing Co., 29 N. Wacker Dr., Chicago, IL 60606; (312) 609-4333, fax 312-726-4103.

American Society of Mechanical Engineers, Annual Meeting, June 11–15, 1995, Kansas City, Missouri. Information: June Leach; phone (212) 705-7795, fax 212-705-7856.

American Nuclear Society, Annual Meeting, June 11–16, 1995, Atlantic City, New Jersey. Information: ANS, 555 N. Kensington Ave., La Grange Park, IL 60525; (312) 352-6611.

7th International Symposium on the Ordovician System, June 12–16, 1995, Las Vegas, Nevada. Information: Margaret Rees, Dept. of Geosciences, University of Nevada, Las Vegas, NV 89154; (702) 895-3262, fax 702-895-4064.

Rapid Excavation and Tunneling Conference, June 18–22, 1995, San Francisco, California. Information: Meetings Dept., Society for Mining, Metallurgy, and Exploration, P.O. Box 625002, Littleton, CO 80162; (303) 973-9550, fax 303-979-3461.

Heavy Oil, International Meeting, June 25–27, 1995, Calgary, Alberta. Information: Society of Petroleum Engineers, Meetings and Exhibitions Dept., Box 833836, Richardson, TX 75083; (214) 952-9393, fax 214-952-9435.

SEPM Research Conference, "Tongues, Ridges, Wedges: Highstand Versus Low Stand Architecture in Marine Basins," June 25–July 1, 1995, Thermopolis and

Casper, Wyoming. Information: Beth Foyle, Dept. of Oceanography, Old Dominion University, Norfolk, VA 23508; (840) 683-4937, fax 804-683-5303.

International Union of Geodesy and Geophysics Meeting, July 2–14, 1995, Boulder, Colorado. Information: IUGG General Assembly, c/o American Geophysical Union, 2000 Florida Ave. N.W., Washington, DC 20009; (202) 462-6900, fax 202-328-0566.

American Association of Petroleum Geologists, Rocky Mountain Section Meeting, July 16–19, 1995, Reno, Nevada. Information: Larry Garside, Nevada Bureau of Mines and Geology, University of Nevada, Reno, NV 89557; (702) 784-6691.

Animal Wastes and the Land/Water Interface, Interdisciplinary Meeting, July 16–19, 1995, Fayetteville, Arkansas. Information: Patti Snodgrass, Arkansas Water Resources Center, 113 Ozark Hall, University of Arkansas, Fayetteville, AR 72701; (501) 575-4403, fax 501-575-3846.

Energy Conversion Engineering Conference, July 31–August 4, 1995, Orlando, Florida. Information: Marisa Scalice, American Society of Mechanical Engineers, Meetings Dept., 345 E. 47th St., New York, NY 10017; (212) 705-7793, fax 212-705-7856.

Ground Control in Mining Conference, August 1–3, 1995, Morgantown, West Virginia. Information: Syd S. Peng, Dept. of Mining Engineering, West Virginia University, Box 6070, Morgantown, WV 26506; (304) 293-7680, fax 304-293-5708.

Soil and Water Conservation Society, 50th Anniversary Meeting, August 6–9, 1995, Des Moines, Iowa. Information: Tim Kautza, Soil and Water Conservation Society, 7515 N.E. Ankeny Rd., Ankeny, IA 50021; (800) 843-7645, ext. 12.

SEPM Congress on Sedimentary Geology, "Linked Earth Systems," August 13–16, 1995, St. Petersburg, Florida. Information: Society for Sedimentary Geology, 1731 E. 71st St., Tulsa, OK 74136; (918) 493-3361 *or* (800) 865-9765, fax 918-493-2093.

GSA Penrose Conference, "Fault-Related Folding," August 22–27, 1995, Banff, Alberta, Canada. Information: David Anastasio, Dept. of Earth and Environmental Sciences, Lehigh University, Bethlehem, PA 18015; (610) 758-5117, fax 610-758-3677.

The Society for Organic Petrology, Annual Meeting, August 27–30, 1995, Houston, Texas. Information: John R. Castaño, DGSI, 8701 New Trails Dr., The Woodlands, TX 77381; (713) 363-2176, fax 713-292-3528.

American Association of Petroleum Geologists, International Meeting, September 10–13, 1995, Nice, France. Information: AAPG Convention Dept., P.O. Box 979, Tulsa, OK 74101; (918) 584-2555, fax 918-584-0469.

American Association of Petroleum Geologists, Mid-Continent Section Meeting, October 8–10, 1995, Tulsa, Oklahoma. Information: Jean R. Lemmon, 1524 S. Cheyenne, Tulsa, OK 74119; (918) 582-8904.

Rockhounds Workshop, October 28–29, 1995, Oklahoma City, Oklahoma. Information: Kenneth S. Johnson or Neil H. Suneson, Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019; (405) 325-3031 *or* (800) 330-3996, fax 405-325-7069.

Geological Society of America, Annual Meeting, November 6–9, 1995, New Orleans, Louisiana. *Abstracts due July 12, 1995.* Information: GSA Meetings Dept., Box 9140, Boulder, CO 80301; (303) 447-2020 *or* (800) 472-1988, fax 303-447-0648.

The following abstracts were presented as part of the Geology Section program at the Oklahoma Academy of Science 83rd annual meeting, Norman, Oklahoma, November 12, 1994.

The Relationships of Textures and Geochemistry of the Feldspar Phases in the Mount Scott Granite, Wichita Mountains, Oklahoma

JONATHAN D. PRICE, JOHN P. HOGAN, and *M. CHARLES GILBERT,*
School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

The Cambrian Mount Scott alkali feldspar granite of southwestern Oklahoma exhibits a variety of textures over a very limited range in bulk-rock composition. There are five distinct feldspar populations in the rock texture: (1) early-crystallizing, ovoid-shaped *anorthoclase-K* (now perthite); (2) abundant ovoid-shaped *anorthoclase-N* (now antiperthite); (3) *plagioclase rims* on alkali feldspar (rapakivi); (4) anhedral to euhedral *plagioclase* grains; and (5) late-crystallizing *alkali feldspar.* These comprise five geochemical groups (Fig. 1). Large (1–5 mm), pink, ovoid-shaped perthites comprise 2–6% of the mode, varying greatly in composition from sample to sample (Or_{60-40}). Gray, ovoid antiperthites (1–4 mm, 4–13% mode), many with pink rims, darken the rock. Their geochemistry varies between Or_{20} and Or_{35} and are more ternary than their perthite counterparts. Many ovoid crystals have plagioclase rims (~200μ, An_{10-20}), that exhibit an increase of plagioclase component from An_{10-12} on rim margins, to An_{17-20} in the center of the rim. Pink alkali feldspar (Or_{60-90}, 20–36% mode) and quartz nucleated around the rims of the ovoids. Small plagioclase crystals (An_{8-15}) are a minor phase and are more abundant in microgranitic samples.

Primary feldspar compositions have been altered by susolidus re-equilibration. Exsolution of the anorthoclase-A and anorthoclase-N crystals resulted in perthite and antiperthite grains. Results of two feldspar equilibration geothermometry data indicate unmixing continued until ~640°C. Readjustment of the feldspar components may have produced the compositional variation seen in the plagioclase rims. Oxidation of trace amounts of iron in feldspar produced the color change from gray to pink.

The textural and geochemical diversity of the feldspar

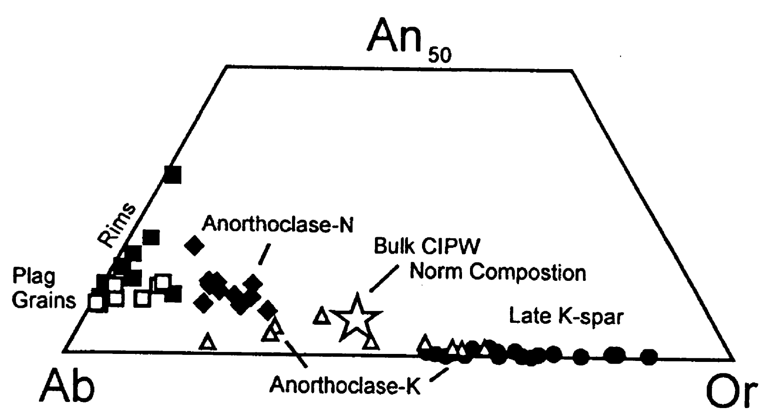


Figure 1. Mount Scott feldspar geochemical compositions plotted on a partial feldspar ternary diagram (An = Anorthite, Ab = Albite, Or = Orthoclase). Bulk composition (☆) indicates the low Ca concentration of the system. The Mount Scott granite is comprised of five geochemically and texturally distinct feldspar populations: anorthoclase-N (◆), anorthoclase-K (Δ), plagioclase rims (■), plagioclase grains (□), and late crystallizing K-spar (●).

phases point to a complex history. Early crystallization of substantial amounts (about 10–20% crystals) of feldspar and quartz, with lesser hornblende, biotite, magnetite, apatite, titanite, and fluorite occurred at depths of about 6–8 km. Anorthoclase-N precipitated as the primary phase; anorthoclase-K precipitated as a coexisting feldspar as the system approached equilibrium. The magma then rapidly ascended to ~0.5 km, intruding along or near the base of coeval Carlton rhyolite. The rapid ascent resulted in resorption of the early phases, producing the ovoid feldspar shapes. Plagioclase rims surround some of the ovoid grains and precipitated as a result of magma decompression during adiabatic ascent (e.g., Nekvasil, 1993). Plagioclase crystallization terminated after depletion of Ca. Alkali feldspar crystallized as the system reapproached equilibrium crystallization. The geochemistry and textures have allowed interpretation of this complex crystallization history, but the conditions and domains of equilibration among these distinct phases are problematic.

Paleomagnetic Investigations of Mount Sheridan Gabbro, Wichita Mountains Igneous Province, Oklahoma

GLENN BIXLER, JOHN P. HOGAN, DOUGLAS ELMORE, and *DEBORAH BARR,* School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

The Southern Oklahoma Aulacogen formed during Cambrian breakup of the Laurentian Supercontinent. Extension was accompanied by voluminous bimodal magmatism. Mafic magmatism in the rift consists of an extensive substrate (3–4 km thick) of anorthositic layered gabbro, the Glen Mountains Layered Complex, and a suite of younger gabbroic plutons, the Roosevelt Gabbros, of which the Mount Sheridan gabbro is a typical example. The Roosevelt Gabbros are internally differentiated and have a pronounced primary igneous lamination. The presence of late primary biotite and amphibole, as well as numerous pegmatite dikes and pods, attest to the intrinsically hydrous nature of these gabbros in contrast to the Glen Mountains Layered Complex. The presence of a widespread Permian conglomerate throughout the Southern Oklahoma Aulacogen indicate that uplift during the late Paleozoic Ouachita Orogeny and subsequent erosion in the Permian

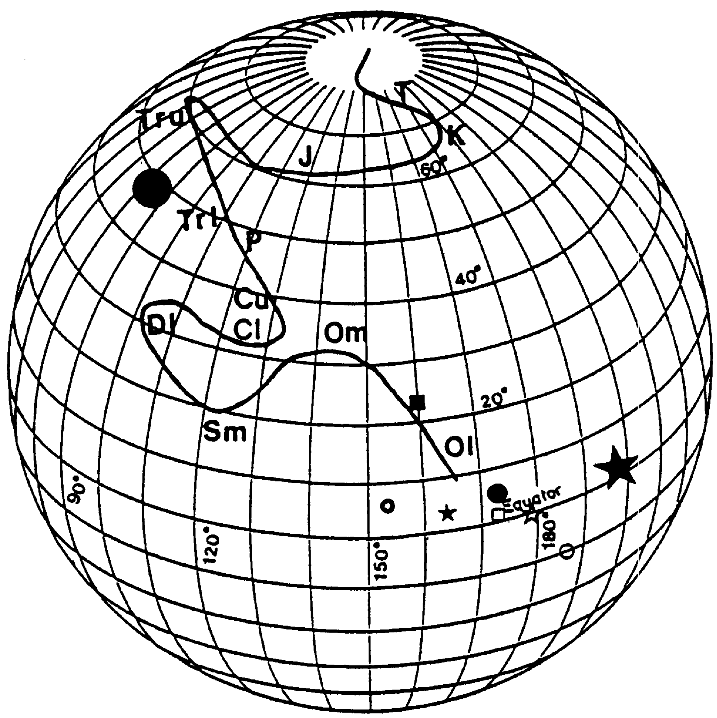


Figure 1. North American apparent polar wander path (Van der Voo, 1989) with the paleopoles calculated from the WS (★, found in gabbro samples only) and S (●, found in pegmatites and some gabbro samples) components. Positions for additional interpreted Cambrian paleopoles are also indicated (Spall, 1970, ★; French and others, 1977, •; Deutsch and Rao, 1977, ■; Brown and Van der Voo, 1982, ☆; Dankers and LaPointe, 1981, ○, □, ✪).

had previously exposed the igneous floor of the rift.

Paleomagnetic investigation of Mount Sheridan gabbro and cognate pegmatite reveals two components of magnetization. One component has southwesterly declinations and shallow–moderate down inclinations (WS). The WS component is present only in gabbro samples and is removed by thermal demagnetization to 580°C. A pole position for WS at 3°N, 163°W is in the vicinity of other interpreted Cambrian pole positions (Fig. 1), and is compatible with the Cambrian age determined for the Mount Sheridan gabbro (U/Pb zircon, Browning and Hoppe, 1982). Thus, this component is interpreted to record a primary magnetization residing in magnetite. The second component has southerly declinations and shallow down inclinations (S). The S component is present in some gabbro samples and is the only component in pegmatite samples. This component is removed during thermal demagnetization by 580°C. A pole for the S component plots at 48°N, 84°E, suggesting remanence aquisition during the Triassic (Fig. 1). This component is interpreted as secondary in origin and to reside in magnetite.

The Triassic age for this remagnetization coincides with final stages of tectonic overthickening in the Anadarko Basin, adjacent to the Wichita Uplift (Gilbert, 1992). Alternation of gabbro and pegmatite along fractures and joints is evident in the field. Secondary alteration minerals are observed in both gabbro and pegmatite, but appear relatively more abundant in pegmatite. Numerous secondary fluid inclusions are present along healed fractures in quartz from pegmatite. These results suggest that the S component represents a chemical remagnetization related to alteration of the primary igneous mineral assemblage by fluids. Fractures within the Mount Sheridan pluton appear to have provided conduits for fluids related to subsidence of the Anadarko Basin. A low modal abundance of mafic minerals (including magnetite) in pegmatite, relative to the gabbro, may have resulted in an increased susceptibility of pegmatite to chemical remagnetization.

References Cited

Brown, P. M.; and Van der Voo, R., 1982, Paleomagnetism of the latest Precambrian/Cambrian Unicoi basalts from the Blue Ridge, northeast Tennessee and southwest Virginia; evidence for Taconic deformation: Earth and Planetary Science Letters, v. 60, p. 407–414.

Browning, S. A.; and Hoppe, W. J., 1982, U/Pb zircon ages from Mount Sheridan Gabbro, Wichita Mountains, *in* Gilbert, M. C.; and Donovan, R. N. (eds.), Geology of the eastern Wichita Mountains, southwestern Oklahoma: Oklahoma Geological Survey Guidebook 21, p. 54–59.

Dankers, P.; and LaPointe, P., 1981, Paleomagnetism of lower Cambrian volcanics and a cross-cutting Cambro–Ordovician diabase dyke from Buckingham (Quebec): Canadian Journal of Earth Sciences, v. 18, p. 1174–1186.

Deutsch, E. R.; and Rao, K. V., 1977, New paleomagnetic evidence fails to support rotation of western Newfoundland: Nature, v. 266, p. 314–318.

French, R. B.; Alexander, D. H.; and Van der Voo, R., 1977, Paleomagnetism of upper Precambrian to lower Paleozoic intrusive rocks from Colorado: Geological Society of America Bulletin, v. 88, p. 1785–1792.

Gilbert, M. C., 1992, Speculations on the origin of the Anadarko Basin, *in* Mason, R. (ed.), Proceedings of the 7th International Conference on Basement Tectonics, Kingston, Ontario: Klower Academic, p. 195–208.

Spall, Henry, 1970, Paleomagnetism of basement granites in southern Oklahoma: final report: Oklahoma Geology Notes, v. 30, p. 136–150.

Van der Voo, R., 1989, Paleomagnetism of North America; the craton, its margins, and the Appalachian Belt, *in* Pakiser, L. C.; and Mooney, W. D., Geophysical framework of the continental United States: Geological Society of America Memoir 172, p. 447–470.

Magnetic Anomaly in the Mount Scott Granite Drill Core from the Ira Smith Quarry, Indiahoma, Oklahoma

JAMES PAYNE, JONATHAN D. PRICE, JOHN P. HOGAN, and *M. CHARLES GILBERT*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

Approximately 300 ft of continuous granite core was retrieved from the A-type Mt. Scott Granite of the Wichita Mountains Granite Group. The core is relatively uniform over its length with respect to grain size and texture. A preliminary magnetic susceptibility survey of the core, at 10-ft intervals, defined a substantial increase in magnetic susceptibility readings beginning at approximately 70 ft below the surface. The origin of this magnetic anomaly is the focus of this investigation. Two possible origins were considered: (1) The magnetic anomaly is intrinsic to the granite's magmatic origin and possibly reflects processes such as gravitational settling of magnetite. (2) The magnetic anomaly is a secondary chemical overprint of the primary mineralogy due to fluid-rock interactions during the complex burial and uplift history of the Wichita Mountain crustal block.

Approximately 90 ft of core was isolated for detailed investigation of the magnetic anomaly. This segment included 30 ft of core above the magnetic susceptibility increase, 30 ft of core over which the increase occurred, and 30 ft of core below where magnetic susceptibility readings stabilized. Diagnostics for the investigation included measurements of (1) grain texture, (2) rock color, (3) color index, (4) fracture density, and (5) magnetic susceptibility readings at 0.5-ft intervals.

Beginning at ≈70 ft the magnetic susceptibility of the core gradually increases from values around 2–5 miliTesla (mT) to a value of 25–28 mT at ≈100 ft, where it then remains relatively constant (Fig. 1). Changes in fracture density, the presence of secondary mineralization, and alteration of magnetite to hematite closely correlate with changes in magnetic susceptibility readings as a function of depth. The abundance and density of fractures decreases markedly below 90 ft. Petrographic observations of thin sections at 52.5 ft, 61.75 ft, 64.5 ft, 65.5 ft, 67.5 ft, 76.45 ft, 78.0 ft, 90.13 ft, 113.0 ft,

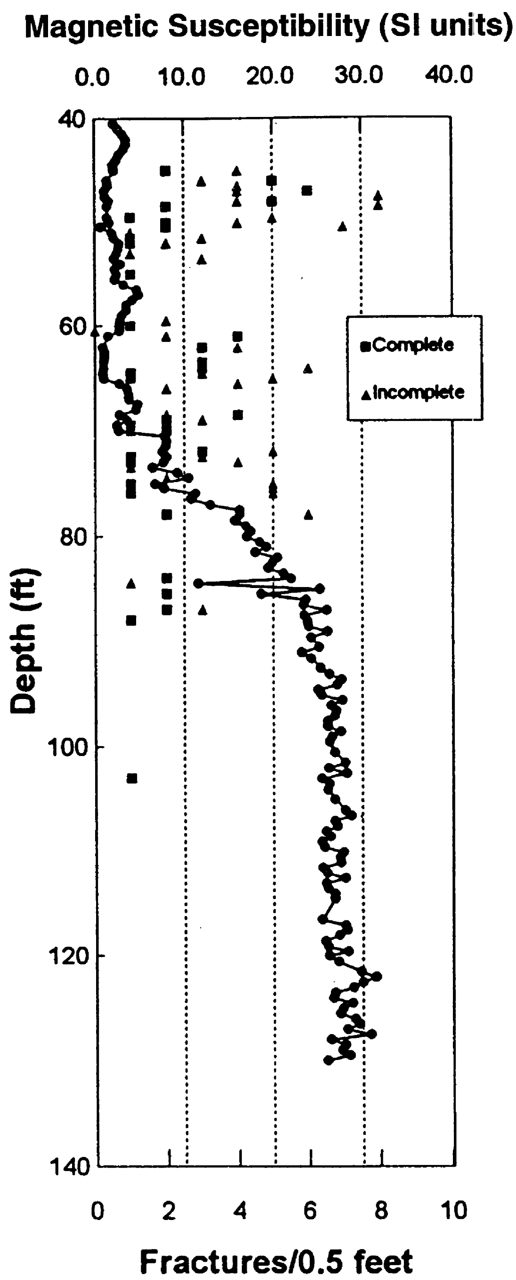


Figure 1. Variation in density of fractures which transect core (■), those which do not transect core (▲), and magnetic susceptibility (●) as a function of depth within the interval of 40–130 ft below the surface in the Mount Scott Granite core from the Ira Smith Quarry, Indiahoma, Oklahoma.

114.4 ft, and 150 ft reveal a significant decrease in the abundance of secondary hematite replacing magnetite. At depths below 75 ft, and low magnetic susceptibility values, magnetite is nearly entirely replaced by hematite and exhibits a "martite" texture. With increasing depth (75–95 ft), and increasing magnetic susceptibility, secondary hematite replacing magnetite is restricted to the margins of grains and the margins of through-going fractures that cut magnetite grains. At depths greater than 95 ft primary magnetite exhibits the least amount of alteration, secondary hematite is scarce, and magnetic susceptibility readings are high (≈28 mT) and stable.

The order of magnitude decrease in magnetic susceptibility of Mt. Scott Granite reflects oxidation of primary titanomagnetite to secondary hematite and hemoilmenite as a result of fluid-rock interaction. Brittle fractures provided conduits for fluid-flow through this crystalline rock. Thus the extent of alteration of the primary igneous mineral assemblage and subsequent change in magnetic susceptibility is a reflection of the fluid/rock ratio which in turn was controlled by fracture density. Extensive(?) movement of fluids appears to have been restricted to depths less than 90 ft below the present erosional surface.

Satisfying the Diverse Needs of Majors Versus Nonmajors in Introductory Geology Courses

VERNON P. SCOTT, School of Geology, Oklahoma State University, Stillwater, OK 74078

Geology majors and nonmajors are both in need of understanding the basic systems that govern the natural world, but for different purposes—majors need to function within the professional community whereas nonmajors need to function as literate members of society. Large geology departments may meet these differing needs by offering separate courses or sections for nonmajors, but smaller departments, particularly those in junior colleges, are usually forced to compromise by offering a single course for both. This paper examines the needs of both groups of students and suggests how courses, either separate or composite, can be improved.

General curricular issues must first be decided: breadth vs. depth, theoretical vs. applied, minds-on vs. hands-on, grouped vs. individualized, qualitative vs. quantitative, inductive vs. deductive sequencing, etc. As presently constituted, nonmajor offerings tend to be broader in coverage, sometimes including other earth sciences such as astronomy and meteorology; they tend to be socio-applicatory in design, emphasizing environmental hazards and resource usage. Nonmajors prefer, perhaps justifiably, less mathematics, although this does not obliviate the need to think in quantitative terms or engage in problem-solving strategies. Nonmajor laboratory work, if it exists at all, tends toward the descriptive, is rarely experimental, and may utilize computer-assisted instruction in specific circumstances. Are these trends justified when offering separate courses? How could this diversity be accommodated in a composite course? I have suggested some guidelines to help departments answer these questions.

Once a department has outlined their general approach, individual instructors need to look at specifics as to what might be included, excluded, or modified for majors vs. nonmajors. Making such judgments should be objective, but is more likely to be influenced by what and how the instructor taught in the past—new rationales rarely change old habits. For example, pertinent labs for nonmajors would best be limited to one lab on mineral identification and another on rock identification, with an additional lab for mineral resources and one for energy resources. But research geologists and T.A.s (who are always majors) find anything less than three rock labs appalling and are stressed to teach material they never encountered when they were students. Differentiating what is essential for the profession vs. the citizen is particularly troublesome when teaching terminology. Technical terms such as "aphanitic" are a must for majors, but all terms that lack reinforcement outside the profession will invariably be forgotten, so why waste a nonmajor's time? And why generate animosity having nonmajors memorize the full-blown geologic time scale when their need is to appreciate the vastness of geologic time and recognize only names they might encounter in a museum or television program? Similarly, geomorphic and structural terms can be limited when a nonmajor's needs only include appreciation of scenery seen on a vacation or avoiding building near geologic hazards. Similarly, enthusiastic detailing of plate tectonics should be reserved for majors, although nonmajors find rudimentary tectonics to be a useful paradigm on which to organize their ideas of how Earth operates. Nor should one attempt to make a course too "applied." A pure environmental course taught outside the context of planetary processes results in sloganeering of environmental issues rather than critical analysis. I have taken an extensive list of topics covered in introductory courses and examined what aspects majors and nonmajors find pertinent or interesting. Although instructors will inevitably disagree with portions of my assessment, it will hopefully stimulate a fruitful dialog for improving instruction at the introductory level.

Shoreline Carbonate-to-Clastic Facies Changes: Chase Group (Early Permian) in the Midcontinent, U.S.A.

JAMES R. CHAPLIN, Oklahoma Geological Survey, Norman, OK 73019

Siliciclastic-dominated mixed carbonate/siliciclastic sediments of the Early Permian Chase Group were deposited in epicontinental marine, marginal marine, and continental environments in the Midcontinent region of North America. The Chase Group includes a predominantly marine, carbonate-dominated lithofacies in southeastern Nebraska and Kansas and a dominantly marginal marine to continental siliciclastic-dominated facies in northern Oklahoma. There is a pervasive north-south facies change from a dominantly marine carbonate platform, shallow water open-marine subtidal facies in Nebraska and Kansas, to restricted marine/marginal-marine subtidal to peritidal, and continental facies in north-central Oklahoma. In central Oklahoma, the carbonate units merge into, and disappear within, a thick wedge of dominantly fluvial/continental red-bed siliciclastics.

The Chase Group in northern Oklahoma is a depositional sequence (340 ft) characterized by clastic-dominated units in recurring carbonate/clastic couplets. The carbonates and clastics of the couplets are correlatable to both major transgressive and regressive surfaces, respectively. Regressive parts are characterized by a thicker (40–125 ft), more clastic-rich marginal marine/continental facies consisting of reddish-brown, greenish-gray, and maroon mudstones/shales locally capped by exposure surfaces and poorly developed paleosols. Transgressive parts consist of a thinner (3–60 ft), more carbonate-rich marine/marginal marine facies dominantly composed of shallowing-upward units of coated-grain, fossiliferous wackestones, packstones, and grainstones.

Thin (1 ft to <1 ft) nodular carbonate units characteristic of the southernmost facies in Noble and Payne Counties, occurring in similar stratigraphic positions as the thicker carbonate intervals in the northern outcrop belt, are interpreted to represent intertidal to supratidal depositional settings on carbonate tidal flats; however, these nodular dolomudstones/dolodismicrites may represent pedogenic features of poorly developed paleosols formed during periodic subaerial exposure of a paleodepositional surface.

Rose Rock Revival!

DAVID LONDON, School of Geology and Geophysics,
University of Oklahoma, Norman, OK 73019

The barite-sand rose was adopted in 1968 as the official rock of the State of Oklahoma. It is a fitting symbol, because barite-sand roses, a.k.a. rose rocks, are virtually unique to the State. They are found in exposures of the Permian Garber Sandstone in central Oklahoma. Late Paleozoic to early Mesozoic red sandstones are common globally but lack barite mineralization as is found in the Garber. This fact implies some unusual geologic processes that operate(d) in the Garber but not in similar rock types elsewhere in space or time.

Rose rocks consist of mostly quartz sand grains cemented by barite. Like the Garber Sandstone they form in, the sand is nearly pure quartz, with only traces of other mineral phases (Baker, 1951). The barite cement also is nearly pure $BaSO_4$, with only trace Fe-oxide and clay minerals. Fe-oxide, which constitutes the cement of the Garber and gives rose rocks their outward brick-red color, is not usually included in the barite. Barite crystals form radial divergent sprays. Radial aggregates shaped like ribbed walnuts consist of any number of tabular barite crystals that intersect along a common axis. The true rose shapes arise from intersections of two pairs of crossed crystals, with each cross rotated 90° to one another (it is not yet known if the opposed pairs are related by twinning). Quartz sand makes up approximately 55 vol% of the barite roses and the Garber; from very preliminary modal mapping using backscattered electron signals, there is no measurable difference in the volumetric abundance of quartz in or outside of the roses. Strontium concentration is low in the one rose mapped to date, and occurs as small patchy highs within barite crystals, not dispersed along growth zones in the barite. One of the most interesting features of the barite rose texture, and indeed the Garber Sandstone as noted by Baker (1951) is that, although chemically mature and well sorted, the quartz grains are angular. Baker (1951) suggested that the angularity might stem from overgrowths, but optical or chemical evidence for overgrowth has not been recognized.

The origin of barite roses is problematic. Barite possesses a very low solubility of 0.01–0.1 mmoles/kg H_2O over a range of salinity and low temperature. This low solubility makes transport of Ba and SO_4 together in a single solution an unlikely means of creating a concentration of barite, unless very large fluid quantities are involved. In addition, once saturated, a fluid would remain saturated in barite and might be expected to precipitate barite along areally extensive horizons of fluid flow. Not only are the barite rose rock horizons isolated in their distribution, but they lack any apparent control by bedding or fractures. Two other means of forming barite that potentially require less fluid and would produce more focused precipitation of barite include (1) mixing between two different ground waters—one a source of Ba and the other a source of sulfate; or (2) changes in the chemistry of a single-source fluid, as for example along an oxidation front or a sharp pH boundary. Oxidation fronts are common in sandstones and siltstones within Oklahoma, e.g., in the redbed Cu deposits of Paoli, Oklahoma, in association with barite nodules. Some barite roses from Noble are covered by colliform masses of Fe-oxide that resemble former pyrite framboids.

At four of the better-known and extensively worked barite rose localities in Noble and Slaughterville, the roses occur within 1 meter of the surface, mostly in soil and down a few centimeters into weathered rock. Some roses retain the fine cross-bedding of the Garber, so they at least formed within the sandstone. Overall, however, the barite rose bodies form discontinuous lenses in soil that parallel the modern surface and are discordant to bedding within the Garber, and roses are not found in subsurface samples

(Charles Mankin, personal communication, 1994). These exposures raise the possibility that the roses do not represent an early strata-bound diagenetic event within the Garber (Ham and Merritt, 1944), but rather have formed in contemporary times, e.g., by near-surface evaporation or oxidation of isolated ground-water springs. The source of Ba remains enigmatic, but several water wells in the rose-rock provinces of the Garber in Cleveland and Oklahoma Counties contain >1 mg/L of dissolved Ba, which almost surely makes these solutions barite saturated (Parkhurst and others, 1994).

References Cited

Baker, F. E., 1951, A mechanical and petrographic analysis of the Garber Sandstone in Cleveland and Pottawatomie Counties: University of Oklahoma unpublished M.S. thesis, 68 p.

Ham, W. E.; and Merritt, C. A., 1944, Barite in Oklahoma: Oklahoma Geological Survey Circular 23, 42 p.

Parkhurst, D. L.; Christenson, S. C.; and Schlottmann, J. L., 1994, Ground-water-quality assessment of the Central Oklahoma Aquifer, Oklahoma—analysis of available water-quality data through 1987: U.S. Geological Survey Water-Supply Paper 2357, Chapter B, p. B1–B74.

(Thanks to George B. Morgan for microprobe analyses and Cliff and Rebecca Ambers for references on soils and water quality.)

The Role of OGS in Solving Stratotype Problems in Oklahoma

LEROY A. HEMISH, Oklahoma Geological Survey, Norman, OK 73019

The designation of a stratotype (type section) is an essential requirement for the definition of most formal geologic units. One of the main problems with Oklahoma's stratigraphic nomenclature is that the literature abounds with names for long- and well-established geologic units for which a type section never was specified. In many instances, a type locality was indicated, but lithologic descriptions are poor. In other instances, units can't be located in the field, or the existing type section is unrepresentative of the unit.

Other problems are that nomenclators frequently violate the North American Stratigraphic Code in naming new units. Lithostratigraphic units are occasionally defined incorrectly in a chronostratigraphic sense. New names may be proposed unnecessarily. At times, names of old, established units are changed without adequate justification.

The Code encourages the establishment of supplementary reference sections for defined units, but little work has been done in this area.

The role of the Oklahoma Geological Survey (OGS) is to commence to establish neostratotypes (principal reference sections) for those well-established stratigraphic units for which a type section never was specified, or has been destroyed, covered, or otherwise made inaccessible. Supplementary reference sections can be designated to illustrate the diversity or heterogeneity of a defined unit. Through core-drilling, the OGS can demonstrate the equivalence of named surface units with subsurface units, and can establish reference wells in type areas of named stratigraphic units. The OGS can also prevent the development of nomenclature problems by ensuring compliance with the Code through the careful review of reports by non-OGS geologists prior to publication, and by working with authors on pending stratigraphic papers.

Kinetics of Blaine Formation Gypsum Dissolution

MICHAEL A. RAINES and *TOM DEWERS*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

Solids and liquids interact through a five-process procedure: (1) transport of reactants from the bulk solution, (2) adsorption of the reactants on the surface, (3) chemical reaction at the surface, (4) desorption of the products, and (5) transport of the products to the bulk solution. The slowest step in this process is the rate limiting step. Gypsum is generally considered to be a transport controlled reaction. Its slowest step is the transfer of Ca^{2+} and SO_4^{2-} ions through a diffusive boundary layer to the bulk solution.

Two groups of factors control the transfer of ions through the boundary layer: hydrodynamics, and thermodynamic or chemical conditions. The geometry of the system (surface area of reacting gypsum, and the volume of fluid passing that surface) and the fluid velocity or flow regime (in terms of degree of turbulence) define the hydrodynamics of a system. When pressure and temperature are not changed, the bulk solution's saturation state (the concentration of Ca^{2+} ions in solution, $[Ca^{2+}]$, relative to equilibrium concentration, $[Ca^{2+}]^{eq}$, and ionic strength (a measure of electrical charges in solution) define the thermodynamics. The $[Ca^{2+}]^{eq}$ of Blaine Formation gypsum in distilled water is ≈15.09 mmolal, and increases slightly with ionic strength over the salinity range of interest.

Current experiments at the University of Oklahoma examine gypsum dissolution kinetics as a function of fluid flow rate, flow regime (laminar vs. turbulent) and saturation state of fluids flowing past gypsum using a mixed flow-rotating disc reactor. The gypsum discs are reacted with a flowing solution and $[Ca^{2+}]$ is monitored with a Ca^{2+} specific electrode until the solution reaches steady state. Flame atomic adsorption analysis confirms initial and final $[Ca^{2+}]$, which are used, along with knowledge of the flow rate through the reactor, to determine dissolution rates at steady-state.

When flow is laminar (spin rates, ω, less than 900 rpm or Reynold's Numbers, Re, less than 10800), dissolution rates increase linearly with $(\omega)^{1/2}$. However, as the system

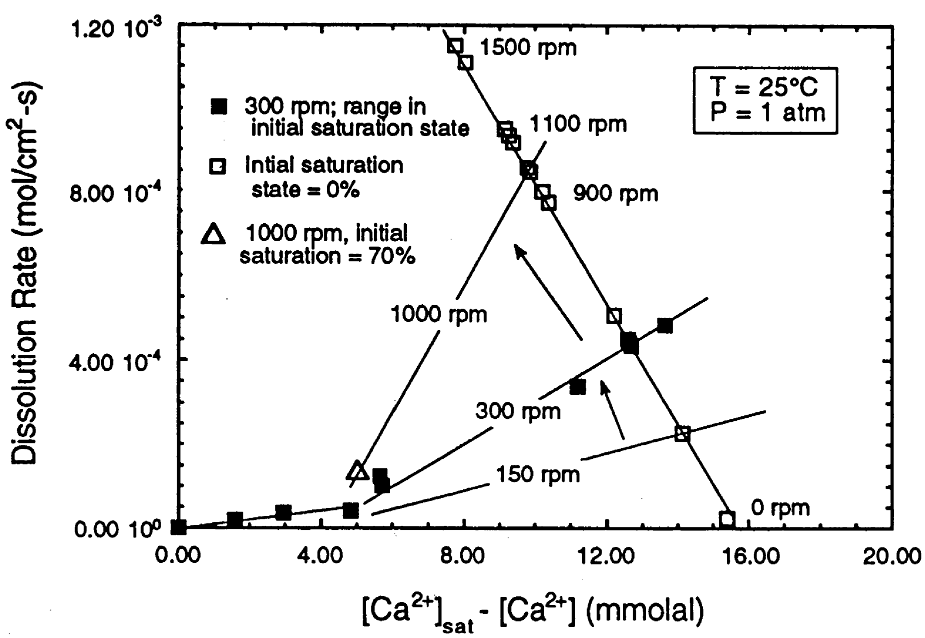


Figure 1. Gypsum dissolution rates vs. relative saturation state. Trends are shown for selected values of ω.

approaches turbulence ($\omega \geq 900$ rpm or Re ≥ 10800), dissolution rates jump above the linear trend.

A series of initial solutions which are far from equilibrium ([Ca^{2+}] less than 10 mmolal) define a linear trend of decreasing dissolution rates with increasing initial [Ca^{2+}] (Fig. 1). This is consistent with transport control. A second series of solutions which are closer to equilibrium seem to follow a different trend, and may reflect a transition from transport to surface-control as the bulk reactor fluid approaches saturation with gypsum. For example, changing ω from 300 to 1000 rpm in initial solutions of distilled water results in a dissolution rate change of $\approx 4 \times 10^{-4}$ mol/cm^2·s. The same ω change for waters with initial [Ca^{2+}] = (.7)[Ca^{2+}]^{eq} yield rate changes of only $\approx 0.25 \times 10^{-4}$ mol/cm^2·s. Runs for $\omega = 300$ rpm suggest that this decrease in transport control with increasing [Ca^{2+}] may be a linear function of solution saturation.

Future experiments will be directed to assess this transition from surface to transport control, effects due to changes in ionic strength, and comparing laboratory-delineated rates with those determined *in situ* in a Blaine Formation karst aquifer.

Geological Archive of Peat Deposits from the Postglacial Lake Erie Basin Lakes, Ohio, U.S.A.

XINYU LI and *R. P. PHILP*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

Three types of wetlands from the Lake Erie Basin were selected to investigate the ecological and climatic evolution of the area by an interdisciplinary study involving geology, palynology, organic geochemistry and diatom analysis of the sediment core samples. One of the wetlands discussed in detail, Springville Marsh, is 64 km south of Lake Erie. The vegetation of Springville Marsh is typically associated with swamps, marshes, fens, and bogs. Springs that carry Ca, Fe, and S support the fen community, which is characterized by obligate calciphile plants, with the pH of the water in the marsh ranging from 6.5 to 8.5. Geological mapping indicates that Springville Marsh may have begun in an estuary of Glacial Lake Maumee I. As the lake receded around 14,000 B.P., the river entrenched into calcareous estuarine sands and was then abandoned. Carbon-14 dating and pollen analysis of a 250-cm core show that by 12,850 B.P., highly calcareous organic muck was deposited in an open-water marsh that may have been surrounded by a spruce forest. The overlying peat was deposited in an environment that had become an inland fen which supported tree species that still grow locally in the modern wetland. Diatom analysis indicates alkaline conditions throughout the history of the wetland. High-Performance-Liquid-Chromatography analyses of pigments and gas chromatography (GC) and GC-mass spectrometry analyses of hydrocarbons, alcohols, and fatty acids in the organic sediments suggest continuous source input from higher plants and algae.

Paleoecological analysis of the 250-cm core shows that aquatic species, particularly diatoms, were more abundant in the lower (100–200 cm) part of the core. The distribution of algal carotenoids suggests the same trend. Geochemical parameters reflect a relatively higher input of algal materials compared to higher plants in the lower part of the core. Therefore, the wetland has probably evolved from an open area with higher water level to a closed terrestrial system. Pollen diagrams suggest that the climate of the area was colder at the earlier stage and has experienced a warming trend as in the other areas of Ohio.

Geological and Geochemical Studies of Hot-Spot Related Oceanic Basaltic-Trachytic Series Rocks from Ascension Island, South Atlantic Ocean

ADITYA M. KAR and *BARRY L. WEAVER*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

Hot-spot related volcanism, especially that located in the interior of oceanic plates, is one of the best means to study the composition of the mantle of the earth. These volcanic rocks, called ocean island basalts (OIB), are derived directly from the mantle and are uncontaminated during their ascent from the mantle through the thin oceanic lithosphere to the surface of the earth. Zindler and Hart (1986), Hart (1988), and Weaver (1991a,b) have reported three distinct OIB sources (HIMU, EMI, and EMII) that exist in the sub-oceanic mantle. Sr-Nd-Pb isotope systematics of Ascension volcanic rocks indicate that the magmas were derived from a mantle source which might be a mixture of N-MORB-HIMU components with a EM-type component.

Ascension Island, situated at 7°56′S and 14°22′W in the South Atlantic Ocean, is a hot-spot related volcanic island. It is located about 80 km west of the Mid Atlantic Ridge on oceanic crust which is 5–6 million years old. The island rises about 4000 m from the bottom of the ocean floor and a little less than 860 m of the island is exposed above sea level. The aerial extent of the island is 98 sq km. Ascension is a composite volcano with close to 50 scoria cones scattered over the island. The island comprises alkali basaltic-trachytic series lava flows, trachytic flow domes, scoria cones, and pyroclastic deposits. Pyroclastic (pumice and scoria) deposits cover about 43% of the surface area of the island. In our present work we geochemically characterized the voluminous scoria, pumice, and airfall deposits, and defined their spatial relations to the lava flows and the trachytic domes. Trachyte is common in the central to eastern parts of the island, and is genetically linked to the pumice. The trachytes mostly form flow domes, with some having explosive centers. Other than the pyroclastic deposits and the trachytes, most of the island is covered by lava flows. The flows, wherever traceable, are found to emanate from a scoria cone. Some of the smaller scoria cones are associated with tongue-shaped flows of small spatial dimensions. After preliminary geochemical studies it was found that these flows range in chemical composition from alkali basalt through hawaiite and mugearite to benmoreite. Alkali basalt flows are more common than any other variety of flows. Hawaiite flows are also common. Some of the youngest geological features of the island are hawaiite flows (1,000 years old). A benmoreite flow at the furthest eastern part (South East Head) of the island is also one of the youngest features on Ascension.

A plot of (Na_2O+K_2O) vs. SiO_2 shows that Ascension rocks are alkaline and show a continuous fractionation series starting from alkali basalt, through hawaiite, mugearite and benmoreite, to the highly fractionated products of trachyte and rhyolite. The abundances of SiO_2, Al_2O_3, Na_2O, and K_2O increase while abundances of MgO, CaO, P_2O_5, TiO_2, and Fe_2O_3 decrease in the more fractionated rocks compared to the basalts. Fractionation of olivine, clinopyroxene, plagioclase, titanomagnetite, and apatite can account for the decrease of these oxides in the more evolved rocks.

A group of incompatible trace elements which include Nb, Zr, and Ta are termed the HFSEs (High Field Strength Elements). Zr/Nb for OIBs are extremely useful in interpreting partial melting and fractional crystallization processes of mantle derived magmas. Data gathered show that a wide variation in Zr/Nb exists for the Ascension rocks. The mafic samples analyzed fall within a Zr/Nb range of 4–6. There are three distinct suites of basalt and hawaiite flows and scoria: (1) in the SW part of the island the volcanic rocks have Zr/Nb of 4.1, (2) in the southern and the SE of the island the Zr/Nb ratio varies between 5.6 and 6.1, and (3) for the rest of the island Zr/Nb is 4.7–5.4. The more differentiated Ascension rocks have a range of Zr/Nb between 5 and 8. High degrees of fractional crystallization or partial melting cannot strongly fractionate ratios of incompatible trace elements. The variation in Zr/Nb observed for the mafic Ascension rocks could be generated by titanomagnetite fractionation, by very low degrees of partial melting of the mantle source in the generation of the basic magmas, by magmas being tapped from different sources with variable Zr/Nb, or a combination of these processes. The REE data show variable degrees of LREE enrichment with respect to the heavy rare earth elements (HREEs). The alkali basalts and scoria show strongly enriched LREE abundances compared to low concentrations of HREEs. Continuous crystal fractionation involving olivine, plagioclase, clinopyroxene and magnetite increases the total REE content of more evolved magmas but does not produce any inter-element fractionation. The characteristic shape of the less differentiated basaltic REE pattern is maintained in the more evolved rocks while the absolute abundances increase. Substantial plagioclase fractionation lead to the development of a negative Eu anomaly.

References Cited

Hart, S. R., 1988, Heterogenous mantle domains: signatures, genesis and mixing chronologies: Earth and Planetary Science Letters, v. 90, p. 27–296.

Weaver, B. L., 1991a, Trace element evidence for the origin of ocean island basalts: Geology, v. 19, p. 123–126.

_______ 1991b, The origin of ocean island basalt end-member compositions: trace element and isotopic constraints: Earth and Planetary Science Letters, v. 104, p. 381–397.

Zindler, A.; and Hart, S. R., 1986, Chemical geodynamics: Annual Reviews of Earth and Planetary Science, v. 14, p. 493–571.

Antioch Earthquake *(continued from page 42)*

TABLE 1. — OKLAHOMA EARTHQUAKES WITH MAGNITUDES ≥4.0

Event no.	Date	Origin time (UTC)[a]	County	Nearest town	Intensity MM[b]	Magnitudes 3Hz	Magnitudes bLg	Magnitudes DUR	Lat. °N	Long. °W
23	1952 Apr 09	1629 15	Canadian	El Reno	7		5.0[c]		35.4	97.8
20	1939 Jun 01	0730	Hughes	Spalding	4		4.4		35.0	96.4
12	1926 Jun 20	1420	Sequoyah	W Marble City	5		4.3		35.6	94.9
52	1959 Jun 17	1027 07	Comanche	NE Faxon	~6		4.2		34.5	98.5
—	1995 Jan 18	1551 39.90	Garvin	Antioch	6	4.1	4.2		34.676	97.413
50	1956 Oct 30	1036 21	Rogers	Catoosa	7		4.1		36.2	95.8
59	1961 Apr 27	0730	Latimer	Wilburton	5		4.1		34.9	95.3
13	1929 Dec 28	0030	Canadian	El Reno	6		4.0		35.5	98.0
51	1959 Jun 15	1245	Pontotoc	Ada	5		4.0		34.8	96.7
838	1990 Nov 15	1144 41.63	Garvin	Lindsay	6	4.0	3.9	3.0	34.761	97.550

[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, p. 60, this issue).

[c]The El Reno earthquake had a Gutenberg-Richter magnitude (mb) of 5.5.

The Antioch earthquake was the strongest Oklahoma earthquake in nearly 36 years (Table 1). The largest known Oklahoma earthquake happened near El Reno, Canadian County, on April 9, 1952. This magnitude 5.5 (mb, Gutenberg-Richter) earthquake was felt in Austin, Texas, as well as Des Moines, Iowa, and covered a felt area of ~362,000 km^2.

Those who felt the Antioch earthquake are encouraged to write James Lawson at P.O. Box 8, Leonard, OK 74043. He would like to know what they felt, heard, and saw during the event. These reports help scientists to determine the size and intensity of the earthquake.

Kenneth V. Luza