OKLAHOMA GEOLOGY

Oklahoma Geological Survey Vol. 52, No. 3 June 1992

On the cover—

Oklahoma Badlands

Badlands topography has developed in an area adjacent to the Arkansas River flood plain in the SE¼SE¼SE¼ sec. 33, T. 12 N., R. 22 E., Sequoyah County, Oklahoma. Although on a much smaller scale, owing to different climate, these landscape features are similar to those found in the Badlands National Monument in western South Dakota. The two areas differ in that western South Dakota has a semiarid climate, whereas eastern Oklahoma has a humid climate.

Where impermeable clay and silt are exposed in steep slopes, such as the sideslopes of large valleys, abundant runoff during violent rainstorms soon creates a system of closely spaced, narrow gullies with little or no vegetation. Initially, sinkholes form by collapse of surface soils into underlying tunnels formed by piping. Subsequent collapse of surface soil between sinkholes (inset photo) creates gullies that expand the badlands area.

Depth of the gullies pictured in the cover photograph typically vary from about 3 to 7 ft. Further information on this erosional phenomenon and the processes involved are given in a paper in this issue (p. 88–98).

LeRoy A. Hemish

Sinkholes formed by collapse of surface soils into underlying tunnels.

OKLAHOMA GEOLOGICAL SURVEY

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OKLAHOMA
GEOLOGICAL
SURVEY

VOL. 52, NO. 3

JUNE 1992

SINKHOLE DEVELOPMENT ON AN ARKANSAS RIVER TERRACE REMNANT, SEQUOYAH NATIONAL WILDLIFE REFUGE, SEQUOYAH COUNTY, OKLAHOMA

LeRoy A. Hemish[1]

Introduction

Development of sinkholes within the boundaries of the Sequoyah National Wildlife Refuge in Sequoyah County, Oklahoma, was recently brought to the attention of the Oklahoma Geological Survey (OGS). Ron Sullivan, manager of the refuge, was concerned about the possibility of large collapse features forming in association with underlying, buried karstic topography. I was asked to investigate the phenomenon on behalf of the OGS, and my interpretations are presented in this paper.

Setting

The Sequoyah National Wildlife Refuge is located in east-central Oklahoma, just west of the Arkansas state line, near the town of Vian in Sequoyah County (Fig. 1). For the most part, the refuge is low-lying and is situated on the flood plains of Little Vian Creek, Vian Creek, Negro Creek, and the Arkansas River. The area where the sinkholes have developed is a point-like terrace remnant that forms a small divide between Vian Creek and the Arkansas River flood plain in the SE¼SE¼SE¼ sec. 33, T. 12 N., R. 22 E. (Fig. 1). The top of the terrace is ~30 ft above the water level of Vian Creek.

Bedrock is not exposed in the immediate area of investigation, but adjacent outcrops indicate that shale and sandstone of the Atoka Formation (Pennsylvanian) underlie Quaternary alluvial deposits (Marcher, 1969, sheet 1). A buried karstic surface is not indicated by these lithologies and can be eliminated as an explanation for development of the sinkholes at the present-day surface.

Lithology of the Terrace Deposits

Figure 2 is a stratigraphic column showing the observed lithologic units at the site of investigation. Only the lithologies of the two major units, each ~15 ft thick, are factors in the geomorphic processes involved in the formation of the sinkholes.

A thin layer of well-sorted eolian silt is present at the top of the terrace, but seems to be absent in the slope where gullying and sinkhole development are occurring. The silt is underlain by a 15-ft-thick, brick-colored, silty clay that dries hard and contains numerous fractures. Although tests were not run on the clay, it is assumed to be an expandable clay because of its shrinking properties when dry.

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[1]Oklahoma Geological Survey.

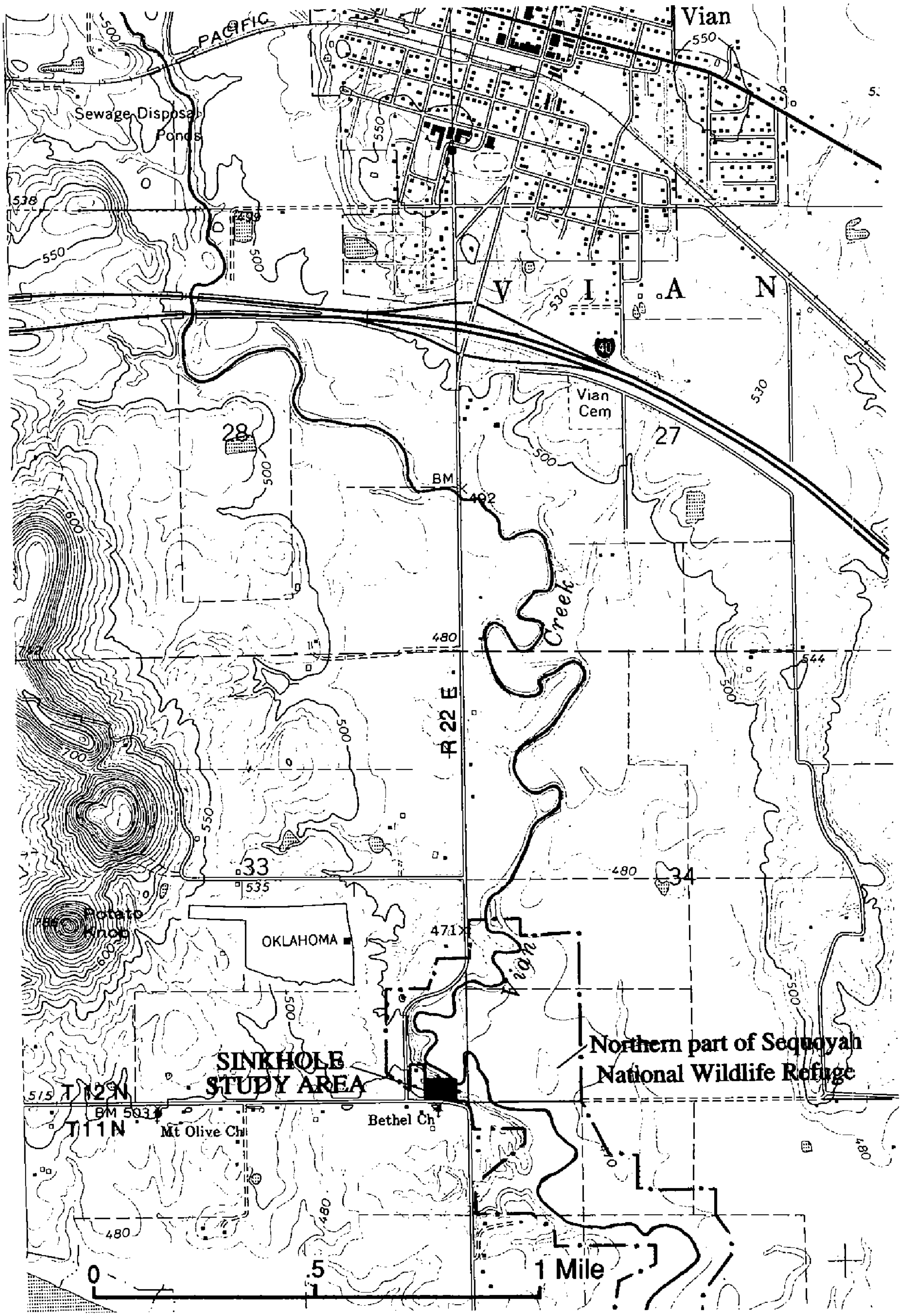

Figure 1. Excerpt from Vian, Oklahoma, 7.5′ quadrangle map showing location of area of sinkhole investigation. Vian Quadrangle shown by black rectangle in index map of Oklahoma (inset).

SYSTEM	LITHOLOGY	THICKNESS (ft.)	DESCRIPTION
QUATERNARY		0.2 – 0.5	Silt, very pale-orange (10 YR 8/2)[1] to grayish-orange (10 YR 7/4), noncalcareous, well-sorted, unbedded, rooted; contains numerous small borings; includes rare gravel clasts.
		15.0	Clay, silty, hard, mottled; light-brown (5 YR 5/6), light-brown (5 YR 6/4), and moderate-brown (5 YR 4/4), noncalcareous; jointed; black manganese dioxide staining on joint surfaces; oxidized; blocky fracture; weathered surfaces knobby; bedding obscure; contains root casts and borings; includes small-scale, very fine-grained sand-filled channels with low-angle cross-laminations; in places contains vertical fractures filled with very fine sand.
		15.0	Sand, moderate-orange-pink (5 YR 8/4) to light-brown (5 YR 6/4), fine- to medium-grained, quartzose, noncalcareous, well-sorted, well-rounded, very friable, poorly exposed, base of unit covered. [1] Classifications used in the Munsell color system (Rock-Color Chart Committee, 1949)

Figure 2. Stratigraphic column with description of lithologic units observed in area of sinkhole development.

The clay is underlain by a light-colored, well-sorted, fine-grained, unconsolidated sand that is poorly exposed in the slope just above Vian Creek. The sand was observed where a burrowing animal had excavated a den ~14 ft above the creek. Springs and seeps emerge just above water level in Vian Creek and in the lower part of the gully. The porous and permeable sand affords almost perfect conditions for occurrence of the springs.

The Sinkholes

At the time of my investigation (June 1991), about two dozen sinkholes were observed adjacent to a gully extending southwestward from Vian Creek to the top of the terrace (Figs. 3,4). Small-scale badlands features (pseudokarst) are present within the gully. The sinkholes have developed in a dendritic pattern associated with the gully and its tributaries. Figure 5 is a generalized sketch showing the distribution of the sinkholes. The sinkholes vary in size and shape, but are generally 0.5–2 ft in diameter. Some are elongated (as much as 2.5 × 5 ft) and have irregular shapes. Figures 6 and 7 show typical sinkholes. Plumbed depths indicate the sinkholes vary from 3 ft (within the gully) to 9 ft (from the uneroded surface). Some of the sinkholes are connected by subsurface tunnels to outlets in steep-sided areas of the gully (Fig. 8); others have no apparent outlet.

Outlets were found one-half to two-thirds of the way down gully walls. In areas where tunnels have collapsed, a continuous tributary gully has formed at the level of the underground passageway. Collapse commonly gives rise to steep or vertical walls. Figure 6 also shows a remnant of surface soil and sod held in place by a tree root to form a bridge separating two collapsing sinkholes.

In places, a grassy depression ~1 in. deep marks the course of underground tunnels where collapse has not yet occurred.

Figure 3. Gully development in slope southwest of Vian Creek. Note pseudokarst features in area barren of vegetation.

Interpretation

Development of the gully and sinkholes can best be explained by the process of erosion by shallow throughflow or outflow of soil water (piping). Although the role of piping in dryland gully development has long been recognized, its importance in humid environments such as eastern Oklahoma was little appreciated prior to the 1960s.

Mears (1968, p. 849) defines piping as "subterranean erosion initiated by percolating waters which remove solid particles from clastic (fragmental) rocks to produce tubular underground conduits." Piping was originally a civil-engineering term used for the flushing of sediment from within, under, or around the fill or

Figure 4 (left). Area of collapsing tunnels, sinkhole development and progressive headward erosion near top of terrace.

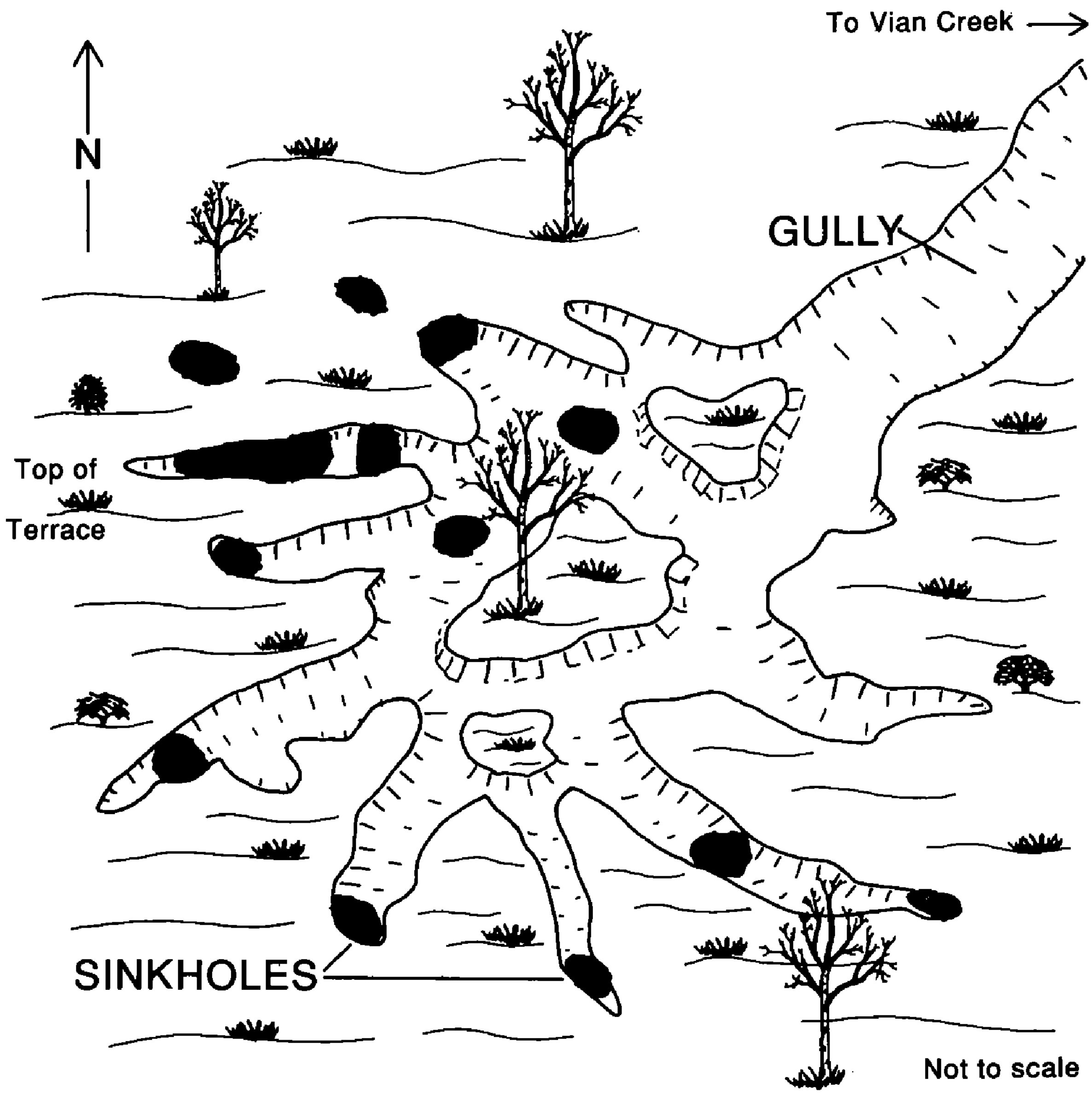

Figure 5. Map view sketch of the gully and sinkholes in the SE¼SE¼SE¼ sec. 33, T. 12 N., R. 22 E.

footings of a dam by water seepage or flowage. This commonly creates internal pipe-like openings and sometimes results in failure of the dam. In the 1940s, the word "piping" was applied by soil scientists and geomorphologists to a form of concentrated soil-water throughflow that creates pipe-like openings in the subsurface, which later may collapse to form a pseudokarst or a surface gully system.

Figure 6 (right). Isolated sinkhole showing irregular shape. Camera case for scale.

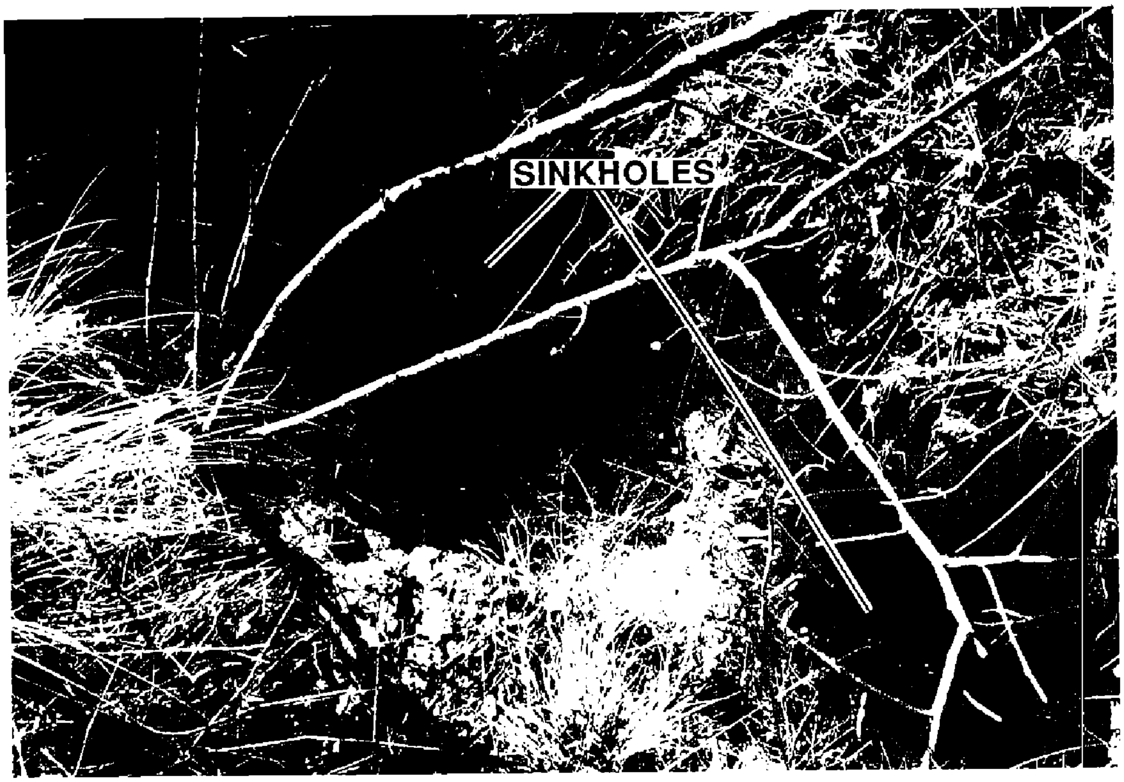

Figure 7. Sinkholes developing owing to tunnel collapse adjacent to main gully. Note "bridge" supported by tree root separating small sinkhole in lower right corner of photograph from larger area of collapse in left center.

Figure 8. Subsurface tunnels with outlets in lower part of gully wall.

MEAN ANNUAL PRECIPITATION
(In Inches)
Period 1958-1987

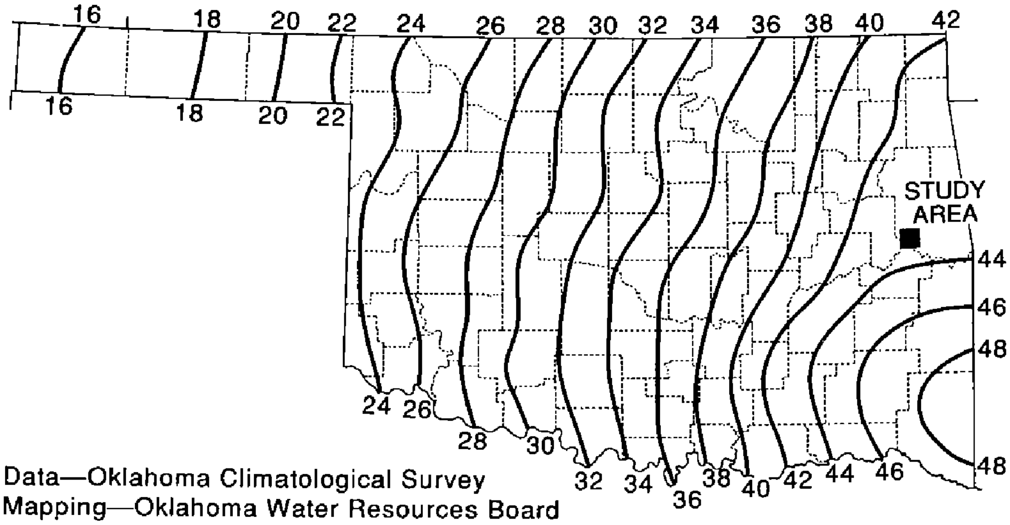

Figure 9. Map showing mean annual precipitation in Oklahoma, 1958–87. Note that the study area, shown by black square on map, receives in excess of 43 in. of precipitation annually. From Whitlow and Vance (1990).

This process, called tunnel-gully erosion, was at first believed restricted to arid and semiarid regions (Higgins, 1984, p. 18–19).

Piping works like this: During infrequent heavy rains, runoff is intercepted into desiccation cracks, animal burrows, or other openings either on hillsides or on relatively level upland or terrace surfaces. The diverted water moves downward until it encounters a particularly porous layer or lateral opening in the subsoil, or until it is blocked by an impermeable layer, by a perched water table, or by the bottom of the vertical opening. Then, it moves laterally, commonly toward a cliff face, a stream bank, or a gully wall. At the point of emergence, the outflow removes clay- and silt-sized particles, enlarging the outlet and gradually extending it back into the hillside as a pipe- or tunnel-like opening. Commonly, particles are removed, not only at the point of outflow, but all along the subsurface flow path, thus forming a continuous underground opening from inlet to outlet. Progressive enlargement and collapse of the tunnel creates sinkholes and extends a gully up the slope or into the upland (Higgins, 1984, p. 19).

Mears (1968, p. 849) stated that the permeability necessary for steep downward percolation and escape of water along gully bottoms reflects either porosity or desiccation cracking in moderately consolidated materials. Such piped materials characteristically contain smectite, or other swelling clay, which induces deep cracking when dried, but it is not clear whether this is a necessary component or merely a local or general association (Higgins, 1984, p. 19). Clearly what is necessary is a sediment or soil sufficiently friable to be entrained and transported grain-by-grain at fairly low-flow velocities. The material must be coherent enough to sustain open tubes and tunnels.

During extended dry periods, deep desiccation cracks develop that allow runoff from storm waters to penetrate deeply before the ground swells and seals. Clays disaggregate readily in downward-moving waters, allowing the removal of solid particles in turbid suspensions (Mears, 1968, p. 849).

In humid regions, the erosional effects of piping were relatively unknown and little studied before the mid-1960s. Once investigators began to look for piping and other erosional effects of subsurface throughflow in humid areas, they found numerous examples. Pseudokarst owing to piping has been reported from humid regions around the world, and investigators in the United Kingdom and in the eastern United States have recognized that soil-water throughflow with piping may initiate and extend surface drainage networks (Higgins, 1984, p. 20).

Figure 9 shows that the mean annual precipitation in the Sequoyah National Wildlife Refuge is >43 in., most of which occurs as rain. The area is clearly humid. However, during some years extended periods of drought occur. If the drought occurs during the summer months when daytime temperatures are in the 90 to 100° range, rapid evaporation occurs and the ground dries and "bakes." Deep desiccation cracks develop in clayey and silty soils (Fig. 10). Water from subsequent heavy rain finds a passageway into the ground through these fractures.

Klimentov (1983, p. 83) stated that water in rocks that fills all pores and fissures is called free-gravitational water. Free-gravitational water may pass through pore space and fissures; it is driven by gravity and flows due to the hydrostatic head difference. The passage of gravitational water through a porous medium, which is the principal way of underground water migration, is called "infiltration."

One of the dominant factors that controls migration of underground water is porosity. Water migrates through the system of open and communicating pores and fissures. If infiltration rates are high, such as in rocks cut with large fissures, the underground water flow may become turbulent, which is a major factor in removal of solid particles from clastic rocks and in the formation of tubular underground conduits.

The source of the infiltering waters which flow into the fissures is heavy rainfall. Rainfall events can be defined in terms of intensity (rate of rainfall), duration of storm, time distribution of rainfall, and return period and associated depth of rain. All these measures are required to adequately define a rainfall storm event (Wanielista, 1990, p. 43). It is beyond the scope of this report to make any quantitative analyses of precipitation events in the study area, but my observations of rain storms in eastern Oklahoma indicate that many are of sufficient intensity and duration to produce the runoff necessary to initiate the piping process.

Figure 10. Example of well-developed desiccation crack resulting from droughty conditions. From Oklahoma Water Resources Board (1973, p. 32).

Conclusions are that the pseudokarst features have formed in the study area as the result of variations in the weather pattern in northeastern Oklahoma over the past few years. During periods of extended drought, desiccation cracks

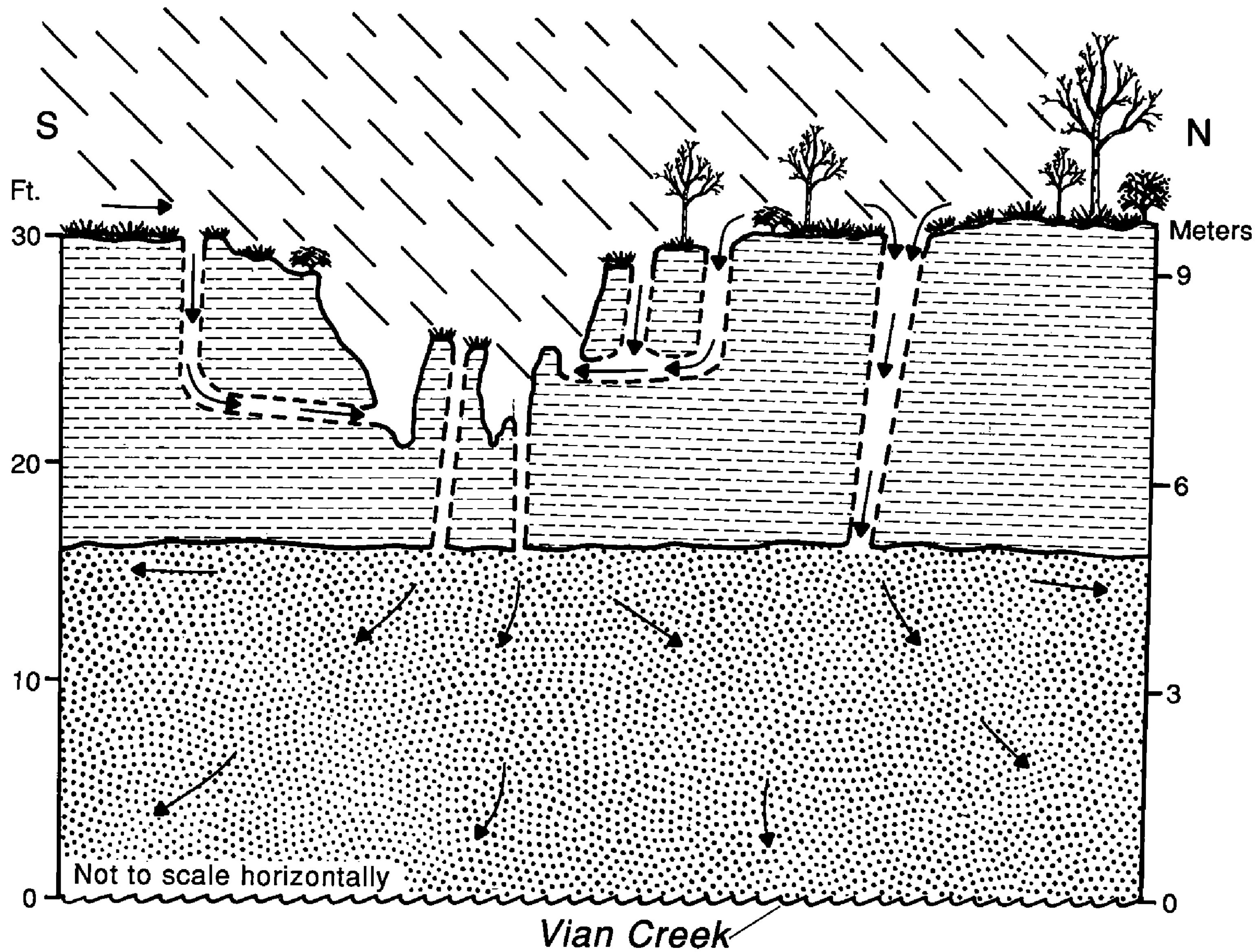

Figure 11. Diagrammatic profile across gully showing movement of surface runoff during heavy rain storms. Piping and pseudokarst development result.

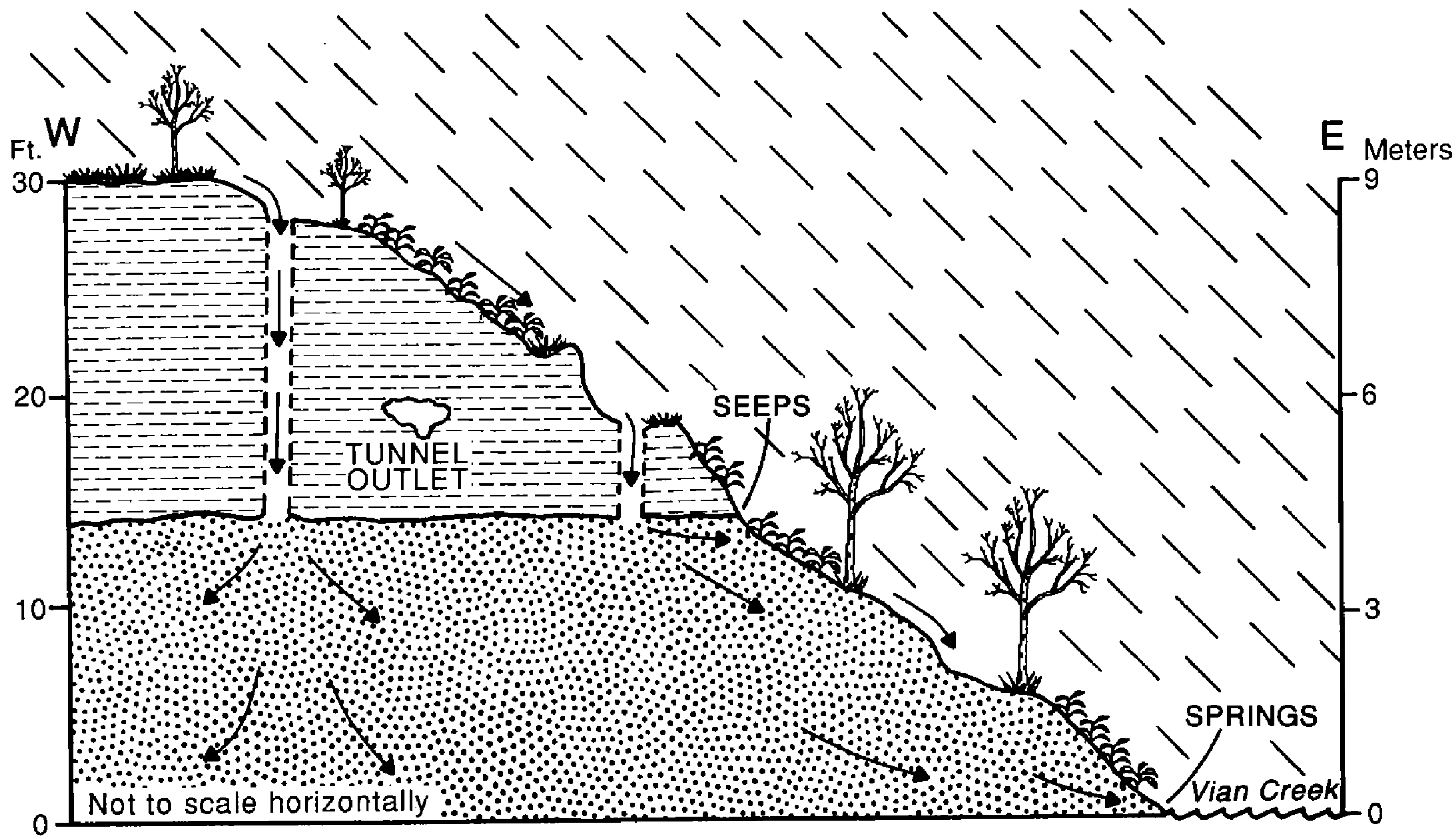

Figure 12. Diagrammatic view paralleling gully showing infiltration of meteoric water and its movement through permeable sand to points of discharge as seeps and springs.

opened in the clays in the upper part of the terrace. Overland runoff from subsequent heavy rains was diverted into these desiccation cracks. The water then flowed laterally at the bottom of the vertical openings toward the gully under the force of gravity, creating a continuous tunnel from inlet to outlet. Swelling of water-saturated clays "healed" the fractures, concealing the tunnels. Sinkholes formed at the inlets, mostly at the juncture of cracks, and were progressively enlarged by collapse of the tunnels. Outlets to some of the pipe-like features are observable in the gully walls.

Once a passageway is opened, water flows through it as a stream, increasing the rate of erosion. The tunnel is thus enlarged until the roof can no longer support the load and parts of it fall in. One or more funnel-shaped depressions form, which serve to collect more water from the surrounding area and pass it into the underground system. As the process continues, the rims between adjacent sinkholes collapse, thus forming a continuous gully.

Where no outlets are observable in association with sinkholes, it is assumed that swelling of wet clays sealed off immature conduits, and the holes now serve only as pipes for recharge into the underlying porous and permeable sand. Springs and seeps present near the base of the slope just above Vian Creek and in the lower part of the gully indicate underground migration of free-gravitational water to the points of discharge.

Figures 11 and 12 are cartoons showing the movement of meteoric waters through the conduit system. The diagrams show how the topography, rock types, rainfall, and force of gravity are all factors in the geomorphic evolution of the landscape in the study area. The entire system is a naturally occurring geologic phenomenon contributing to headward and lateral erosion in the gully. The rate of erosion is slow in years of normal rainfall and gentle rains, but is greatly accelerated by heavy rains following an extended period of drought, particularly when sinkholes and their associated conduits collapse, exposing unvegetated soil.

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NOTES ON NEW PUBLICATIONS

National Water Summary 1988–89—Hydrologic Events and Floods and Droughts

This USGS water supply paper is the sixth volume in the National Water Summary series describing the status of the nation's water resources. Compiled by R. W. Paulson, E. B. Chase, R. S. Roberts, and D. W. Moody, the 591-page report contains a state-by-state discussion of major floods and droughts as defined by stream-discharge data. A description of each state's climate is included, as well as multicolor illustrations that show the sources of the moisture that the atmosphere conveys to the state and the areal extent and expected recurrence of major floods and droughts. The report also contains essay articles on the role of climate in the cause of floods and droughts; the significance of evapotranspiration in droughts; the study of floods and droughts that occurred before the advent of systematic data collection; the roles of three federal agencies—the National Weather Service, the U.S. Army Corps of Engineers, and the Federal Emergency Management Agency—in the forecasting, prevention, or mitigation of the effects of floods and droughts; and the planning for floods and droughts at the local level.

Order W 2375 from: U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225; phone (303) 236-7476. The price is $39; add 25% to the price for foreign shipment.

SEPM MIDCONTINENT SECTION PLANS FIELD TRIP

The 1992 SEPM Midcontinent Section Annual Meeting will be held in Knoxville, Tennessee, October 9–11. The focus of the field conference will be on recognition and interpretation of paleosols and paleoweathering surfaces in outcrop exposures in eastern Tennessee, which range in age from Ordovician to Mississippian. Paleosols and paleoweathering surfaces developed in both siliciclastic and carbonate sequences, and in some cases define major sequence boundaries. Trip leaders include Steven G. Driese and Kenneth R. Walker (University of Tennessee) and Frank W. Stapor (Tennessee Tech).

For additional information contact Steven G. Driese, Dept. of Geological Sciences, University of Tennessee, Knoxville, TN 37996-1410; phone (615) 974-2366, fax 615-974-2368.

UPCOMING MEETINGS

American Association of Petroleum Geologists, International Meeting, August 2–5, 1992, Sydney, Australia. Information: Convention Dept., AAPG, P.O. Box 979, Tulsa, OK 74101; (918) 584-2555, fax 918-584-0469.

International Society for Photogrammetry and Remote Sensing, International Congress, August 2–14, 1992, Washington, D.C. Information: ISPRS Congress Secretariat, P.O. Box 7147, Reston, VA 22091; (703) 648-4144, fax 703-648-5585.

10th International Conference on Basement Tectonics, August 3–7, 1992, Duluth, Minnesota. Information: Richard Ojakangas, Dept. of Geology, University of Minnesota, Duluth, MN 55812; (218) 726-7238, fax 218-726-6360.

Society of Economic Paleontologists and Mineralogists, Annual Theme Meeting, "Mesozoic of the Western Interior," August 17–19, 1992, Fort Collins, Colorado. Information: Frank G. Ethridge, Dept. of Earth Resources, Colorado State University, Fort Collins, CO 80523; (303) 491-6307.

29th International Geological Congress, August 24–September 3, 1992, Kyoto, Japan. Information: Secretary General, IGC-92 Office, P.O. Box 65, Tsukuba, Ibaraki 305, Japan; phone 81-298-54-3627, fax 81-298-54-3629, telex 3652511 GSJ J.

23rd Annual Binghamton Geomorphology Symposium: Geomorphic Systems, September 25–27, 1992, Oxford, Ohio. Information: Bill Renwick, Dept. of Geography, Miami University, Oxford, OH 45056; (513) 529-1362.

American Institute of Professional Geologists, Annual Meeting, September 27–October 1, 1992, Lake Tahoe, Nevada. Information: Jon Price, AIPG, P.O. Box 665, Carson City, NV 89702; (702) 784-6691.

National Ground Water Association, Annual Meeting, September 30–October 2, 1992, Las Vegas, Nevada. Information: NGWA, 6375 Riverside Dr., Dublin, OH 43017; (614) 761-1711, fax 614-761-3446.

Association of Engineering Geologists, Annual Meeting, October 2–9, 1992, Long Beach, California. Information: AEG '92, c/o Rosenberg & Risinger, 11287 W. Washington Blvd., Culver City, CA 90230; (310) 397-6338.

Society of Petroleum Engineers, Annual Meeting, October 4–7, 1992, Washington, D.C. Information: SPE, Box 833836, Richardson, TX 75083; (214) 669-3377, fax 214-669-0135.

Hydrology and Hydrogeology Meeting, October 17–22, 1992, Portland, Oregon. Information: American Institute of Hydrology, 3416 University Ave., S.E., Minneapolis, MN 55414; (612) 379-1030.

Geological Society of America, Annual Meeting, October 26–29, 1992, Cincinnati, Ohio. *Abstracts due July 8.* Information: Meetings Dept., GSA, P.O. Box 9140, Boulder, CO 80301; (303) 447-2020, fax 303-447-1133.

Industrial Minerals Development in Oklahoma, A Workshop, November 10–11, 1992, Norman, Oklahoma. Information: Kenneth S. Johnson, Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019; (405) 325-3031, fax 405-325-3180.

OKLAHOMA ABSTRACTS

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

Exceptional Preservation of Bivalved Molluscs in the Buckhorn Asphalt Deposit (Pennsylvanian) of Oklahoma

M. J. HEANEY and T. E. YANCEY, Dept. of Geology, Texas A&M University, College Station, TX 77843

Exceptionally well preserved bivalves can be extracted from sediments of the Buckhorn asphalt deposit, in the Desmoinesian Deese Group of south-central Oklahoma, allowing documentation of prodissoconch (both PI and PII) and juvenile growth stages, recovery of lightly mineralized organic ligament fibers, and documentation of original shell mineralogy, shell microstructure, microornamentation, and muscle scars for taxa in the Nuculoida, Arcoida, Pterioida, Pectinoida, Mytiloida, Trigonioida, Veneroida, and Pholadomyoida, as well as for two undescribed genera of undetermined relationship. Most shells show distinct boundaries between prodissoconch I–II and prodissoconch II–dissoconch, and in two genera major changes in shell growth occurred at metamorphosis. Documentation of previously unknown character states—prodissoconch and juvenile ontogenies and ligament types—for several families allows re-evaluation of relationships between established Paleozoic clades. It is possible to categorize larval morphotypes, determine times of metamorphosis, and postulate larval life histories for these groups. Some shells have parasitization scars, and many shell surfaces show microborings produced by fungae or other microborers while resident on the seafloor. In a single Buckhorn sample from a shallow marine shelly sand substrate containing charcoalized wood and reworked bitumen clasts there is a diverse (50+ species) bivalve and gastropod fauna present containing many minute or small taxa or species represented by post-larval juveniles and small adults. The bivalve component of the fauna is dominated by small epibyssate species.

Reprinted as published in the Geological Society of America *Abstracts with Programs, 1991*, v. 23, no. 5, p. A166–A167.

Trilobite Succession within the Lower Ordovician Kindblade Formation of Southern Oklahoma

JAMES D. LOCH, Dept. of Geological Sciences, University of Missouri, Columbia, MO 65211

The Ordovician Kindblade Formation (Ibexian Stage) has yielded a diverse trilobite fauna significant for correlation throughout the eastern and central United States. Detailed sampling from the Kindblade limestones yielded 264 trilobite-bear-

ing collections from two measured sections of up to 1,500 ft in stratigraphic thickness. Zonation of the Kindblade based upon the stratigraphic ranges of nearly 40 species of trilobites allows for more precise correlation of the Kindblade than previously possible.

Species of *Ranasasus* and *Jeffersonia* s.s. characterize the base of the Kindblade, as well as the base of the Jefferson City Fm in Missouri and the Honeycut Fm in Texas. The presence of *Isoteloides peri, Strigigenalis caudata,* and *Petigurus* sp. A of Boyce allow for correlation of the middle member of the Kindblade with the Cotter Formation in Missouri, the Axemann Fm in Pennsylvania, and the Catoche Fm in Newfoundland. In contrast to these contemporaneous formations, the Kindblade is the only formation east of the Rocky Mountains to span this interval and to have escaped pervasive dolomitization.

The recovery of *Benthamaspis obreptus* confirms previous assignments of the Kindblade to Zone G of Ross and Hintze in the Lower Ordovician succession at Ibex, Utah. Contrasts between the trilobite faunas of the Kindblade and those of the Great Basin suggest a zonal terminology based upon the Kindblade is better suited for intra-regional correlation of the southern U.S.

Reprinted as published in the Geological Society of America *Abstracts with Programs, 1991,* v. 23, no. 5, p. A296.

A Sedimentological Explanation for the Distribution of Archaeological Sites in a Meander Belt as Stated by the "Relict Channel Rule"

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Port Allen, LA 70767

Archaeological surveys performed for the U.S. Army Corps of Engineers within the lower Mississippi River and Red River Valleys have noted that archaeological deposits found on the natural levees of relict river channels consist only of surficial sites that postdate the abandonment of the associated river channel. From the results of these surveys, Richard Weinstein and David Kelley proposed the "Relict Channel Rule" in 1989. Their rule states that the archaeological deposits associated with the natural levees of an abandoned river channel will consist only of surficial sites that postdate the abandonment of the river channel.

The Relict Channel Rule has been explained as the result of preferences by prehistoric cultures to avoid the occupation of natural levees of active river channels. Archaeologists have suggested that the lack of rich biotic resources associated with an active channel and the hazards created by periodic flooding caused prehistoric cultures to avoid settling the natural levees of active river channels. Rather, it has been proposed that prehistoric cultures settled around oxbow lakes within abandoned channel segments. In addition, archaeological studies of the Red River within Arkansas have speculated that the danger posed by rapidly eroding cut banks was another factor that discouraged the settlement of the natural levees of active river channels.

Sedimentological processes provide an alternative explanation for the Relict Channel Rule. While active, a typical meandering river channel rapidly migrates back and forth across its meander belt. During this time, its channel would rapidly migrate away from any archaeological deposits that formed adjacent to an active point bar. Simultaneously, overbank processes would quickly bury them. Also, an actively laterally migrating channel would consume the sites that form on the natural levee of a rapidly migrating cutbank. If a river cutbank were to migrate up to and stop at a preexisting site, that site would by that time be buried beneath natural levee deposits. Finally, archaeological sites formed during the initial establishment of a river course would eventually be either deeply buried by aggradation of natural levees or destroyed by lateral migration. As a result, only those archaeological deposits that date to a few tens of years prior to and postdate the abandonment of the channel will occur as surface sites. Therefore, regardless of whether the natural levees of a channel of an actively meandering river were used before or after its abandonment, the rapid lateral migration of its channel while active will produce the distribution of surface sites noted by the Relict Channel Rule.

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Use of Sequence Stratigraphy Along with Petrology and Fossil Content to Distinguish Offshore from Nearshore Black Shales

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Although all Midcontinent Pennsylvanian black shales were once regarded as shallow water deposits, the widespread, phosphatic, conodont-rich black shales that lack benthic fossils and lie stratigraphically between marine transgressive and regressive limestones in a cyclothem (=T-R sequence) are now recognized as the offshore sediment-starved condensed-section deposits, which accumulated slowly in anoxic water below a pycnocline. In contrast, less widespread (and often overlooked) phosphate- and conodont-poor black shales that grade vertically and laterally into shoreline/terrestrial deposits and often contain a sparse benthic fauna probably formed under conditions of organic overload in nearshore dysoxic environments. However, at least one widespread black shale that overlies a coal contains plant fragments and sparse shallow-water conodonts locally in the base, but phosphate nodules and abundant offshore conodonts in the top (Anna Shale in an Iowa core). Moreover, Price (1984) showed that the upper Anna in southern Kansas is the more offshore lower-shelf equivalent of both the overlying limestone (Myrick Station) and the upper Anna in Iowa. Wignall and Maynard (in press) report two stratigraphically distinct black shales in a Namurian cyclothem in England: the lower (Owd Bett's horizon) overlies a marine flooding surface and is conodont-poor, whereas the higher (*G. cumbriense* horizon) is conodont-bearing and ammonoid-rich, separated from the lower by a grey shale, and time-equivalent to distant nearshore highstand deposits. J. R. Hatch (USGS) reports the Anna Shale in the Iowa core to have two zones of organic enrichment (15%, 19%) in the base and top, respectively, separated by a less organic-rich (3.5%) zone. The basal Anna and

Owd Bett's horizon were probably deposited during early transgression in near-shore environments subject to organic overload, whereas the top of the Anna and the *G. cumbriense* horizon were deposited offshore at maximum transgression beneath a pycnocline.

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Pre-Paleozoic Clastic Sedimentary Rocks in the Midcontinent Rift System in Kansas

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Clastic sedimentary rocks of pre-Upper Cambrian age present in two linear NNE-trending basins in eastern Kansas were traditionally assigned to the lithostratigraphically defined Rice Formation. However, several new drill penetrations, due to a renewed interest in the economic potential of the rift, allow a much better understanding of the structural setting and petrography of these rocks. They are now chronostratigraphically classified as the Rice Series. This series includes a sedimentary and minor volcanic sequence of rocks laid down in a rift tectonic setting after cessation of the main phase of rifting, which is characterized by voluminous outpourings of basic igneous rocks, and before deposition of the Upper Cambrian Reagan (Lamotte) Sandstone.

New modal and heavy mineral analysis of samples from 19 drill holes in Kansas and from surface exposures in Minnesota, Wisconsin, and Michigan is the basis for preliminary classification and correlation within a rift-tectonic setting. Volcanogenic sedimentary rocks (Oronto Group, Solor Church Formation equivalents) represent depositional systems that developed in early formed basins during the final stages of rifting, directly after cessation of volcanic activity. Subsequently, increasingly mature, arkosic sedimentary rocks (Jacobsville Sandstone, Bayfield Group equivalents), that are characterized by more textural, petrographic, and spatial diversity, are deposited. Tectonic activity played an important role in the distribution and preservation of rocks of the Rice Series.

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Quantitative Modeling of Pennsylvanian Cyclothems: Implications for Understanding Relative Sea-Level Histories

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Microcomputer-based quantitative forward modeling of three stacked lower Missourian cyclothems in the midcontinent indicates that sea-level variations similar to late Quaternary glacial-eustatic fluctuations probably controlled their deposition. Furthermore, the modeling suggests that the periodicity of major early Missourian eustatic events was closer to 400 k.y. than to the 100 k.y. events that characterized the late Quaternary.

These cyclothems developed along a local shelf-slope-basin transition in southeastern Kansas. On the shelf the cyclothems are asymmetric and carbonate-dominated, and at any particular location successively higher major cyclothems tend to be more complex (they contain one or more minor cycles). The cyclothems that are simple on the shelf become progressively more complex basinward before thinning and pinching out into either a starved basin or siliciclastic succession.

Many aspects of these observed stratal relationships can be successfully reproduced by a model that incorporates relatively high-order (e.g., 100- to 400- k.y.), high-amplitude (50- to 125-m) asymmetric eustatic cycles superimposed on a lower-order relative sea-level rise. The modeling also indicates that at a given location the relative proportions of transgressive and highstand facies and cyclothem thicknesses are related more to rates of change of relative sea level and to the shape of the sea-level curve than to variations in the magnitude of sea-level fluctuation. These relationships suggest that the interpretations of base-level histories that are based solely or primarily on cycle thicknesses may be oversimplifications.

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Stratigraphic Architecture and Facies Distribution of Upper Middle Carboniferous Cyclic Depositional Sequences (Cyclothems), Southeastern Kansas, USA

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The significant lateral variability of facies and thickness patterns that characterizes cyclic lower Missourian depositional sequences (cyclothems) has not been emphasized in previous studies, but may be important for understanding their origin. This variability involves carbonate-to-siliciclastic transitions, sub-sequence-scale packaging, the presence and degree of development of porous, reservoir-quality lithofacies, and shifts in loci of accumulation.

Individual sequences vary along a shelf-to-basin transect from simple carbonate-dominated transgressive-regressive successions at high-shelf positions (classic "Kansas cyclothems") to mixed carbonate-siliciclastic intervals at intermediate-shelf locations to mainly siliciclastic sequences at low-shelf positions that are proximal to siliciclastic sources. In addition to such lateral variations within individual sequences, there are significant differences among vertically adjacent sequences. For example, the Hertha sequence contains a 30-m-thick generally non-porous phylloid-algal bank complex immediately basinward of the underlying slope break, whereas the immediately overlying Swope and Mound Valley sequences have well-developed porous oolitic deposits in similar paleotopographic positions. These three sequences exhibit progressively basinward-stepping slope breaks. The overlying Dennis sequence contains thick oolitic and skeletal grainstones that developed in a more ramp-like setting at a position landward of the self-slope transition in the

underlying sequence. The Cherryvale Shale and oolitic-skeletal Drum Limestone that overlie the Dennis sequence subsequently stepped progressively basinward.

The mechanisms that controlled the complex depositional architecture of these sequences are not fully understood. Basinward- and shelfward-stepping slope-breaks and thickness trends probably reflect a combination of migrating loci of accumulation, complex eustatic histories, and perhaps systematic, lower-order base-level changes.

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Siliciclastic Sedimentology and Petrology of Upper Pennsylvanian (Missourian) Swope and Lower Dennis Sequences, S.E. Kansas

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The Swope Sequence in southeastern Kansas consists of, in ascending order, the Hushpuckney Shale, Bethany Falls Limestone, Ladore Shale, the Mound Valley Limestone and the lower portion of the Galesburg Shale. It is separated from the overlying Dennis Sequence by an erosional surface within the Galesburg. Sedimentologic and petrographic studies of the Ladore and Galesburg document the progradation of fluvial-deltaic complexes across the Cherokee Shelf during times of marine lowstands. These complexes are separated in eastern Kansas by the transgressive Mound Valley Limestone which pinches out in Oklahoma, where they are recognized as portions of the Coffeyville Formation.

Ladore complexes were mud-dominated, lobate sediment thicks that appear to be deposited from point sources to the south–southeast of the study area and were probably derived from the Ouachita Mountains. Meteoric waters hosted early deposition of iron-carbonate nodules and partial dissolution of feldspar grains in siltstone and very fine-grained sandstone units. This was followed by calcite cementation during deposition of the overlying Mound Valley Limestone, prior to extensive compaction. Later stages of diagenesis include the conversion of smectite to illite, chlorite formation, further feldspar dissolution, and a late stage of calcite cementation.

Galesburg complexes are sandier, but were mud-dominated and also appear to have had a southern source. Early calcite cementation and alteration of feldspars to kaolinite and illite mark meteoric regime diagenesis of sublitharenitic units. Clay diagenesis within the compactional regime supplied silica that formed quartz overgrowths prior to extensive sandstone compaction. Late ferroan calcite completed cementation.

Recent weathering of Ladore and Galesburg silstone-sandstone resulted in the formation of secondary porosity and hematite box-work-like structures formed as ferroan carbonates were dissolved.

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Regional Diagenetic Variation in Maximum-Transgression Phosphates from Midcontinent Pennsylvanian Shales

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Phosphate nodules are common in high-stand black and dark gray shales in Midcontinent phosphates. The phosphate forms as a very early diagenetic phase that can nucleate on one or many grains or replace carbonate during nodule growth. The texture, composition, and diagenetic history of Upper Desmoinesian–Missourian phosphates vary regionally from Kansas south to Texas.

Nodules with multiple nucleii (radiolarians and peloids) are most characteristic of Kansas shales, whereas equivalent units in Oklahoma and Texas tend to have single nucleii (invertebrates, plant material, bone material). Pyrite, calcite, and quartz are present in varying degrees within many phosphate nodules, but their expression also varies regionally.

Lateral variation in shale compaction history may be recorded in septarian concretion types. Septarian phosphate concretions are most completely developed in Oklahoma, less well-developed in Texas, and are undeveloped in Kansas. The Oklahoma nodules may have formed in shale that was more substantially compacted (perhaps caused by faster shale deposition) than in the other two areas.

Rare earth element chemistry of the phosphates varies regionally, with HREE depletion in southern Kansas and northern Oklahoma relative to samples analyzed further north in Kansas. LREE depletions also occur in some samples. Within individual shales, total REE content of phosphates is lowest at and near the center of the shale and highest near the contact with underlying and overlying rocks.

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Stress Measurements in Quimby Granite, and the State of Stress in the Western Midcontinent

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The Midcontinent stress province, stretching from the Appalachians to the Rockies, is considered tectonically stable and subjected to a compressive stress regime characterized by uniform northeastern maximum horizontal stress (S_{Hmax}) direction. However, this stress regime is based only on measurements east of the Midcontinent Rift. Recently two sets of data became available which cast doubt on the continuity of the stress regime west of the Rift. Near-surface in situ stress measurements near Sioux Falls, SD and a composite focal mechanism solution of an earthquake in north-central Kansas both indicate a possible 90° rotation in the di-

rection of S_{Hmax}. This rotation, if verified by more exhaustive in situ tests, would have required a redistribution of the stress provinces in the conterminous U.S. Moreover, it would have demanded an explanation as to the source of such a stress discontinuity.

The Quimby Scientific Hole which was drilled by DOSECC in Cherokee County, NW Iowa, and penetrated 100 m of basement granite at 500–600 m depth, provided a unique opportunity for a verification of the apparent stress paradox. In situ hydrofrac stress measurements, funded by NSF, were conducted in the summer of 1991 with the cooperation of the Geological Survey Bureau of the Iowa Department of Natural Resources. Eleven tests were carried out within the granite segment available. Nine of the tests were remarkably consistent, illustrating the repeatability of hydrofrac tests, as well as the uniformity of the rock and of the state of stress. The results overwhelmingly demonstrate that the stress regime at Quimby is very much like that east of the Midcontinent Rift, with S_{Hmax} direction at N52°E (±5°) and a condition of compressive stress such that $S_{Hmin} < S_{vert} < S_{Hmax}$. The Quimby hole results are by far the most reliable west of the Rift. The Sioux Falls hydrofrac tests were limited to 30 m depth and results might have been affected by topographic relief and surficial factors such as abundant jointing and fracturing and diurnal and seasonal temperature fluctuations. The reliability of the focal mechanism Kansas is not known but due to its composite nature, the quality is suspect. Thus, based on the data available to date we assert that the Midcontinent stress province does indeed extend westward, seemingly unaffected by the Midcontinent Rift and the present-day activity of its bounding faults.

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Sequence Stratigraphy of a Lower Mississippian Carbonate Ramp in Arkansas and Missouri—Shelf to Basin Facies and Geometry

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Lower Mississippian carbonates were deposited on a south-sloping ramp along the southern margin of the North American craton in Arkansas and southwestern Missouri and form a depositional sequence, approximately 10 m.y. in duration. Regional unconformities at the base of the St. Joe and the top of the Boone formations, are the depositional sequence boundaries. St. Joe (Bachelor, Compton, Northview, and Pierson formations in Missouri) strata represent the transgressive systems tract and they are made up of several lithologically distinctive parasequences. These strata are >100 ft thick in Missouri, but they thin basinward to a featheredge in Arkansas and northeastern Oklahoma, because of sediment starvation and possibly submarine erosion.

The Bachelor–Compton parasequence, which unconformably overlies Ordovi-

cian to Devonian rocks, comprises a think quartz sand, with phosphate nodules, or green shale overlain by <1 to 20 ft of echinoderm-bryozoan limestones. Local thickening (up to 60 ft) corresponds to the presence of Waulsortian mounds. The overlying Northview parasequence is up to 80 ft thick in Missouri, where it coarsens upward from silty shale to fine-grained dolomitic sandstone. It thins southward into <2 ft of silty carbonate, which was deposited in a sediment-starved deeper shelf. Clear-water flooding of the Northview parasequence led to deposition of the Pierson parasequence, a succession of crinoid-bryozoan wacke-packstones up to 40 ft thick. A maximum flooding interval, comprising a hardground and bored bioclast wackestones-packstones with *Zoophycus*, comprises the top of the Pierson.

The overlying highstand Boone Formation (Reed Springs, Elsey, Burlington–Keokuk formations in Missouri), which is >300 ft thick, records a shoaling-upward history and southward progradation of the ramp. Early highstand deposition took place in a quiet, deep ramp setting. Facies include nodular and layered chert, and spiculitic lime mudstone-wackestone with fine bryozoan debris and crinoid ossicles. Middle–late highstand deposits consist of cherty to chert-free packstones and grainstones with medium to very coarse sand-size crinoids, brachiopods, and bryozoans. Cross-bedding is most abundant in the coarse-grained crinoid grainstones. Coated grains and ooids are locally present near the top of the Boone and Keokuk formations. These highstand deposits record deposition in a wave-dominated shallow ramp setting.

The sequence terminated in early Meramec time as relative sea-level dropped, exposing the shelf as far south as Limestone, Arkansas. Local erosional relief may have reached 50 ft prior to transgression.

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Pennsylvanian Sea-Level Change: How Much Tectonic? How Much Glacio-Eustatic? How Much Long-Term Climate Change?

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New sedimentological determinations of water depth and associated sea-level change of Midcontinent Pennsylvanian cyclothems shows that they accumulated in water depths ranging from as little as 40 m to as much as 160 m, depending on which model is used to establish the deepest water facies. These depth determinations also indicate that regardless of model, depth variations existed for different cyclothems both laterally and in time. Average water depth determinations and sea-level change for models of Heckel and Gerhard are approximately 96 and 86 m, respectively. Similar determination in the Illinois and Appalachian basins yield sea-level changes ranging from 18 to 30, and 20 to 30 m, respectively.

Determination of both per-cycle tectonic subsidence and paleoclimate modelling establish the magnitude of tectonic and climatic contributions to Pennsylvanian sea-level change. In the Midcontinent, tectonic subsidence accounts for approximately 5 to 20% of sea-level change, whereas in the Illinois and Appalachian basins, tectonic subsidence accounts for 11 to 92%, and 9 to 100% of sea-level change, re-

spectively. Glacio-eustasy accounts for 70% of sea-level change in the Midcontinent, and from 8 to 89% and 0 to 91% of sea-level change in the Illinois and Appalachian basins, respectively. In the Midcontinent, an additional 15% of sea-level change is attributed to long-term climate change.

These findings suggest that away from orogenic belts, climatic change is the principal driving mechanism controlling Pennsylvanian sea-level change, whereas within orogenic belts, climate becomes somewhat more subordinate as a driving mechanism for Pennsylvanian sea-level change, even though indicators of climate change itself are preserved.

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Pennsylvanian Cyclothems: Methods of Distinguishing Tectonically Induced Changes in Sea Level from Climatically Induced Changes

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Analysis of tectonic subsidence permits calculation of the magnitude of tectonic processes and associated climatic effects, which controlled changes in sea level during deposition of Pennsylvanian cyclothems. Far-field tectonic effects in response to regional orogenic movements influenced Pennsylvanian sea-level change in the Midcontinent of North America and the Illinois basin. Organization of Virgilian and Missourian Midcontinent cyclothems into fourfold to fivefold bundles shows that sea-level changes in Midcontinent platform areas were influenced partly by Milankovitch orbital parameters, whereas Desmoinesian sea-level change apparently was influenced more strongly by tectonic subsidence. Sea-level change associated with cyclothems in the Central Appalachian basin and the Asturias basin of Spain were controlled mostly by foreland-basin subsidence and later strike-slip faulting. Methods developed herein permit calculation of magnitudes of both tectonic and glacio-eustatic components of sea-level change influencing Pennsylvanian cyclothem deposition and may be applicable to other cyclic sequences.

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Diagenesis of Upper Pennsylvanian (Missourian) Galesburg Sublitharenites, S.E. Kansas and N.E. Oklahoma

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The Upper Pennsylvanian (Missourian) Galesburg sandstones of southeastern Kansas and northeastern Oklahoma were deposited in fluvial-deltaic complexes during a marine lowstand. Analyses of core and outcrop samples show that sandstone units are fine-grained to very fine-grained sublitharenites. Lithic fragments

consist primarily of muscovite schist. In addition, significant amounts of muscovite and feldspar grains are present in these sandstones.

The composition and texture of Galesburg sandstones were substantially altered by the effects of meteoric and compactional regime diagenesis during burial. Soon after deposition, supersaturation of marine connate water within the sands initiated an early stage of calcite cementation in marine-influenced units. In more fluvially influenced units, decaying organic matter increased the acidity of meteoric waters promoting the alteration of feldspars to kaolinite and illite. Subsequent compaction of Galesburg sediments provided a flush of compactional waters, and more significantly, allowed ions liberated from clay diagenesis in adjacent shales to be transported through permeable Galesburg sandstones. Precipitation of quartz overgrowths occurred early within the compactional regime as waters became enriched in silica ions released from the diagenesis of mixed-layered clays and from the continued alteration and partial dissolution of detrital feldspar and mica grains. Late-stage conversion of mixed illite/smectite clays to illite liberated iron and magnesium ions. These ions played an important role in kaolinite to aluminous chlorite conversion and in late-stage ferroan calcite cementation. Subaerial exposure of Galesburg sandstones resulted in the weathering of ferroan carbonates and the formation of secondary porosity and iron oxide precipitates.

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Paleogeography of the Upper Pennsylvanian (Missourian) Galesburg Shale, S.E. Kansas

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In southeastern Kansas, the Upper Pennsylvanian (Missourian) Galesburg Shale consists of siliciclastics deposited during a marine lowstand. It is bounded by two transgressive units, the underlying Mound Valley Limestone and the overlying Canville Limestone. Lithofacies analysis of the Galesburg based on data from outcrop sections, well cores, and geophysical well logs, suggest that this formation records prograding lobate, fluvial-dominated deltaic complexes.

Seven lithofacies were recognized in the Galesburg Shale: (1) very fine to fine-grained, calcite-cemented sandstone; (2) fine to medium-grained, cross-stratified sandstone; (3) interstratified convoluted shale, siltstone and sandstone; (4) bioturbated siltstone and carboniferous shale; (5) a blockly mudstone commonly overlain by a thin coal; (6) fossiliferous (marine) shale; and (7) thinly laminated clay shale. Internal characteristics and lateral and vertical relationships with other lithologies suggest that these 7 lithofacies represent: (1) distributary mouth bar/delta-front sand; (2) distributary channel sands; (3) interdistributary bay/crevasse splay deposits; (4) interdistributary bay fill; (5) marsh or swamp deposits; (6) open marine muds; and (7) prodeltaic muds, respectively.

Isopach maps and cross sections indicate that the Galesburg Shale thickens southward towards the Oklahoma border where it has been recognized as an interval in the upper portion of the Coffeyville Formation. The fine-grained prodeltaic and

open marine lithofacies are more commonly found to the north while thicker, coarser-grained lithofacies thicken to the south. Sandstone isolith maps show that the thickest sands were deposited in narrow, north–south oriented elongated bodies that thin northward. These characteristics suggest that the Galesburg sediments were derived from a southern source area and that the deltaic deposits prograded northward as an extension of Coffeyville deposition. Sandstones have high percentages of muscovite schist fragments as well as mica grains suggesting that they were derived from the Ouachita Fold-Thrust Belt in southern Oklahoma.

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Morphologic Evolution in Early Missourian (Pennsylvanian) Species of *Idiognathodus* and the Origin of *Streptognathodus* (Conodonts)

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A distinctive clade of *Idiognathodus* species characterizes lower Missourian strata in the North American Midcontinent region. The morphology of these forms is the result of paedomorphosis, where features characteristic of small (juvenile) Pa elements of Desmoinesian species were progressively retained in large (adult) Pa elements of Missourian species. Understanding of the evolution and correct taxonomic placement of these forms is possible only by careful consideration of morphology relative to element size.

The earliest Missourian species, *Idiognathodus sulciferous* Gunnell, possesses a long carina, large lobes with coarse nodes, and continuous posterior transverse ridges. In younger strata, a complex series of partially intergrading morphotypes appear, all characterized by modifications of the upper platform surface: *I. eccentricus* (Ellison), with an eccentric longitudinal groove; *I. clavatulus* (Gunnell), with a deep medial groove; and *I.* n. sp., which has a nodose carina extending the length of the platform, and flanked on both sides by shallow longitudinal grooves.

The oldest species of *Streptognathodus, S. cancellosus* (Gunnell) appears in the third major Missourian marine cycle (Swope/Hushpuckney). The dominance of flaring adcarinal ridges, reduced to absent lobes, and a medial row of carinal nodes, all juvenile features of *I.* n. sp., characterize the Pa element. The dominance of the adcarinal ridges and their continuation posteriorly as high outer platform margins are the diagnostic characters of *Streptognathodus.* Two separate clades characterize younger Missourian marine intervals: *Idiognathodus* with regular transverse posterior ridges (*I. magnificus* group) and *Streptognathodus* with flaring adcarinal ridges and a clear medial groove (*S. gracilis* group). Many authors claim intergradation between the two genera as a result of erroneously comparing the adult morphology of *Streptognathodus* with the juvenile morphology of *Idiognathodus.*

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Lower Ordovician Conodonts from the Reelfoot Basin, Southern Midcontinent, U.S.A.

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Early Ordovician conodonts recently recovered from the subsurface in the Reelfoot basin of the mid-Mississippi River Valley permit some preliminary correlations with coeval exposed sequences of the Midcontinent and elsewhere. For the lower, middle, and much of the upper part of the Ibexian Series, faunas are typical of shallow, warm-water platform carbonate depositional environments. Correlations can be made with the Knox, Arbuckle, and Prairie du Chien Groups, and with the Ozark shelf sequence. Uppermost Ibexian rocks and faunas generally are quite different, however, from those of adjacent Midcontinent sequences. The highest preserved Ibexian strata encountered in the subsurface consists of dark gray, argillaceous lime mudstone to wackestone containing some species typical of the North American Midcontinent Province *Oepikodus communis* Zone, but also containing species indicative of cooler and (or) deeper environments. Some of the latter species are cosmopolitan in distribution and some indicate correlation with the North Atlantic Province *Oepikodus smithensis* Zone. Typical restricted-shelf species of the *Diaphorodus* biofacies are absent; however, typical North Atlantic Province indicators *O. smithensis* and *Periodon* also are absent. Several of the species present in this interval are characteristic of the middle Arenigian sequence of the Precordilleran region of Argentina, where the sedimentological sequence also is dominated by cooler, deeper lithofacies and faunas. Thus, the conodont faunas from the upper Ibexian interval of the Reelfoot basin indicate that this area had free communication with the open ocean and limited influence from the restricted-circulation shallow cratonic seas immediately to the west, north, and east.

The Reelfoot basin conodonts display anomalously high color alteration index (CAI) values for their present burial depths. Estimates of former deeper burial are inadequate to account for the observed CAI values; therefore, high regional heat flow, proximity to intrusions, and (or) passage of hydrothermal fluids must have been contributory factors.

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Ichnological Recognition of Transgressive/Regressive Events in Mixed Carbonate–Siliciclastic Depositional Systems: Early Permian, Midcontinent, U.S.A.

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Early Permian rocks (Chase Group) of north-central Oklahoma are characterized by cyclic sequences of mixed carbonates and siliciclastics composed of repetitive carbonate-shale couplets. Regressive parts of the sequences are much thicker, more clastic-rich than transgressive parts of the sequences and characterized by nonmarine to marginal marine mudstones/shales capped by ubiquitous exposure surfaces and paleosols. Transgressive parts of the sequences are thinner, more carbonate-rich and composed of chert-bearing limestones.

Ichnologically, the sole of the lowest (first) transgressive carbonate bed is ubiquitously covered with horizontal boxworks of *Thalassinoides* constructed as excavations into the underlying regressive mudstones. These networks demarcate a discontinuity surface at the base of the casting marine limestone marking the culmination of a regressive event and the initial onset of a transgressive event. The burrow-fill skeletal concentrates indicate a truncation surface associated with a storm event bed in which storms have selectively pumped coarser skeletal material into the burrow networks.

Cast on the top bedding plane surfaces of the highest (last) carbonate unit are horizontal forms of the trace fossil *Rhizocorallium* marking the culmination of a transgressive event and the initial onset of a regressive, above wave-base event. The cast *Rhizocorallium* burrows indicate only minor event erosion as opposed to the *Thalassinoides* systems.

Caution must be employed when correlating trace fossil marker horizons with major eustatic events. Discontinuity surfaces may not necessarily correspond to regionally important sequence stratigraphic boundaries but can also develop in response to autocyclic processes including episodic storm erosion.

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Conodont and Ichnofaunal Changes Across the Frasnian–Famennian Boundary (Late Devonian) Within the Lower Woodford Shale, Oklahoma

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The Woodford Shale in south-central Oklahoma was deposited in an offshore, quiet-water, oxygen-poor setting on the southern margin of North America. The basal Woodford consists of quartzose sand, phosphate and limestone pebble conglomerate, and green-brown shale deposited unconformably over lower Paleozoic carbonates as a south to north transgressive unit during the Frasnian and early Famennian. Dark-colored organic-rich shales and cherts directly overlie the basal beds.

The Frasnian–Famennian boundary lies within the lower 12 m of the Woodford Formation in the Arbuckle Mountain region. Frasnian strata is thickest in the southernmost exposures, thinning to less than 1 meter locally and on the Lawrence Uplift. The boundary is recognized by the extinction of species of *Ancryodella* and *Palmatolepis linguliformis,* the occurrence of *Ancryognathus ubiquitus* and *Pa. praetriangularis,* which are indicative of the boundary interval, and the appearance of *Pa. triangularis.* The Frasnian–Famennian boundary is recognized to a discrete horizon in three separate sections where it is marked by a conodont lag deposit and thin layer of phosphate nodules. Conodont faunas change from a palmatolepid fauna characteristic of offshore biofacies below the boundary to a more nearshore palmatolepid–polygnathid fauna across the boundary, and back to a palmatolepid biofacies above the boundary. The change in conodont biofacies and coarse-grained beds at the boundary are indicative of higher energy conditions related to a fall in sea level associated with the Frasnian–Famennian boundary interval.

The benthic- and ichnofauna from the boundary beds indicate a progressive change in substrate and bottom water dissolved oxygen concentration from dysoxic to anoxic. On the Lawrence Uplift black shales directly above the basal coarse clastic beds contain *'Lingula'*, *Planolites,* and *Chondrites* that are characteristic of dysoxic conditions, and very small vermiform burrows (~0.2 mm in diameter). This fauna extends upward to the Frasnian–Famennian boundary. Above the boundary horizon only the small vermiform burrow structures persist, indicating a decrease in bottom water and benthic dissolved oxygen content that may be related to sea level rise and transgression of an oxygen minimum zone in the early Famennian.

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Morrowan–Atokan (Early Pennsylvanian) Conodonts of the Dimple Limestone, Marathon Basin, Texas

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An apparently continuous sequence of conodont faunas across the Morrowan–Atokan boundary is preserved in the Dimple Limestone. Evolution within the genus *Idiognathodus* provides a biostratigraphic basis for subdivision of the Dimple into five faunal intervals. Intervals A and B are recognized on the occurrence of morphotypes of *I. sinuosus.* Interval C is recognized by the appearance of *I. klapperi*, and Intervals D and E are recognized by first occurrences of morphotypes of *I. incurvus.* The appearance of *Idiognathodus incurvus* occurs elsewhere at or near the base of the Atokan (Grayson, 1990), and in the absence of Zone 21 foraminifers, may be a reliable indicator of this boundary.

Conodont faunas of the Dimple Limestone are dominated by Pa elements of *Idiognathoides* (55%), *Idiognathodus* (14%), and *Declinognathodus* (7%), with lesser numbers of *Neognathodus, Neogondolella,* and "naked" gondolellids. The holotype of *D. noduliferus,* the genotype of *Declinognathodus,* is a juvenile specimen, and it is unclear if it belongs to the few, apparently reworked specimens of *D. noduliferus,* or to the more common, indigenous Dimple species, *D. nevadensis* Dunn. Ramiform elements, including those of *Idioprioniodus,* make up about 12% of the fauna, and older reworked conodonts comprise about 7%. Reworked conodonts represent several discrete intervals of time: Frasnian–Fammenian and Kinderhookian forms from the Woodford Shale, and Chesterian and lower Morrowan forms from the Barnett Shale.

During submarine canyon downcutting, shelf allochems of late Morrowan–early Atokan age were mixed with the debris from the older cratonic shales. This material was transported down submarine channels into the basin for incorporation into the Dimple turbidites. Unlike correlative parts of the Wapanucka and lower Atoka Formations of Oklahoma, the Dimple Limestone shows no evidence of the regional unconformity that occurs elsewhere at the Morrowan–Atokan boundary.

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Potential for Producing Oil and Gas from the Woodford Shale (Devonian–Mississippian) in the Southern Mid-Continent, USA

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The Woodford Shale is a prolific oil source rock throughout the southern mid-continent of the United States. Extrapolation of thickness and organic geochemical data based on the analysis of 614 samples from the region indicate that on the order of 100×10^9 bbl of oil (300×10^{12} ft^3 of natural gas equivalent) reside in the Woodford in Oklahoma and northwestern Arkansas. The Woodford in west Texas and southeastern New Mexico contains on the order of 80×10^9 bbl of oil (240×10^{12} ft^3 of natural gas equivalent).

Tapping this resource is most feasible in areas where the Woodford subcrop contains competent lithofacies (e.g., chert, sandstone, siltstone, dolostone) and is highly fractured. Horizontal drilling may provide the optimum exploitation technique. Areas with the greatest potential and the most prospective lithologies include (1) the Nemaha uplift (chert, sandstone, dolostone), (2) Marietta–Ardmore basin (chert), (3) southern flank of the Anadarko basin along the Wichita Mountain uplift (chert), (4) frontal zone of the Ouachita tectonic belt in Oklahoma (chert), and (5) the Central Basin platform in west Texas and New Mexico (chert and siltstone).

In virtually all of these areas, the Woodford is in the oil or gas window. Thus, fracture porosity would be continuously fed by hydrocarbons generated in the enclosing source rocks. Reservoir systems such as these typically have produced at low to moderate flow rates for many decades.

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Developing and Extending Oil and Gas Fields Without Use of Computers, Remote Sensing, Seismic, and Nonconventional Methods

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Most of the geologists who work either as independents or for nonmajor oil companies do not have access to sophisticated seismic data, remote sensing information, and computer-derived maps. Nevertheless, geologists at small companies, such as Cross Timbers Oil, continue to extend oil and gas fields, and develop significant new reserves. They manage to do this by using the same tools (observation and deduction) used by geologists who worked the Permian basin before the 1970s, with the synergistic addition of input from engineers and production personnel. To paraphrase Wallace Pratt, these oil and gas reserves are being found in the minds of engineers, geologists, and production people who are working as a team. The team has had to overcome log analyses that were wrong due to incorrect conclusions about the composition of reservoir beds, miscorrelations of the reservoirs due to use of erroneous geological models, and disastrous completion techniques used by majors and independents. These errors were overcome by rational thinking.

Several stratigraphically trapped oil and gas fields in the Knox–Baylor basin of north Texas and on the Anadarko shelf of Oklahoma were extended by using only basic geologic and engineering concepts. The concepts may be useful for geologists who work in the Permian basin.

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Karst-Related Diagenesis and Reservoir Development in the Arbuckle Group, Wilburton Field, Oklahoma

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Wilburton field is a multizone reservoir on the southwestern edge of the Arkoma basin. The most recent zone to be declared commercial is the Cambrian–Ordovician Arbuckle Group. Faults, structural position, depositional environment, and diagenetic alterations play a role in controlling reservoir quality, communication of fluids and pressures within the reservoir, and stratigraphic correlations.

The Arbuckle Group in Wilburton field consists of dolomite, calcareous dolomite and minor clastic-rich intervals, chert, and dolomitic limestones. The depositional environment was a low-energy, shallow, subtidal to intertidal setting resulting in deposition of a thick sequence of lime muds. Early diagenesis consisted of pervasive dolomitization that created a dolomudstone with low (12%) intercrystalline porosity. Other types of secondary porosity (vugs, fractures, breccias) also are important to reservoir behavior.

The regionally extensive Middle Ordovician unconformity, which occurs at the top of the Arbuckle Group, exposed that carbonate surface to meteoric conditions that resulted in formation of karst. The porosity development or enhancement associated with karsting modified depositional textures and their related pore geometries. One such modification was the development of breccias within the Arbuckle caused by freshwater solution, weakening, and collapse of the overlying rock. The three types of breccias present in Wilburton field include in-situ, clast-supported and matrix-supported breccias. Following brecciation, burial cements (rhombic dolomite, baroque dolomite, coarsely crystalline calcite, and coarsely crystalline quartz) precipitated during and after hydrocarbon migration.

Stratigraphically, the Arbuckle section can be divided into two zones. An upper zone, 200–250 ft thick, is characterized by a lack of fracturing and brecciation, and by fluid flow mainly through the matrix or intercrystalline pore system. Porosity development in these intervals extends across the field. The lower zone is characterized by multiple intervals of fracturing, brecciation (all three types), and solution collapse. With the exception of a single matrix-supported breccia, none of these zones can be correlated across the field with any certainty. The Arbuckle is most likely productive where solution has enhanced intercrystalline, fracture, and breccia porosity, and burial cements have failed to completely fill pore spaces. We anticipate that porosity development in Arbuckle carbonates in other areas is similarly controlled and should be productive.

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Comparitive Ore Microscopy of the Red-Bed Sandstone-Hosted Silver–Copper Deposit at Paoli, Oklahoma, with the Shale-Hosted Copper–Silver Deposit at Creta, Oklahoma

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The Creta copper–silver deposit is located 15 mi southwest of Altus, Oklahoma, was mined from 1965 to 1975, and was the largest shale-hosted copper producer among the red-bed and copper shale deposits of the southwestern United States. The Paoli silver–copper deposit is located 35 mi southeast of Norman, Oklahoma, was intensively drilled from 1967 to 1974, and is characterized by unusually silver contents. Because these two mineral deposits are only 120 mi apart, occur in Permian rocks, and contain similar ore minerals, it is important to compare their textures and modes of formation by ore microscopy.

Both deposits occur within Permian clastic sedimentary rocks, Creta in the Flowerpot Shale (Guadalupean Series), and Paoli in the Wellington Formation (Leonardian Series). The ores at both deposits consist of copper sulfides with some silver. The two deposits contrast especially with respect to their host rocks and geometries. The Creta deposit is hosted largely by shale with minor siltstone and it is remarkably stratabound. The Paoli deposit is hosted largely by sandstone with lesser amounts of shaly siltstone, and it exhibits a roll front shape.

Microscopic study of the ores show that both deposits are epigenetic, and that the ore minerals replace sedimentary and diagenetic minerals in the host rocks. At Creta, copper sulfides replace 120 μm megaspores, 20–40 μm colloform pyrite grains, and 10 μm pyrrhotite crystals. At Paoli, copper sulfides replace 15–200 μm pyrite crystals and grains, 20–110 μm hematite grains and cement, and dolomite cement. Where copper and copper–iron sulfide minerals replace hematite at Paoli, their paragenetic sequence is chalcocite, digenite, bornite, and chalcopyrite. Silver occurs as stromeyerite, argentiferous djurleite, and argentiferous chalcocite at Creta, but as native silver at Paoli.

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Quaternary of the Southern Great Plains, U.S.A.—Paleoclimatic vs. Nonclimatic Paleoenvironmental Indicators

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Quaternary deposits of the southern Great Plains provide a detailed paleoenvironmental record based on litho-, pedo-, and biostratigraphy and dense chronologic control. Most investigators have misread variations in this record as proxy indications of paleoclimate. More likely, paleoenvironment was forced by geomorphic threshholds and groundwater discharge within a relatively narrow climatic spectrum. Quaternary landscape evolution follows a pattern established in the Miocene. Uplift-induced denu-

dation created a vast unconformity lacking Upper Cretaceous–Paleogene deposits. Late Miocene aggradation (fluvial/eolian) produced the Ogallala Formation in the rain shadow of the Southern Rockies/Sierra Madre Occidental. Subsequent dissolution of Permian evaporites caused widespread subsidence, which: (1) enhanced peripheral erosion and valley incision, dividing the Great Plains into the Southern and Central High Plains along the Canadian River; and (2) formed karstic basins that dropped below the water table in the Ogallala aquifer, creating perennial lakes where thick lacustrine sequences (Rita Blanca, Cita Canyon, Tule, and other Pliocene–Pleistocene formations) accumulated over ≤3.5 Ma. Between these lakes, Pliocene–modern eolian deposition produced the Blackwater Draw Formation. Continued subsidence promoted backwasting of the Ogallala, producing the Pecos River Valley and Rolling Plains and leaving broad aprons of sediment (≤120 m thick) that became secondary aquifers. Middle Pleistocene–modern discharge of groundwater into subsidence basins created additional lakes until erosion drained the secondary aquifers or detached them from the Ogallala, lowering water tables. Few lakes remain, but lacustrine deposits preserve Pliocene–Quaternary records of aquatic environments and surrounding watersheds. Uplands remained semi-arid grasslands. Aquatic habitats were sustained by groundwater discharge prior to aquifer dissection.

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Morphology and Evolution of *Neochonetes* and *Mesolobus* (Chonetid Brachiopods), Lower Middle Pennsylvanian, Ardmore Basin (South-Central Oklahoma)

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Neochonetes and *Mesolobus* are common in shale intervals within the upper Dornick Hills (including Bostwick, Shale 3, Lester, Shale 4, Frensley, Shale 5, and Pumpkin Creek Members) and basal Deese (including Shale 6 Member) Groups (Uppermost Atokan, Lower Desmoinesian) of the Ardmore Basin. A succession of four species is recognizable within this stratigraphic interval. The individual species are primarily distinguished by the degree of convexity of the pedicle valve, strength of the sulcus (on pedicle valve) and mesial fold within (if present), and overall size. Each species is highly variable morphologically.

Neochonetes cf. *henryi* (upper Bostwick through middle Shale 3) is a medium-sized form with moderate convexity and moderately developed sulcus in the pedicle valve. *Mesolobus obsoletus* (upper Shale 3 through Shale 6) is a small, highly convex species with a pronounced mesial fold within the sulcus. *Mesolobus striatus* (upper Shale 3 through Shale 6) is represented by medium-sized, gently convex forms with a generally shallow sulcus and low mesial fold. *Mesolobus profundus* (upper Shale 4 through Shale 6) is a medium-sized form with moderate to strong convexity and a pronounced sulcus and mesial fold.

Morphologically and stratigraphically intermediate populations are definitely present between *Neochonetes* cf. *henryi* and *Mesolobus obsoletus*, and *M. striatus* and *M. profundus;* and possibly between *N.* cf. *henryi* and *M. striatus.* Therefore, it is concluded that *N.* cf. *henryi* evolved into two stocks of *Mesolobus,* one represented by *M. obsoletus* and the other by *M. striatus.* Subsequently, *M. profundus* evolved from *M. striatus.*

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Tidal Influence on Depositional Sequences within the Lower Deese Group (Pennsylvanian, Desmoinesian Series) in the Ardmore Basin

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The Lower Deese Group near Ardmore, Oklahoma, consists of fining and coarsening upward sequences interpreted as recording deposition on tidal flats and tidally influenced deltas, respectively. Reactivation surfaces, bi-directional current indicators including herringbone cross-stratification, and flaser to lenticular bedding provide evidence for tides.

The fining upward sequences start with rippled (unidirectional and interference patterns) and flaser bedded sandstones with herringbone cross-stratification, which are interpreted to record deposition on a sandflat. Some sandstone beds contain burrows and tracks. Above the sandstones are alternating wavy to lenticular bedded and mudcracked sandstone and shale units deposited on a mixed flat. Interbedded sandstones in these deposits contain ripple and small scale crossbedded units with opposite directions of flow. The sequences are capped by lenticular bedded mudstones which record deposition on mudflats.

The coarsening upward sequences begin with lenticular bedded mudstones, interpreted as pro-delta deposits, above which are wavy bedded sandstones and shales of a distal delta mouth bar. Some beds have soft sediment deformation structures or hummocky cross stratification. Above these are rippled sandstones, with flaser bedding or herringbone cross-stratification, deposited in tide influenced delta mouth bars. Successive beds have small scale tabular and/or trough cross-bedding indicating alternating flow directions. Some sequences are capped with large-scale and coarse grained crossbedded units from river channels and/or fan deltas.

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