OKLAHOMA GEOLOGY

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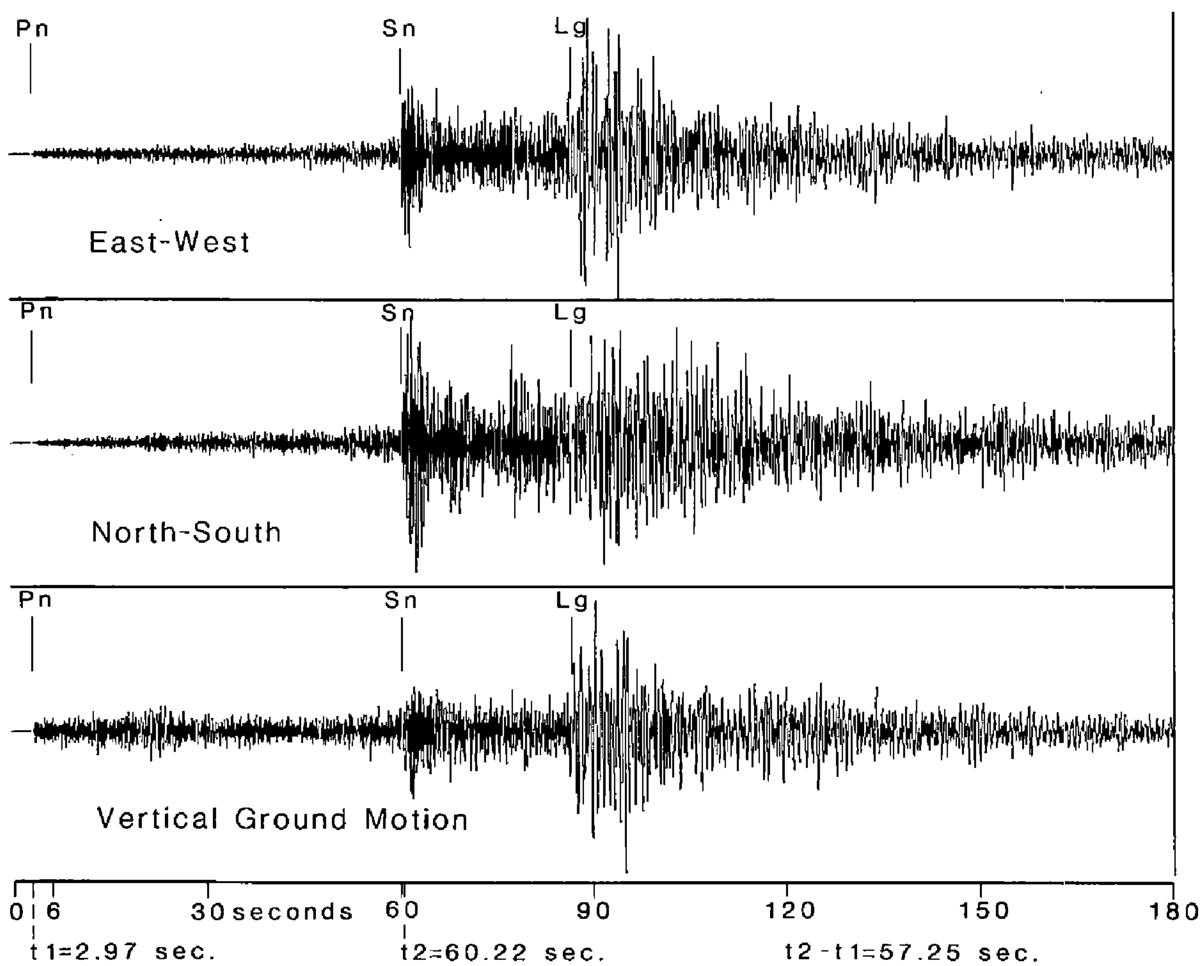

On the cover—

New Madrid Region Earthquake Recorded by the OGS Digital Seismic System

An earthquake in the New Madrid region on September 26, 1990, caused slight damage in Cape Girardeau, Missouri, and southern Illinois. It was felt in southern Missouri, southern Illinois, western Kentucky, and in parts of Tennessee, Arkansas, Indiana, and at Cincinatti, Ohio. The actual epicenter was 50 km (31 mi) north of the nearest segment of the New Madrid fault.

The seismograms on the cover show (from the top down) east-west, north-south, and vertical ground motion recorded by the Oklahoma Geological Survey (OGS) at its geophysical observatory near Leonard, in southeast Tulsa County. The recordings were made by a digital seismic system manufactured by Teledyne-Geotech for the Defense Advanced Research Projects Agency/Nuclear Monitoring Research Office. The OGS at Leonard is the Beta (development) site for this seismic system. The system will be used in part to compare data with those obtained by Soviet scientists from nuclear detonations at the Nevada test site.

In the Threshold Test Ban Treaty, signed by Presidents Bush and Gorbachev on June 1, 1990, the OGS Leonard site was named a designated seismic station for the Soviet Union's verification of the explosive yield of American underground nuclear tests in Nevada. The Soviet Union's seismic compound, ~50 m (~55 yd) from the OGS underground seismometer vault, will have instruments to record seismic waves generated by nuclear blasts in Nevada. The Threshold Test Ban Treaty limits the size of underground nuclear-weapon tests to 150 kilotons or less.

The seismograms on the cover were produced from digital data files which continuously record 24-bit samples, 40

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OKLAHOMA GEOLOGY NOTES

CONTENTS

EFFECT OF FUTURE NEW MADRID REGION EARTHQUAKES ON OKLAHOMA

James E. Lawson, Jr.[1]

Abstract

The New Madrid seismic zone was the location of three destructive earthquakes in 1811 and 1812, and probably the site of other large earthquakes in the past 2,300 years. Because Oklahoma's east and west borders are 450 and 1,200 km (280 and 750 mi) from New Madrid, a recent scientifically unsound prediction for another large New Madrid earthquake caused much interest and concern in the State. This paper is an attempt to quantify risk to Oklahoma from future New Madrid earthquakes.

New Madrid earthquakes of four different magnitudes (expressed as mb) and their effects (expressed as Modified Mercalli intensities) on Oklahoma are defined:

1) Expected earthquake: magnitude (mb) 6.0. Intensity IV to V in Oklahoma.
2) Likely earthquake: magnitude (mb) 6.6. Intensity V to VI in most of Oklahoma.
3) Possible earthquake: magnitude (mb) 7.0. Intensity VI to VII in Oklahoma.
4) Worst-case earthquake: magnitude (mb) 7.4. Intensity VII to VIII in Oklahoma.

Intensities of IV to VIII have been experienced during this century in various parts of Oklahoma from earthquakes within the State. Preparations for New Madrid and Oklahoma earthquakes should center on ways to minimize injuries the instant an earthquake is felt. An example of these preparations is the "drop" drill practiced in schools. Even in a worst-case earthquake located at New Madrid, extended disruptions of utilities or emergency services are not likely to occur.

Introduction

The New Madrid seismic zone is of particular interest to Oklahomans, because of its relatively high seismic activity and its proximity to Oklahoma. Interest in the effects of large New Madrid earthquakes on Oklahoma increased in November 1990, because of a scientifically unsound, but widely publicized, prediction for a damaging New Madrid earthquake during the first 5 days of December 1990.

Location of the New Madrid Seismic Zone and Its Proximity to Oklahoma

Figure 1 shows earthquakes in the New Madrid region recorded by St. Louis University during a 4-year period. The earthquakes seem to define a three-segment fault in Missouri, Arkansas, and Tennessee, with the northern segment (between seismograph stations LST and DWM) less noticeable than the other two. The three segments of the New Madrid fault zone have not been mapped directly, because they are covered by 1 km (3,300 ft) or more of unfaulted sedimentary rock and river-deposited alluvium.

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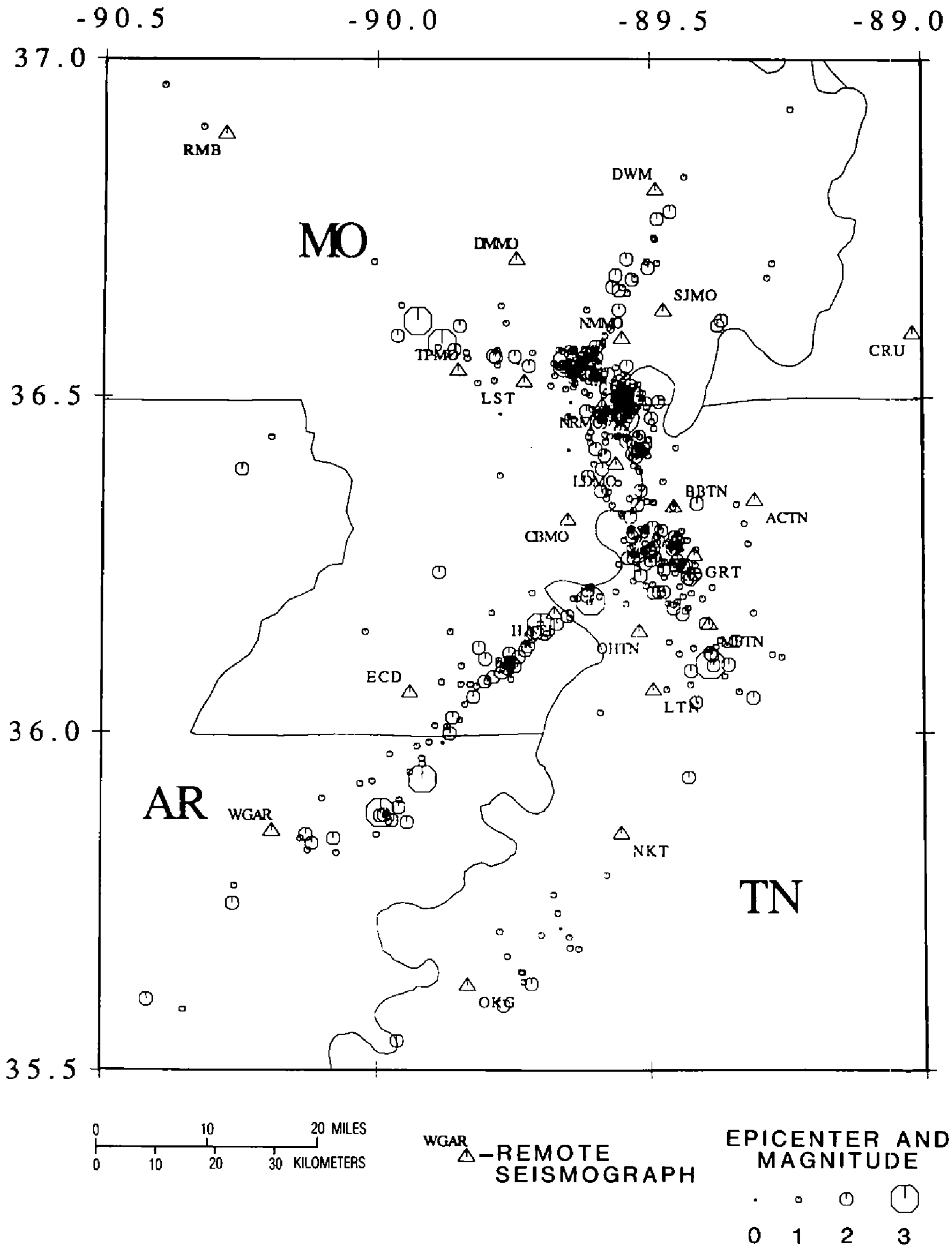

Figure 1. Earthquakes in the New Madrid region located by St. Louis University from July 1, 1982, to June 30, 1986. (From Central Mississippi Valley Earthquake Bulletin, no. 63.)

Distances from the New Madrid earthquake zone to Oklahoma are measured from the town of New Madrid, which is near the center of the three faults, and very near the most intensive seismicity. The northeast corner of Oklahoma is 453 km (281 mi) and the western boundary of the Oklahoma Panhandle is 1,200 km (746 mi) from New Madrid. Tulsa is 588 km (365 mi) and Oklahoma City is 735 km (457 mi) from New Madrid.

Past Seismicity in the New Madrid Seismic Zone

In 1811 and 1812 three large earthquakes occurred in the New Madrid region. The estimated magnitudes on the mb scale (body wave magnitude scale) by Nuttli (1973) were 7.2 (December 16, 1811), 7.1 (January 23, 1812), and 7.4 (February 7, 1812). Mr. Jared Brooks of Louisville, Kentucky, cataloged 1,874 earthquakes which he felt between December 16, 1811, and May 5, 1812 (Fuller, 1912). Otto Nuttli (1973) considers 547 of these to be aftershocks of the December 16 earthquake, 163 aftershocks of the January 23 earthquake, and 1,161 aftershocks of the February 7 earthquake. Nuttli (1973) estimates that 25 of the aftershocks had mb magnitudes from 6.3 to 6.7. Some sources, such as Hamilton and Johnston (1990), list an additional earthquake of mb 7.0 on December 16, 1811. Between 1843 and 1895 Hamilton and Johnston (1990) list three other New Madrid area earthquakes which were larger than the April 9, 1952, El Reno, Oklahoma, earthquake of magnitude mb 5.5, and they list a 1968 New Madrid area earthquake as large as the El Reno earthquake. The same authors list 24 "damaging" earthquakes in the New Madrid region between 1838 and 1987, with magnitudes of mb 4.2 to 5.4.

The three large New Madrid earthquakes, plus the 1,871 other events felt by Brooks, plus many more which probably occurred but were not cataloged by Brooks, may be considered one major "slip event," which relieved most of the accumulated strain along the three fault segments. Russ (1979), who examined near-surface sediments in the New Madrid region by trenching, believes that two similar slip events occurred within the last 2,250 years. These previous events may have had one or several principal earthquakes. This suggests that the recurrence time for such major slip events may be as large as 750 years (2,250 ÷ 3).

Struder and others (1990) summarize 16 years of monitoring by St. Louis University's Central Mississippi Valley Seismic Network. In a rectangular area centered on New Madrid (556 km [345 mi] along a north-south line, and 357 km [222 mi] along an east-west line), the network detected 2,047 earthquakes of magnitude mbLg (considered to be equivalent to mb) ≥1.5, or an average of one each 2.85 days.

New Madrid Earthquake "Prediction" for December 1990

Iban Browning (Davis and others, 1990) predicted that there was a 50% probability that a magnitude (scale unspecified) 6.5 to 7.5 earthquake would occur in the New Madrid area within ± 2 days of December 3, 1990. I can find no published statement of Browning's prediction, and newspaper articles give conflicting statements. Therefore, I relied on the "Evaluation of the December 2–3, 1990, New Madrid Seismic Zone Prediction" (Davis and others, 1990) to determine what Browning's prediction actually stated. There has been discussion in the media as to whether Browning's statement(s) were prediction(s), forecast(s), or projection(s). I will follow the terminology of Davis and others (1990) by using only the term "prediction." This prediction was given much publicity because Browning (or others) apparently claimed he had successfully predicted other earthquakes in the past, and because Browning apparently stated that the earth-tidal potential (a real physical effect) would trigger the earthquake.

Earth-tidal potential is the normal gravitational attraction of the moon and sun upon the Earth. This attraction stresses the solid earth sufficiently to cause its surface to rise and fall, changing the distance from the Earth's center to its surface by as much as 360 mm (14.2 in.) (Melchior, 1966). The primary tidal cycle is repeated nearly twice per day (12 hr 20 min per cycle). The magnitude of the rise and fall from the 12 hr 20 min cycle increases to a maximum and decreases to a minimum twice a month. The twice-daily cycle is caused by the Earth's rotation with respect to the sun and moon, and the twice-monthly cycle is caused by the revolution of the moon about the Earth. Variations in the Earth-moon and Earth-sun distances, and other changes in the relative position of the Earth-moon-sun, cause many other variations with periods of months, years, or decades that are superimposed on the twice-daily tides.

The Davis and others (1990) evaluation found that Browning's predictions of other earthquakes in the past were no better "than . . . random guessing." They specifically "[rejected] the claim that [Browning] predicted the Loma Prieta (Santa Cruz–San Francisco) October 17, 1989, earthquake."

Davis and others (1990) state that there is no theoretical or empirical basis for tidal potential triggering earthquakes. They determined that the peak tidal right-lateral shear strain on a vertically dipping plane striking N. 45° E. at New Madrid on December 3, 1990, would be 1.186×10^{-8}, or 30 millibars of stress. Greater stresses may be produced in the New Madrid area by the change in air pressure from the passage of a weather front or a change in water level in the Mississippi River. Also, the tidal shear strain reached 1.177×10^{-8} in January 1988, and frequently reached 1.10×10^{-8} between January 1988 and December 1990. No damaging New Madrid earthquakes were caused by these previous tidal peaks (B. J. Mitchell and A. C. Johnston, personal communication, 1990).

Mitchell and Johnston (personal communication, 1990) note that one of the three 1811–12 New Madrid earthquakes occurred at the time of a tidal maximum, but that it was no higher than the typical maximum occurring every 2 weeks. The other two 1811–12 earthquakes occurred closer to tidal minima. They also noted that the two largest New Madrid earthquakes since 1812 (mb 6.0 on January 4, 1843, and mb 6.2 on October 31, 1895) occurred closer to tidal minima than to maxima.

There is no clear evidence for tidal triggering of earthquakes, and large past earthquakes in the New Madrid area have not correlated with higher-than-usual tidal maxima, or even typical maxima which occur every 2 weeks. In addition, the tidal maxima of December 3, 1990, did not trigger any detectable earthquakes. St. Louis University's network of 17 remote seismographs can reliably detect and locate earthquakes of magnitude 1.5 (mbLg) or larger, but no earthquakes were detected during the period between November 30 and December 7 (Bob Hermann, personal communication). As these small earthquakes occur about every 3 days on the average, their absence during the prediction period suggests that earth-tidal potential is not a significant earthquake triggering process.

In a *San Francisco Chronicle* interview (Carroll, 1990), Browning suggested that if a destructive earthquake was not triggered on December 3, 1990, it might be triggered by a higher tidal potential on January 18, 1992. Any future Browning earthquake prediction, for January 1992, or any other time, should be evaluated with due consideration to the lack of any theoretical or empirical basis for tidal triggering of earthquakes. The lack of any detectable New Madrid earthquake during the first week of December 1990 also should be considered in assessing such a future prediction.

Probability of Future Destructive New Madrid Earthquakes

In 1985, Arch Johnston and Susan Nava reviewed past studies of New Madrid seismicity (Johnston and Nava, 1985). Using both historical and instrumental data, they estimated recurrence intervals for earthquakes of various magnitudes. They applied a variety of statistical methods to the recurrence intervals to determine a range of probabilities for occurrence of earthquakes of different magnitudes by 2035 A.D. Table 1 consists of data taken directly from their table 7.

I consider their estimates to be the best available, and doubt that there will be improved estimates any earlier than 2000 A.D. when 10 more years monitoring of instrumental seismicity will be available. Even at that time, large changes in the probabilities are unlikely.

From the numbers in Table 1, a magnitude 6.0 New Madrid earthquake seems almost a certainty by 2035. This should be considered the "expected earthquake," and Oklahomans should be prepared for its consequences. Magnitude 6.6 should be considered the "likely earthquake." Oklahoma should take adequate steps to be prepared so that the likely earthquake would cause no serious structural damage and would cause few if any injuries. Even though a magnitude 7.0 earthquake seems to have no more than a 4% probability of occurrence by 2035, it should be considered the "possible earthquake." Preparation for the possible earthquake should ensure that no serious damage occur to any building. Finally, a "worst-case earthquake" the size of the largest 1811–12 New Madrid earthquake of magnitude 7.4 should be considered. Preparations should ensure that no building with a

TABLE 1. — REPEAT TIMES AND PROBABILITY OF OCCURRENCE OF MAGNITUDE (mb) 6.0, 6.6, AND 7.0 EARTHQUAKES IN THE NEW MADRID REGION*

Magnitude (mb)	Average repeat time (years)	Probability by 2035 A.D. (%)
≥6.0	70 (±15)	86–97
≥6.6	254 (±60)	19–29
≥7.0	550 (±125)	2.7–4.0

*Taken directly from Johnston and Nava (1985, table 7).

number of occupants (schools, office buildings) should experience major damage, no lifeline services (roads, electricity, oil and natural gas pipelines, emergency services) should be disrupted, and no critical structures such as dams or nuclear power plants (if any are built in Oklahoma) should be damaged significantly by the worst-case earthquake.

Modified Mercalli Intensity in Oklahoma from the Expected, Likely, Possible, and Worst-Case New Madrid Earthquakes

The Modified Mercalli (MM) intensity scale, as revised by Brazee (1978), is a list of earthquake felt effects for 12 intensity levels. Intensity refers to the felt effects of an earthquake at a particular location. In general, intensity decreases with distance from the earthquake epicenter. Brazee's lists are more detailed than the original Wood and Neumann (1931) MM scale, and they are included in the Appendix because they give a very accurate and precise description of actual effects.

Otto Nuttli (1973) published an isoseismal (intensity) map for a large New Madrid earthquake, the December 16, 1811, mb 7.2 earthquake. Because of a lack of reports by observers, his isoseismal lines, which extend to the East Coast, are not drawn farther west than central Arkansas. Other maps, such as that in Hamilton and Johnston (1990), use the 1843 and 1895 New Madrid region earthquake-intensity data to construct hypothetical intensity maps for the 1811–12 earthquake series. The maps of Hopper and others (1983) for the 1843 and 1895 earthquakes show intensity falling off much more rapidly west of New Madrid than east of New Madrid. However, both maps include only one observation between Little Rock, Arkansas, and the Oklahoma border, and no observations in Oklahoma. Data do not exist to indicate clearly that intensities in Oklahoma would be six units less than epicentral intensity, as shown on the maps by Hopper and others (1983).

For this article, a mathematical formula is used to determine intensity as a function of magnitude and distance (Nuttli and Hermann, 1978):

$$I = -0.4 + 2mb - 2.46 \log(R)$$

where I = MM intensity,
mb = body-wave magnitude,
R = distance from epicenter in kilometers with $R \geq 20$ km.

From this, specific isoseismal maps of Oklahoma from different New Madrid earthquakes may be drawn.

The use of this formula can be tested on some recent New Madrid earthquakes. The March 25, 1976, earthquake of mb 4.9 would be calculated as intensity III in Tulsa and Oklahoma City. Intensity II was reported for Tulsa by Coffman and Stover (1978). The November 9, 1968, mb 5.3 earthquake was reported as causing intensity "I–IV" effects in Durant, Oklahoma City, Tulsa, and elsewhere in Oklahoma (Coffman and Cloud, 1970). The formula would predict intensity III as far west as Oklahoma City. Thus, based on these two observations, the Nuttli and Hermann (1978) formula seems to give values as high as one intensity greater than observed.

In this article it is assumed that the intensity given by the formula could be experienced at some locations in an area, but that much of the area will experience intensities one unit lower than given by the formula. If an intensity is V according to the formula, an intensity range of IV–V will be listed; if it is VI by the formula, V–

VI will be listed, etc. The upper intensity (e.g., VII, if VI–VII is listed) is liable to be the maximum experienced at any location. The lowest intensity experienced at any location in an area may be a full unit below the lower number.

Expected Earthquake, mb = 6.0

The expected earthquake would produce effects of intensity IV–V from northeast Oklahoma to the eastern part of the Panhandle. Few or no injuries would be expected, and no damage should occur. No preparations at all should be necessary for the expected earthquake. On September 16, 1990, an earthquake very near Haileyville, Oklahoma, produced MM V effects in Haileyville and Hartshorne. In 26 letters received from persons who felt this earthquake, the only physical effect noted was a vial of straight pins tipping over.

Likely Earthquake, mb = 6.6

Areas east of Muskogee and north of Poteau might experience effects of intensity VI–VII. Some injuries might be caused from falling bricks, particularly if persons ran from buildings when the shaking occurred. Some structural damage would be expected. The rest of Oklahoma might experience intensities as high as MM V–VI. Very slight damage and a few minor injuries may occur. Oklahoma experienced intensities of MM VI in Garvin County on November 15, 1990, and in Kingfisher County on December 8, 1987, from earthquakes in those counties. In Kingfisher County, Christmas trees fell over, knickknacks fell off shelves, and large furniture was disturbed but did not fall. In Garvin County, at least six persons fell out of bed or were knocked out of bed. Knickknacks fell, and pictures were tilted or knocked off walls. One bookcase fell, and merchandise on store shelves fell into aisles. Some cracked plaster was reported.

Possible Earthquake, mb = 7.0

Intensities might reach VI–VII in all of Oklahoma except the western two-thirds of the Panhandle, where intensity V–VI could occur. This would be similar to the intensity in the epicentral region of the April 9, 1952, El Reno, Oklahoma, earthquake of mb 5.5. Damage and several minor injuries could be expected. Preparation should center on what to do immediately when shaking is felt, such as not to run into or from a building, but to stand in an inner doorway or under heavy furniture. Schools should consider the "drop" drill in which students immediately get under their desks when the teacher instructs them to do so. Evacuating a classroom before the shaking ceases would increase the chances of students being hit by falling light fixtures or plaster.

Worst-Case Earthquake, mb = 7.4

Intensities could reach MM VII–VIII in Oklahoma as far west as Lawton and Woodward, and MM VI–VII farther west. Considerable damage, as described in the Appendix, may occur. Oklahoma has probably experienced intensity MM VIII at a few locations from the April 9, 1952, El Reno earthquake (Lawson, unpublished data) and at Ft. Gibson on October 22, 1882 (*Cherokee Advocate,* 1882).

Intensity VIII should be considered a possibility, in spite of the rarity of earthquakes causing this intensity with epicenters near New Madrid or in Oklahoma. Preparations should emphasize protection from falling objects at the time of the earthquake. Utility services are not likely to be severely disrupted for any extended period, and emergency services are not likely to be interrupted.

Conclusion

With respect to the New Madrid seismic zone, Oklahoma should be prepared for an "expected earthquake" (mb = 6.0, MM IV–V), and a "likely earthquake" (mb = 6.6, MM V–VI), and at least some planning should be made for a "possible earthquake" (mb = 7.0, MM VI–VII) and a "worst-case earthquake" (mb = 7.4, MM VII–VIII). Those same intensities also could be produced by earthquakes that might occur inside Oklahoma, but the Oklahoma earthquakes would have smaller felt areas.

Acknowledgments

Charles Mankin, Ken Johnson, and Ken Luza reviewed this manuscript and made helpful comments. Appreciation is also expressed to Shirley Jackson, Rick Watkins, Dan Moss, and Ruth King who 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. Some of our knowledge of Oklahoma seismicity is due to equipment, facilities, or grants from the Sarkeys Foundation, the Nuclear Regulatory Commission, U.S. Army Corps of Engineers, Defense Advanced Research Projects Agency/Nuclear Monitoring Research Office, and Lawrence Livermore National Laboratories/U.S. Department of Energy.

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APPENDIX: Revised Modified Mercalli Intensity Scale (according to Brazee, 1978)

IV.
a. Objects were disturbed.
b. Frightened few; caused slight excitement.
c. Motion was described as abrupt, sharp, jolting, or rapid.
d. Hanging objects swung (no qualifying adjective used by observer).
e. Felt by many. Felt by all in home or all in building.
f. Felt outdoors by few or some.
g. Dizziness or nausea was experienced by some.
h. Dishes, windows, and doors rattled. Dishes and glasses knocked together on shelves. Walls creaked.
i. Liquids in open vessels were disturbed.
j. Awakened many or most. Awakened all in home.
k. Noises like gusts of wind were reported.
l. Described as moderate.
m. Trees and bushes were shaken slightly.
n. Direction of motion was noted indoors, or without specification of location (indoors or outdoors).
o. Pendulum clock stopped, started, or changed rates markedly.

V.
a. Rumbling, thunderous, or subterranean sounds were reported.
b. Hanging objects swung in numerous instances. Hanging objects or doors swung generally or considerably.
c. Described as strong.
d. Trees and bushes were shaken moderately.
e. Small objects were shifted from position; light furnishings were shifted from position.

f. Pictures were knocked against the wall or swung out of position.
g. Felt by practically all. Felt by most or almost everyone.
h. Sensation similar to that of a truck striking the building was reported.
i. Animals were frightened, stampeded, or broke out of their enclosures.
j. Disturbances of poles and other tall objects were noted in some instances. Buildings swayed.
k. Vibrations similar to those caused by the passing of a light truck were reported.
l. Plaster was cracked.

VI. a. Liquids were spilled from containers.
b. Roaring sounds were reported.
c. Direction of motion was estimated by observers who were outdoors.
d. Liquids were set in strong motion.
e. Slight damage was incurred. Poor construction was sometimes specified.
f. Small bells rang (church, chapel, school, etc.). Fire and burglar alarms were activated.
g. Buildings trembled throughout.
h. Many ran outdoors.
i. Felt by all (without qualification). Felt by all in community.
j. Many were frightened. Excitement was general with some alarm.
k. Small, unstable objects were overturned.
l. Knickknacks fell.
m. Some furniture of moderately heavy kind (chairs, tables, small sofas, small dressers, etc.) were moved from position.
n. Objects were thrown from shelves and mantles. Merchandise was thrown from shelves in stores.
o. Water or gas pipes were broken in isolated instances.
p. Trees and bushes were shaken strongly.
q. All were awakened.
r. Plaster fell in small-to-moderate amounts. Chimneys were cracked.
s. Some dishes, glassware, and windows were broken.

VII. a. Free-standing and exterior masonry walls were cracked.
b. All were frightened. There was general alarm.
c. Permanent or temporary changes in flow from springs and wells were reported; changes in temperature of water from these sources were noted.
d. Well-built ordinary structures were damaged slightly to moderately.
e. Cornices, brickwork, tiles, and stones fell from exterior walls and parapets of buildings.
f. Several landslides were reported. Small quantities or rocks and boulders were shaken from hillsides and embankments in single instances.
g. Chimneys were broken. Chimneys, with ratio of height above roof to lateral dimension at roof exceeding 5, were broken sharply at roofline.

VIII. a. Free-standing walls and exterior masonry walls of buildings fell.
b. Ordinary, substantial buildings were damaged considerably.
c. Furniture was broken in some instances.
d. Furniture was overturned. This includes that described as "heavy" as well as reports without qualifying adjectives.
e. Waves were seen on surface of ground.
f. Telephones were put out of service.
g. Chimneys, monuments, factory stacks, etc., fell. Monuments were rotated on their bases.

h. Doors and shutters were opened and closed abruptly (cabinet and cupboard doors included).
i. Poorly built or badly designed structures were damaged greatly. Panel walls were thrown out of frame structures. Poorly built or badly designed structures sustained considerable damage.
j. Railroad rails were bent slightly, moderately.
k. Numerous windows were broken.
l. Everybody ran outdoors.
m. Free-standing solid stone walls were seriously cracked and broken.

New Madrid Region Earthquake—*continued from p. 2*

times per second, from each of the three short-period seismometers. Ten samples per second are recorded from each of the three broadband seismometers (the broadband seismograms are not shown).

The first seismic wave from the earthquake arrived at Leonard ~76 seconds after the earthquake, whose epicenter was 578 km (359 mi) away. This wave, labeled Pn, is particularly prominent on the vertical component. It is a longitudinal wave and, except at the two ends of its path, was critically refracted along the upper mantle just below the crust at ~40 km (~25 mi) depth. The wave arriving 57.25 seconds (t2–t1 on cover) after Pn is the Sn phase, which is a transverse wave following a path similar to Pn. Sn is seen best on the two horizontal seismograms. The third phase, labeled Lg, is a surface wave guided within the 20-km-thick (12-mi-thick) upper crust. Waves continued to exceed background earth noise until ~840 seconds after the Pn arrival, which is more than four times the 180 second time window in the seismograms on the cover. This "coda" is at least partly due to backscattering and multiple scattering of S waves from inhomogeneities in the Earth's crust, within a radius of ≥100 km (≥62 mi) surrounding Leonard.

For regional earthquakes in the central U.S., the most reliable magnitude is mbLg, calculated from the amplitudes of Lg waves. The mbLg magnitude is the common logarithm of ground amplitude of vertical-component Lg-waves, measured by a seismograph, with a factor added to allow for the distance from the earthquake epicenter to the seismograph. P-wave magnitudes are similar, but use the amplitude of vertical-component P-waves. (The term "Richter scale" is limited to a logarithmic magnitude scale used with horizontal-component Lg-waves in southern California.) The ground motion for the September 26 earthquake was so large that paper seismograms from Leonard and the OGS Statewide network of 10 remote seismographs recorded mainly just the first arrival time of Pn seismic waves. These arrivals gave accurate times to use in locating the epicenter. After the first arrival, the very rapid pen motion produced illegible lines, from which amplitude measurements for calculating magnitudes could not be made. A P-wave magnitude of 4.7 for this earthquake was calculated from P waves recorded at distant sites (e.g., Canada, Alaska). Because the OGS digital system is able to record waves in a range up to 8 million times the size of the smallest wave it can record, it makes faithful recordings of very small and very large motions. When these seismograms were expanded and measured, they indicated a vertical Lg amplitude of .0078 mm (.00031 in.), from which an mbLg magnitude of 5.0 was calculated for this earthquake.

James E. Lawson, Jr.

PETROLEUM-RESERVOIR GEOLOGY WORKSHOP
Norman, Oklahoma, March 26–27, 1991

A workshop on "Petroleum-Reservoir Geology in the Southern Midcontinent," co-sponsored by the Oklahoma Geological Survey and the Bartlesville Project Office of the U.S. Department of Energy, will be held March 26–27, 1991, at the Oklahoma Center for Continuing Education (OCCE) of the University of Oklahoma in Norman.

The workshop will present current and ongoing research and studies dealing with clastic reservoirs, carbonate reservoirs, fractured reservoirs, horizontal drilling, and enhanced oil recovery. Provisional titles and speakers are listed below:

March 26

Role of Reservoir Characterization in Improved Petroleum Recovery, by James M. Forgotson, Jr., University of Oklahoma, Norman, OK

The Influence of Provenance on the Diagenetic History of Pennsylvanian and Permian Detrital Reservoirs in the Southern Oklahoma Aulacogen, by R. Nowell Donovan and T. Butaud, Texas Christian University, Fort Worth, TX

Petrology of Morrow/Springer Rocks and Effects on Reservoir Quality, by C. William Keighin and Romeo M. Flores, U.S. Geological Survey, Denver, CO

Reservoir Characterization of Upper Morrow Fan-Delta Chert Conglomerate in Cheyenne and Reydon Fields: Completely Sealed Gas-Bearing Pressure Compartments, by Zuhair Al-Shaieb, Oklahoma State University, Stillwater, OK

Depositional Variations and Reservoir Characterization in the Red Fork Sandstone, Northwest Tecumseh Field, Pottawatomie County, Oklahoma, by Fletcher Lewis, Fletcher Lewis Engineering, Oklahoma City, OK

Reservoir Characterization of the Springer Field Constrained by Geological Modeling and Reservoir Simulation, by Daniel J. Garvey, Mark C. Potts, James M. Forgotson, Jr., and Roy M. Knapp, University of Oklahoma, Norman, OK

Facies Controls on Porosity, Permeability, and Oil Production in McFarland/Magutex (Queen) Reservoirs, Permian Basin, Texas, by Mark H. Holtz, Bureau of Economic Geology, Austin, TX

Application of Horizontal Drilling in Fractured Carbonates of Oklahoma, by Richard D. Fritz, MASERA Corp., Tulsa, OK

Secondary Recovery of Oil through Mine Workings in the Keystone Field, Northeastern Oklahoma, by Maynard F. Ayler, Hydrocarbon Mining Co., Golden, CO; Tom L. Bingham, Oklahoma Geological Survey, Norman, OK; and Carl Brechtel, Agapito & Associates, Inc., Grand Junction, CO

Geology of the Woodford Shale in the Anadarko Basin—An Overview of Relevance to Horizontal Drilling, by Timothy C. Hester and James W. Schmoker, U.S. Geological Survey, Denver, CO

March 27

Depositionally and Diagenetically Controlled Distribution of Remaining Mobil Oil in a Mature Dolomite Reservoir, by R. P. Major and Mark H. Holtz, Bureau of Economic Geology, Austin, TX

Diagenesis, Continuity, and Reservoir Character of Grainstone Lenses: Lansing–Kansas City "I" "J" Zone, Pen Field, Graham County, Kansas, by Rod Phares and Anthony W. Walton, University of Kansas, Lawrence, KS

Unusual Occurrence of Oil in the Viola Limestone, Pratt Anticline, Kansas, by Harold A. Brown, Consultant Geologist, Wichita, KS; and Alan D. Banta, Trans Pacific Oil Corp., Wichita, KS

Geology and Reservoir Characteristics of the Arbuckle Group Brown Zone in the Cottonwood Creek Field, Carter County, Oklahoma, by David L. Read, Consultant Geologist, Littleton, CO; and Grant Richmond, CNG Producing Co., New Orleans, LA

The Influence of Depositional Facies and Karst Development on the Arbuckle Brown Zone Reservoir, Healdton Field, Carter County, Oklahoma, by Robert Todd Waddell, Huaibo Liu, and James M. Forgotson, Jr., University of Oklahoma, Norman, OK

Paleokarstic Features and Reservoir Characteristics of the Hunton Group in the Anadarko Basin, by Felicia D. Matthews, Oklahoma State University, Stillwater, OK

Feasibility Study of Heavy-Oil Recovery in the Midcontinent Region (Oklahoma, Kansas, and Missouri), by David K. Olsen and William I. Johnson, National Institute for Petroleum and Energy Research, Bartlesville, OK

Potential of Microbial Enhanced Oil Recovery (MEOR) in the Petroleum Reservoirs of the Midcontinent Region, by E. O. Udegbunam, R. M. Knapp, M. J. McInerney, and R. S. Tanner, University of Oklahoma, Norman, OK

Three-Dimensional Reservoir Description Using Conditional Simulation, by Mohan Kelkar, University of Tulsa, Tulsa, OK

Poster Session, March 26

The Influence of Depositional Facies and Karst Development on the Arbuckle Brown Zone Reservoir, Healdton Field, Carter County, Oklahoma, by Robert Todd Waddell, Huaibo Liu, and James M. Forgotson, Jr., University of Oklahoma, Norman, OK

Lithology and Reservoir Development of the Arbuckle Dolomite, Wilburton Field, Latimer County, Oklahoma, by P. K. Mescher and D. J. Schultz, ARCO Oil and Gas, Plano, TX; and S. J. Hendrick, M. A. Ward, and J. A. Schwarz, ARCO Oil and Gas, Midland, TX

Distribution and Orientation of Fracture Patterns in the Arbuckle Group in the Slick Hills, Southwestern Oklahoma: An Analogy for Fractured Arbuckle Reservoirs in Southern Oklahoma, by R. Nowell Donovan, M. Stephenson, and K. M. Morgan, Texas Christian University, Fort Worth, TX

Arbuckle Group: Subaerial Karst or Deep-Buried Diagenesis?, by Gary F. Lawyer and C. Kent Chamberlain, Exploration Methods, Inc., Englewood, CO

Eola Field—A Transpressional Tectonic Model Applied to Fractured Reservoir Development, by Jerry J. Kendall, Mobil Oil Exploration and Production, U.S., Oklahoma City, OK

Upper Strawn (Desmoinesian) Carbonate and Clastic Depositional Environments, Southeast King County, Texas, by Todd H. Boring, Oryx Energy Co., Oklahoma City, OK

Trends of Sandstone Porosity in the Anadarko Basin, by Timothy C. Hester and James W. Schmoker, U.S. Geological Survey, Denver, CO

The Role of Surface Sedimentary Analyses in Predicting Subsurface Reservoir Character of Sandstone Facies, Frontal Ouachita Mountains, Oklahoma, by Robert C. Grayson, Jr., Baylor University, Waco, TX

Midcontinent Fluvial Depositional Environments and Their Influence on Enhanced Oil Recovery, by W. I. Johnson and D. K. Olsen, NIPER, Bartlesville, OK

Geologic and Production Characteristics of Deep Oil and Gas Wells and Reservoirs, by T. S. Dyman and D. D. Rice, U.S. Geological Survey, Denver, CO

Kinta Field—Characterization and Geology of a Multi-Reservoir Giant Arkoma Basin Gas Field, by Robert A. Northcutt, Consultant Geologist, Oklahoma City, OK; and David P. Brown, Geological Information Systems, Norman, OK

Outcrop Characteristics of Bitumen-Rich Sandstone, Black Warrior Basin, Alabama: Application to Subsurface Studies of Reservoir Heterogeneity, by Jack C. Pashin and Ralph L. Kugler, Geological Survey of Alabama, Tuscaloosa, AL

Microseismic Monitoring as a Tool for Mapping Fractures in the San Andres Dolomite, by James Rutledge, Los Alamos National Laboratory, Los Alamos, NM

Structural and Stratigraphic Controls on Natural-Gas Accumulation, Batson Field, Arkoma Basin, Arkansas, by Doy L. Zachry and Roy B. Van Arsdale, University of Arkansas, Fayetteville, AR

Petroleum Production from Potentially Fractured Pre-Pennsylvanian Reservoirs in Oklahoma, by Jock A. Campbell, David P. Brown, Brian J. Cardott, and Anne Mycek-Memoli, Oklahoma Geological Survey and Geological Information Systems, Norman, OK

Advance registration (prior to March 1) is $50, which includes two lunches and a copy of the proceedings. On-site registration will be $60 per person. Lodging will be available on the OU campus or at local motels.

Contact Kenneth S. Johnson or Jock A. Campbell, General Co-Chairs, Oklahoma Geological Survey, University of Oklahoma, 100 E. Boyd, Room N-131, Norman, OK 73019, phone (405) 325-3031, for registration forms and/or more information.

NEW OGS PUBLICATION

GEOLOGIC MAP GM-33. *Coal Geology of Tulsa, Wagoner, Creek, and Washington Counties, Oklahoma,* by LeRoy A. Hemish, 3 sheets, scale 1:63,360, with accompanying text. Price: $13.

The Oklahoma Geological Survey has published the third in a series of studies that evaluates the coal reserves and resources of Oklahoma on a county basis. Issued as Map GM-33, the new report covers Tulsa, Wagoner, Creek, and Washington Counties in northeastern Oklahoma.

Author LeRoy A. Hemish, a coal geologist at the OGS, conducted this study to determine the location, amounts, and quality of the coal beds, and the stratigraphy of the coal beds and associated strata. While some 21,597,000 short tons of coal have been mined or lost in mining in the area, Hemish has estimated the remaining resources at 337,952,000 short tons, with estimated reserves of 50,620,000 short tons. "Remaining resources" is the term used for all the coal still in the ground that has the potential for economic extraction. Current price levels, however, may not be sufficient to make mining of all resources economical. The term "reserves" is used for that portion of the resources that can be mined currently at a profit.

The Dawson coal leads with 23,879,000 short tons of reserves, as well as having the greatest remaining resources, 169,825,000 short tons.

Summary information on reserves and resources is contained in tables and is listed according to township, coal thickness, county, and coal bed. Detailed data on estimated original, mined, and remaining coal resources and reserves are tabulated by township for each county according to coal thickness, overburden thickness, and reliability category. The text, which is printed on the map plates, covers coal quality, coal rank, geology, and economics. The publication is illustrated with photographs of active and abandoned coal mines and includes histograms showing reported coal production.

GM-33 includes three plates that show the outcrop boundaries of commercially important coal beds. The maps show the thickness of both the beds and the overburden. Two plates contain stratigraphic cross sections that form a crisscrossing network throughout the study area.

Appendixes, printed in a separate 117-page booklet, provide details on resources and reserves, measured sections and core-hole logs, coal analyses, and cleat orientations.

GM-33 can be obtained over the counter or by mail from the Survey at 100 E. Boyd, Room N-131, Norman, OK 73019; phone (405) 325-3031. Add 10% to the cost of publication(s) for mail orders, with a minimum of 50¢ per order.

NOTES READERS REPLY TO QUESTIONNAIRE

In an effort to be more responsive to the needs and interests of the public it serves, the Oklahoma Geological Survey included in the October 1990 issue of *Oklahoma Geology Notes* a questionnaire soliciting input from *Notes* readers. A total of 221 people returned the questionnaire. This report summarizes the results of that survey.

Out of 543 paid subscribers to the *Notes*, 188 (35%) returned the questionnaire. In addition, there were 33 replies (8%) from the 422 names on our exchange-subscription list. Response totals for each of the questions asked are given in Figure 1.

The three technical topics (Question 1) of greatest interest to readers are oil and gas, environmental geology, and paleontology/biostratigraphy, in that order. Topics most frequently listed under the "Others" category involve some aspect of stratigraphy, structure, sedimentology, geomorphology, or tectonics.

Responses to Question 2 indicate that subscribers also want to be informed mainly about OGS publications and projects, and theses and dissertations dealing with Oklahoma geology.

Readers appear to be satisfied with the current format and publication frequency, although one-third have no preference with regard to size, and a significant num-

OGS NOTES QUESTIONNAIRE

1. **Technical Topics: Please check three that are of greatest interest to you.**

163	Oil & Gas	82	Paleontology/Biostratigraphy
49	Coal	46	Geography
66	Non-fuel Minerals	23	Meteorology/Climatology
58	Water Resources	43	Archaeology
102	Environmental Geology	27	Others ______

2. **General Information: Please check three that are of greatest interest to you.**

139	Ongoing OGS Projects	16	Agendas for National/Regional Meetings
158	New Publications	139	Abstracts of Theses and Dissertations
69	News & Announcements	86	Reprinted Abstracts (GSA, AAPG, etc.)
52	Earth Science Education	4	Others ______

3. **What format would you prefer?**

111	6" x 9" (no change)	37	8.5" x 11"	73	No Preference

4. **What publication frequency would your prefer?**

167	Bimonthly (no change)	14	Quarterly	40	No Preference

5. **Occupation/Special Interest**

168	Geologist/Geophysicist	13	Engineer
17	Teacher	12	Mining
16	Rock/Mineral Collector	33	Other (please specify) ______
8	Hydrologist		

6. **Comments** 80

Figure 1. Reproduction of questions from questionnaire showing total number of responses for each. Out of 965 questionnaires sent out, 221 (23%) were returned in time for this report.

ber would prefer that the *Notes* be changed to a standard 8.5″ × 11″ format. The frequency of publication favored by readers clearly is bimonthly, presumably because this enables the *Notes* to be timely in presenting announcements and current research to the public.

Not surprisingly, the greatest number of readers classified themselves as geologist/geophysicist. Occupations listed more than once in the "Other" category were: librarian (8), media/information specialist (4), administrator (3), soil scientist (3), student (3), consultant (2), and fossil collector (2).

A total of 80 people (36% of respondents) chose to comment in Question 6. Of those commenting, 45 expressed only compliments. The other 35 commented on a variety of subjects: the number, types and/or subject matter of articles they would like to see in the *Notes* (25); the reasons for their choices in Questions 1–5 (15); their desire to receive a publications list or have their address changed (4); selection of typeface and paper for the publication (3); and the need for a new geologic map of Oklahoma (1).

In summary, although the majority of *Notes* readers are geologists interested primarily in oil and gas topics, the questionnaire reveals that the overall appeal and usefulness of the publication lie in the variety of material on Oklahoma geology that it offers to a diverse readership.

The OGS staff thank all of you who took time to respond to the questionnaire. To the extent possible, we shall try to incorporate your preferences in planning future issues. To achieve that goal, we are continually seeking new material and therefore would welcome your articles for consideration.

Jane Weber

UPCOMING MEETINGS

14th International Radiocarbon Conference, May 20–24, 1991, Tucson, Arizona. Information: Austin Long, Dept. of Geosciences, University of Arizona, Tucson, AZ 85721; (602) 621-8888.

American Geophysical Union, Spring Meeting, May 28–June 1, 1991, Baltimore, Maryland. Information: AGU, 2000 Florida Ave., N.W., Washington, DC 20009; (202) 462-6900.

10th Rapid Excavation and Tunneling Conference, June 16–20, 1991, Seattle, Washington. Information: Meetings Dept., Society of Mining, Metallurgy, and Exploration, Inc., P.O. Box 625002, Littleton, CO 80162; (303) 973-9550.

U.S. Rock Mechanics Meeting, July 10–12, 1991, Norman, Oklahoma. Information: Sally Goldesberry, Society of Petroleum Engineers, Box 833836, Richardson, TX 75083; (214) 669-3377.

Association of Ground Water Scientists and Engineers, Environmental Site Assessments Conference, July 29–31, 1991, Columbus, Ohio. Information: National Water Well Association, 6375 Riverside Dr., Dublin, OH 43017; (614) 761-1711.

AAPG ANNUAL CONVENTION
Dallas, Texas, April 7–10, 1991

The theme of the 1991 convention celebrating AAPG's Diamond Jubilee Anniversary is "A Look Back—A Look Forward."

All in all, the past 75 years have been our testing period. We have found the "easy" oil and gas. We have located and produced the larger accumulations. Our job in the next 75 years will be to find the "hard" oil and gas. In addition, we must learn how to recover economically the oil that is left in the reservoir after primary and secondary production operations.

With these thoughts in mind, we have designed our program for the Diamond Jubilee celebration. In our "looking back," we will have special sessions on the *Treatise of Petroleum Geology* and the "History of the AAPG and the Petroleum Industry." Also, we will have many oral and poster sessions devoted to case histories of oil and gas fields worldwide. In addition, we will offer short courses on "old well log" interpretation and reservoir geology for secondary and enhanced oil recovery projects.

A majority of the papers in the technical program will be a "look forward," with emphasis on new plays and new concepts on a global scale. A special short course on how to prepare for participation in the international "oil game" will be offered, along with a number of timely and informative field trips.

This will be the tenth time in the past 76 years that the Association has honored Dallas by holding its annual convention in this city. Come join us for "A Look Back—A Look Forward" during the 75th Anniversary Diamond Jubilee Celebration.

— Charles F. Dodge
General Chairman

A LOOK BACK —

A LOOK FORWARD

AAPG Annual Convention Agenda

Technical Program

April 8

SEPM/AAPG Variations in Siliciclastic Depositional Systems within a Sequence Stratigraphic Framework: Applications to Exploration
AAPG/SPE/SEG Integrated Development Case Histories
AAPG New and Emerging Trends and Plays in the United States and Canada
AAPG/SEPM Petroleum Geochemistry in Exploration
AAPG/SEPM Geology and Petroleum Potential of Europe
AAPG History of AAPG and the Petroleum Industry
NAMS/SEPM High-Resolution Analysis of Slope Environments, Paleoenvironments, and Stratigraphy, Gulf of Mexico: Multi-Disciplinary Approaches
AAPG/SEPM Geology and Petroleum Potential of the Soviet Union
SEPM/AAPG Variations in Carbonate Depositional Systems within a Sequence Stratigraphic Framework: Applications to Exploration
SEPM/AAPG Petroleum Source Rocks in a Sequence Stratigraphic Framework
SEPM Porosity Prediction in Siliciclastic Rocks
EMD Geothermal Basin Maturation/Remote Sensing

April 9

AAPG Development Geology: Quantification of Reservoir Architecture
AAPG Treatise on Petroleum Geology
AAPG Oil Spills in Retrospect: Different Perspectives and New Initiatives
AAPG/SEPM Geology and Exploration in Central and Southern Africa
SEPM/AAPG Biostratigraphic Aspects of Sequence Stratigraphy
SEPM Research Conference—Applied Magnetostratigraphy and Sedimentary Paleomagnetism
SEPM Porosity Prediction in Siliciclastic Rocks
AAPG Petroleum Geology of North Africa and Asia
AAPG Oil Spills in Retrospect: Experiences with Natural Processes, Response and Technology
AAPG Geologic Aspects of Horizontal Drilling
AAPG Development Geology: Reservoir Geologic Modeling
AAPG Fluid Seals
SEPM/AAPG Variations in Siliciclastic Depositional Systems within a Sequence Stratigraphic Framework *(continued)*

A LOOK BACK —

April 10

SEPM Recent Advances in Carbonate Diagenesis
AAPG Development Geology: Quantification of Faults and their Effect on Fluid Flow
AAPG Gulf of Mexico Structure and Salt Tectonics
AAPG Building and Maintaining Large Databases
AAPG/SEPM Geology and Exploration in South America
SEPM Tectonics and Sedimentation
AAPG/SEPM Simulation of Geologic Processes and Systems
AAPG Petroleum Systems from Source to Trap
SEPM Deep-Water Carbonate Processes, Slope Failure, and Sedimentary Cycles
AAPG/SEPM Geology and Exploration in Southwestern Pacific
SEPM Cenozoic Depositional Systems of the Northern Gulf of Mexico
AAPG Surface Expression of Subsurface Hydrocarbon Accumulations
AAPG Regional Tectonics and Hydrocarbon Accumulations
AAPG Fractals, Statistics, and Chaos in Exploration and Development
SEPM Sedimentology of Evaporite Sediments
EMD Coal Bed Methane

Short Courses

AAPG Well Log–Seismic Sequence Stratigraphy: Utilizing High-Resolution Biostratigraphy and Recognition of Condensed Sections on Well Logs, *April 5–6*
DGS Scanalizing Logs in Geological Exploration, *April 6*
SEPM Luminescence Microscopy: Qualitative and Quantitative Applications, *April 6*
DGS International Exploration: A Viable Option for Growth in the 1990s, *April 6*
AAPG Geological Aspects of Horizontal Drilling, *April 6–7*
EMD Remote Sensing for Energy Exploration, *April 6–7*
SEG An Introduction to Reflection Seismic Interpretation, *April 6–7*
SEG Seismic Stratigraphy: Geological Systems—Seismic Responses, *April 6–7*
DGS Geology for Improved and Enhanced Oil Recovery, *April 7*
AGS & SW/AAPG Subsurface Methods in Fluvial Channel, Delta, and Submarine Canyon and Fan Prospecting, Eastern Midland Basin, Texas, *April 7*
SEPM Core Workshop: Mixed Carbonate–Siliciclastic Sequences, *April 7*
AAPG Fractal Geometry and Its Application in the Petroleum Industry, *April 11*
AAPG Planning Hydrologic and Geologic Investigations and Reports, *April 11–12*

Field Trips

DGS Sedimentation and Diagenesis of Middle Cretaceous Platform Margins, East-Central Mexico, *April 3–7*

DGS Remote Sensing Techniques Applied to Structural Geology and Oil Exploration in South-Central Oklahoma, *April 4–7*

DGS Scales of Geological Heterogeneity of Pennsylvanian Jackfork Group, Ouachita Mountains, Arkansas: Applications to Field Development and Exploration for Deep-Water Sandstones, *April 4–7*

EMD Hydrogeology of the Jewett Lignite Mine, East Texas, *April 6*

DGS Near Shore Clastic-Carbonate Facies and Dinosaur Trackways in the Glen Rose Formation (Lower Cretaceous), Central Texas, *April 6*

DGS Stratigraphy, Structure, and Depositional Environments of Upper Cretaceous Rocks in the Vicinity of the Superconducting Super Collider, Northern Ellis County, Texas, *April 6*

DGS Surface Geology of the Keechi and Palestine Salt Domes, Anderson County, Texas, *April 6*

DGS Controls on Fracture Development, Spacing and Geometry in the Austin Chalk Formation, Central Texas: Considerations for Exploration and Production, *April 6–7*

DGS Dinosaur Tracks in the Cretaceous Glen Rose Formation of Central Texas, *April 7*

DGS Sequence Stratigraphy and Cyclicity of Lower Austin/Upper Eagle Ford Outcrops (Turonian–Coniacian), Dallas County, Texas, *April 7*

EMD Fracture and Structure of Principal Coal Beds Related to Coal Mining and Coalbed Methane, Arkoma Basin, Eastern Oklahoma, *April 10–11*

DGS Structure and Stratigraphy of the Arbuckle Mountains, Southern Oklahoma, *April 10–12*

DGS The Slick Hills of Southwestern Oklahoma—Fragments of an Aulacogen, *April 10–12*

MC/AAPG The Western Ouachita Mountains Frontal Belt, Oklahoma, *April 10–12*

PBS/SEPM Sequence Stratigraphy, Facies, and Reservoir Geometries of the San Andres/Grayburg/Queen Formations, Guadalupe Mountains, New Mexico and Texas, *April 10–13*

DGS Structure and Stratigraphy of Trans-Pecos Texas, *April 10–14*

DGS Carboniferous Geology and Tectonic History of the Southern Fort Worth (Foreland) Basin and Concho Platform, Texas, *April 11–12*

AAPG Classic Mississippian to Permian Reefal Carbonates: Deposition, Diagenesis, and Reservoir Geology, *April 11–16*

For further information about the annual meeting, contact AAPG, Convention Dept., P.O. Box 979, Tulsa, OK 74104; (918) 584-2555. The preregistration deadline is February 22.

GSA ROCKY MOUNTAIN AND SOUTH-CENTRAL SECTIONS ANNUAL MEETING
Albuquerque, New Mexico, April 21–24, 1991

The Rocky Mountain and South-Central Sections of the Geological Society of America, the Rocky Mountain Section of the Paleontological Society of America, and the New Mexico Geological Society will meet jointly in Albuquerque, New Mexico. The meeting is sponsored by the University of New Mexico Department of Geology and Institute of Meteoritics, assisted by the New Mexico Bureau of Mines and Mineral Resources, and the University of Texas at El Paso Department of Geological Sciences.

Fifteen symposia are planned, including three symposia of regional interest to geologists in the south-central areas: "Time Framework and Geologic History of the Carboniferous," by Walter L. Manger; "Plate Margin and Foreland Deformation: The Ouachita Orogeny and Ancestral Rocky Mountains," by Kent Nielsen and Kristian Soegaard; and "Pennsylvanian and Wolfcampian Cyclic Sedimentation in the Ancestral Rocky Mountains and Ouachita–Marathon Foreland," by Gary Smith and Thomas Yancey.

Thirteen premeeting and postmeeting field trips will visit areas in New Mexico, Colorado, and western Texas.

For further information about the meeting, contact G. Randy Keller, Dept. of Geological Sciences, University of Texas at El Paso, El Paso, TX 79968; (915) 747-5501. The preregistration deadline is March 15.

THE GEOLOGICAL SOCIETY OF AMERICA
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NOTES ON NEW PUBLICATIONS

USGS Research on Energy Resources, 1990; Program and Abstracts

The 92 extended abstracts in this 99-page volume, edited by L. M. H. Carter, are summaries of the papers and posters presented at the Sixth V. E. McKelvey Forum on Mineral and Energy Resources. They represent an overview of the scientific breadth of USGS research on energy resources.

Order C 1060 from: U.S. Geological Survey, Books and Open-File Reports, Federal Center, Box 25425, Denver, CO 80225; phone (303) 236-7476. The circular is available free of charge.

OKLAHOMA ABSTRACTS

The following are abstracts from University of Oklahoma M.S. theses. Permission of the authors to reproduce the abstracts is gratefully acknowledged.

Depositional Environments and Pedogenic Alteration of Palustrine and Lacustrine Deposits: An Example from the Lower Cretaceous Baum Limestone, South-Central Oklahoma

JAMES FREDRICK SWARTZ, University of Oklahoma, Norman, M.S. thesis, 1990

A facies and geochemical study of the lower Cretaceous Baum Limestone Member (basal member of the Antlers Formation, south-central Oklahoma) was undertaken to determine its depositional setting and to infer the factors controlling sedimentation. The deposits are restricted to a paleotopographic basin developed largely within a pre-existing syncline, indicating that structural fabric strongly influenced paleotopography. The structures of the area formed during Late Paleozoic uplift of the Arbuckle Mountains and were modified by an extensive period of erosion prior to deposition of Cretaceous sediments.

The Baum Limestone Member varies in thickness from 10 to 30 meters and consists of paludal mudstones, fluvial clastics, lacustrine limestones, tufa, and palustrine carbonates. Paludal mudstones contain abundant charophyte gyrogonites, representing periods of permanent marsh inundation. Small lenses of fluvial sandstone are infrequently associated with the mudstones. Lacustrine limestones are thin, laterally restricted, and noted for having large quantities of charophytes and ostracods. The palustrine carbonates make up the bulk of the member, resulting from pedogenic alteration of paludal mudstones and lacustrine limestones during periods of intermittent inundation and desiccation. Small mounds and tabular bodies of tufa are sporadically interspersed with the palustrine limestones. The tufa deposits are interpreted to have formed by secondary replacement of micrite. The results of analysis of carbon and oxygen stable isotopes are consistent with deposition of the Baum Limestone Member by fresh water.

Changing levels of inundation identified within the vertical facies sequence provide the framework for inferring relative sea level variations as the primary cause for changes in the depositional environments. During transgression, base level rose, depositing suspended fine grained sediments in permanent marshes created by ponding of stream waters behind barrier bars. Periods of regression are marked by intermittent desiccation and development of palustrine carbonates. Deposition of fluvial conglomerates occurs within the palustrine deposits as a result of increased stream gradients accompanying a base level drop. A combination of eustatic changes in sea level and perhaps downwarping of the coastal plain is inferred to have caused the base level changes.

Boggy–Thurman (Middle Pennsylvanian) Relationships—Sedimentological Evidence in the Arkoma Basin, Oklahoma, for the Time of Recurrent Uplift in the Ouachita Fold Belt

PERRY B. WHITE, University of Oklahoma, Norman, M.S. thesis, 1989

Paleocurrent, petrographic, and sedimentologic data from the Boggy and Thurman formations (early to middle Desmoinesian) in the Arkoma basin, Oklahoma, documents the recurrent uplift of the Ouachita fold belt. The Boggy is composed of sandstone-shale sequences which record progradation of coal-bearing, fluvially dominated deltaic complexes from north to south. Folding and faulting in the Boggy suggests this unit was involved in thrusting during the uplift of the Ouachita fold belt and the closing of the Arkoma basin, prior to deposition of the Thurman. Paleocurrent indicators in the dominantly shallow marine facies of the overlying Thurman indicate some variability, but with a source to the southeast. The change in paleoslope and the presence of pebbles eroded from Ordovician to Devonian chert units in the Thurman documents the uplift of the Ouachita core area. Accompanying the uplift was a distinct change in the nature of the cyclothems, from longer, typically coal-bearing nonmarine cycles in the Boggy to shorter, marine clastic cycles in the Thurman. The cycles in the Boggy were probably controlled by glacial-eustatic changes in seal level or by avulsion within the delta system. Cycles in the Thurman were probably strongly influenced by episodic thrust loading in the Ouachitas during plate collision.

Pervasive In Situ Remagnetization and Localized Fluid-Related Remagnetization, Ordovician Viola Limestone, Southern Oklahoma

DONALD SHEPHERD BAGLEY II, University of Oklahoma, Norman, M.S. thesis, 1989

Paleomagnetic and rock magnetic results from the Ordovician Viola Limestone in south-central Oklahoma indicate the presence of two chemical remanent magnetizations (CRMs). One is a CRM that is pervasive in the unfractured, non-mineralized Viola and resides in magnetite. An incremental fold test shows that this CRM was acquired during Pennsylvanian folding. Previous work has shown that the Viola was non-porous at the time of folding which probably excludes the possibility of remagnetization by externally derived fluids. A thermoviscous origin of this remagnetization can probably also be ruled out due to low maximum burial temperatures. Because of this, an in situ chemical process of remagnetization, such as the maturation of hydrocarbons, is invoked to explain the pervasive synfolding magnetization.

A Permian CRM residing in hematite occurs in a highly porous brecciated zone as well as in alteration halos around mineralized fractures. Geochemical studies indicate the fluids which caused the mineralization and alteration were primarily basinal in origin. Thus, it appears that the migration of basinal fluids through the fractures and through the highly permeable brecciated zone caused the remagnetization residing in hematite.

Mississippian Facies Relationships, Eastern Anadarko Basin, Oklahoma

HUGH WILLIAM PEACE, University of Oklahoma, Norman,
M.S. thesis, 1989

Mississippian strata in the eastern Anadarko basin record a gradual deepening of the Anadarko basin. During Early Mississippian time, much of Oklahoma was submerged beneath a single large sea. This simple structural make up was radically altered by two tectonic events. Late and Post Mississippian tectonism (Wichita and Arbuckle Orogenies) fragmented the single large basin into the series of paired basins and uplifts (Anadarko basin, Wichita Mountains, Hardeman basin, Ardmore basin, Arbuckle Mountains, Criner Hills, Marietta basin, and Nemaha ridge) recognized in the southern half of Oklahoma today.

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

Fault Distribution in the Sulphur, Oklahoma, Area Based on Gravity, Magnetic and Structural Data

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M.S. thesis, 1989

Declining water flow from springs in the Travertine District, Chickasaw National Recreation Area (CNRA) spurred geologic investigation of the area. Because geologic structure may influence hydrology, knowledge of structure was needed to understand the problem of declining spring flow. Pennsylvanian-aged conglomerate covers CNRA, obscuring the geology beneath the park that controls the hydrology. To further understand the geologic structure below and contiguous to CNRA, a geological and geophysical investigation was carried out. Ordovician outcrop is found east of CNRA and at a few isolated locations where it has been exposed by erosion of Pennsylvanian rock. Subsurface data from oil wells is available for the area west of CNRA. In those areas where Pre-Pennsylvanian rocks can be seen, surface geological reconnaissance was done. Maps and cross-sections were constructed from subsurface and outcrop data to define structural trends.

Gravity and magnetic data were acquired for the area surrounding and including CNRA between the outcrop data and the subsurface data. Analysis of gravity and magnetic data, obtained from 180 data stations in a 125 square kilometer area surrounding, and including, CNRA, is presented. These data are analyzed using a Fast Fourier Transform computer program. Second vertical derivatives are computed and incremental downward continuation of the gravity and magnetic fields is carried out.

Utilizing geologic data from various sources, density model inversion of gravity data was done using a least-squares matrix inversion computer program. North-south observed gravity profiles were used to develop geologically feasible models of the structural geometry for areas of limited geologic data.

Interpretation and synthesis of these data sets resulted in the interpolation of fault locations beneath the Pennsylvanian-aged conglomerate.

Porosity Determination Using Amplitude Variation with Offset and Velocity Analysis in the Mississippian Chappel Formation, Hardeman County, Texas

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Amplitude variation with offset (AVO) and stacking velocity analysis of the Mississippian Chappel Formation, Hardeman Basin, reveal that geologically constrained interpretation of pre- and post-stack data can be used to characterize subsurface porosity. A 24 fold, vibroseis source profile acquired over a productive bioherm and a smaller dry anomaly, in conjunction with subsequent well data, facilitated a comparison of pre-drill interpretations of porosity to that actually present in the subsurface. Bioherms similar to Waulsortian mounds in Europe commonly occur within the Chappel Formation and produce hydrocarbons from dolomitized mudstone cores. These biohermal reservoirs are challenging exploration targets because the variations in that porosity control production are not easily detected with conventional interpretation of stacked sections.

Meaningful information was extracted from the seismic data by reprocessing to reduce noise and other aberations that could affect pre- and post-stack amplitudes. The data were compensated for instrument phase distortion and FK filtered to reduce the effects of noise contamination. Surface consistent deconvolution was applied to reduce the effect of near surface distortions upon the wavelet and surface consistent residual static corrections improved reflector alignment on the unstacked data. Detailed velocity analyses detected velocity variations within the Chappel interval and provided an accurate stacked section. The resulting reprocessed stack was far superior to the originally processed stack in terms of resolution and reflector continuity. Interpretation of the final stack revealed detail within the Chappel interval that was not shown on the original section.

Analyses of stacked section amplitude changes and instantaneous attributes demonstrate that reduced amplitudes of the Chappel trough reflector and low frequency anomalies on instantaneous frequency displays coincide with areas of Chappel porosity. However, results of these analyses also demonstrate that amplitude anomalies and low frequency zones are not reliable indicators of subsurface porosity and can result in erroneous interpretations.

Stacking velocity analyses of the Chappel interval indicate the presence of a velocity inversion associated with documented fluid filled porosity. The considerable variation exhibited by this inversion suggests that stacking velocity analysis can indicate the presence of subsurface porosity and detect variations in reservoir quality.

AVO analysis of the Chappel interval can distinguish areas with fluid filled porosity from areas with no associated porosity. AVO signatures associated with 1.6% average porosity differ from those with 3.5% average porosity indicating that AVO analysis can detect changes in reservoir quality.

Analysis of Two-Dimensional Finite Fracture Accommodated Strain in a Fractured Carbonate Rock

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This study estimates two-dimensional finite strain recorded by mineral-filled fractures, where the mineral-filled fractures intersect a bedding surface to form fracture bounded polygons. Two-dimensional finite fracture strain is estimated by using three non-parallel coplanar fracture extensions (strain rosette solution). The object of this work is to investigate the applicability of the strain rosette solution as a method to characterize strain recorded by mineral-filled fractures. [The site selected for detailed study is located in the northwestern Arbuckle Mountains in southern Oklahoma.]

The procedure uses the centers of gravity of fracture bounded polygons, lines connecting the centers of adjacent polygons and thicknesses of the mineral-filling (apertures) within the fractures bounding the polygons. Two methods are used to estimate fracture extension along lines connecting the centers of gravity of adjacent polygons. One method assumes that fracture displacement occurred parallel to lines connecting the centers of adjacent polygons, and the other method assumes that fracture displacement occurred perpendicular to the fracture planes. Strain rosette solutions are also applied to hypothetical idealized test cases involving two fracture sets, where fracture aperture, spacing and orientation variations are evaluated.

The fracture strain distribution across the outcrop is fairly uniform in magnitude (most magnitudes range between 1 and 3%), yet principal strain orientations span the entire spectrum of potential orientations. Despite this spread, the data show a small group of preferred orientations.

At individual stations (average station area <50 cm^2), fractures can be grouped into two or three sets based on orientation. Polygon shapes are irregular at most stations, and principally consist of 3-, 4-, and 5-sided figures.

The most consistent strain results at individual stations occur where bounding

fractures are consistent in aperature and orientation. Consistent results also occur, to a lesser degree, where only two fracture sets are present, and the spread within the sets is small. The list of fracture characteristics effecting rosette solutions, in order of relative importance, are aperture, orientation and spacing.

Variation in strain rosette configuration is the most common feature producing error in strain calculations. The largest errors observed (up to 40% extension and 40% shortening) might be caused by replacement of host rock during fracture filling. Replacement of host rock would produce an exaggerated fracture aperture, and thus, an overstated fracture strain magnitude. Other explanations for error in strain calculations are variations in fracture displacement direction and intrapolygon strain, such as strain recorded by non-bounding fractures.

Most evidence indicates that bounding fractures opened perpendicular, or nearly perpendicular, to fracture planes, rather than parallel to lines connecting centers of adjacent polygons. Non-bounding fractures record up to 54% (average of 33%) of the total fracture strain in the rock. This result shows that polygons did not deform entirely as rigid plates moving with respect to each other.

Numerical simulations are conducted at stations with the most consistent fracture geometries observed. Simulations model fracture aperture, spacing and orientation of two fracture sets. For the method assuming that fractures opened perpendicular to fracture planes, simulated strain magnitudes are approximately equal to rosette derived strain magnitudes, and simulated strain orientations differ by only 6° compared to rosette derived orientations.

For the method assuming fractures opened parallel to lines connecting the centers of polygons, rosette derived strain magnitudes are approximately two times larger than simulated strain magnitudes, and rosette derived orientations differ by about 11° compared to simulated orientations.