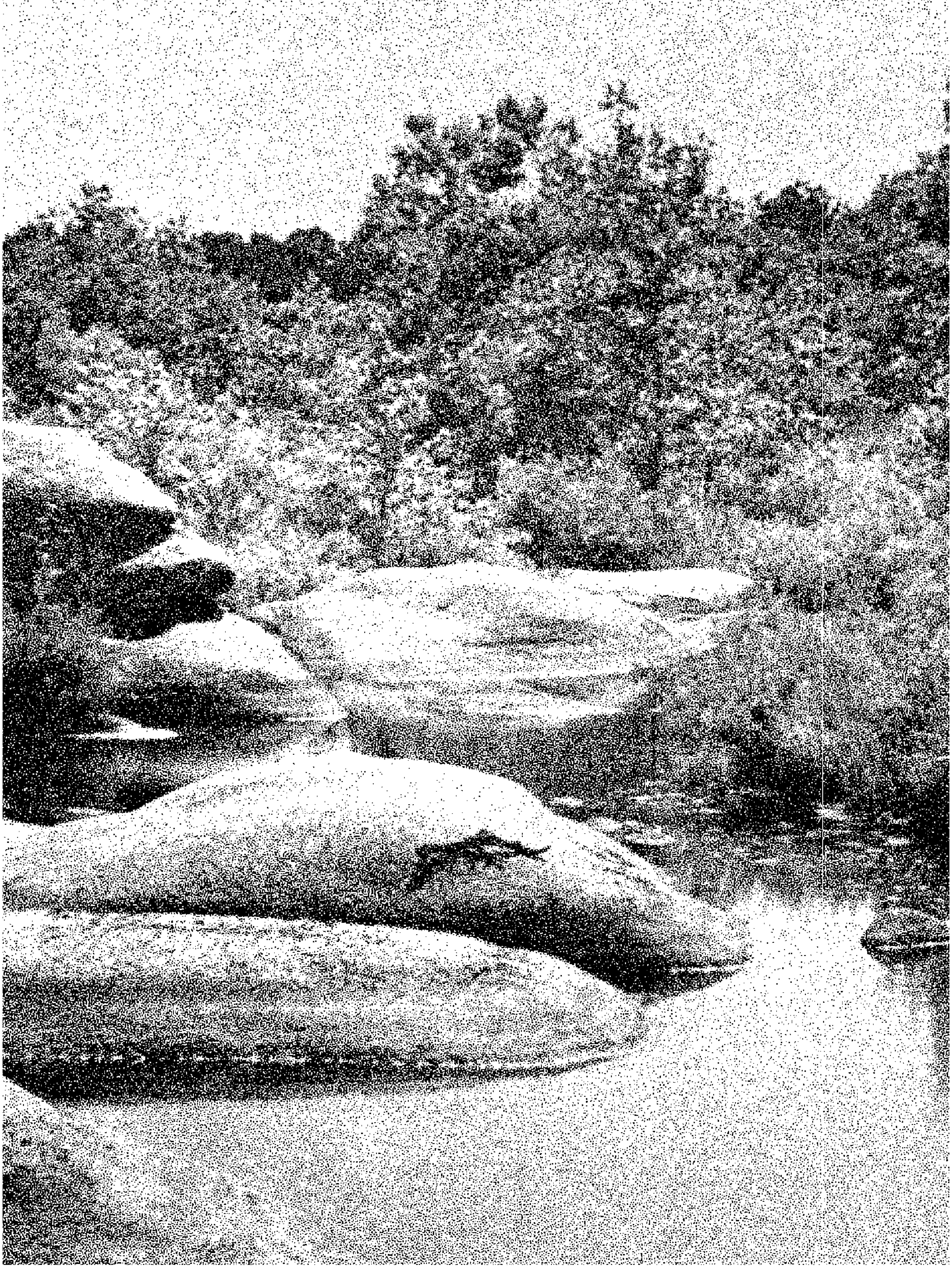
KLAHOMA GEOLOGY NOTES

0030–1736 VOLUME 40 NUMBER 3 June 1980

HOMA GEOLOGICAL SURVEY / THE UNIVERSITY OF OKLAHOMA / NORMAN, OKLAHOMA 7301



Cover Picture

PRECAMBRIAN GRANITE IN THE ARBUCKLE MOUNTAINS

On the cover is shown an outcrop of the Precambrian Tishomingo Granite along Rock Creek in the Arbuckle Mountains of south-central Oklahoma. The outcrop is about one mile east of Troy, in NE¼ sec. 3, T. 3 S., R. 5 E., Johnston County. The Tishomingo Granite, isotopically dated as being 1,260–1,360 m.y. old (OGS Bulletin 95, *Basement Rocks and Structural Evolution of Southern Oklahoma*), is one of the oldest rock units in the State. In southern Oklahoma, it is predated only by the Troy Granite and the Blue River Gneiss, both of which have similar 1,260–1,360 m.y. Precambrian ages but which are intruded by the Tishomingo Granite.

In spite of the strong resistance of the Tishomingo Granite to weathering and erosion, outcrops of the rock unit are characterized by low relief. This results mainly from earlier stages of erosion and planation of the Arbuckle Mountains region: the Arbuckles were deeply eroded and truncated during Late Pennsylvanian and Permian times, and then were nearly peneplained in the south prior to Early Cretaceous sedimentation in the area. The pre-Cretaceous erosional surface is now being exhumed in the south part of the Arbuckle Mountains, and modern streams and rivers are carving new relief into the main granite outcrops.

—Kenneth S. Johnson

Editorial staff: William D. Rose, Elizabeth A. Ham, Connie Smith

Oklahoma Geology Notes is published bimonthly by the Oklahoma Geological Survey. It contains short technical articles, mineral-industry and petroleum news and statistics, an annual bibliography of Oklahoma geology, reviews, and announcements of general pertinence to Oklahoma geology. Single copies, $1.00; yearly subscription, $4.00. All subscription orders should be sent to the address on the front cover.

Short articles on aspects of Oklahoma geology are welcome from contributors. A set of guidelines will be forwarded on request.

This publication, printed by The University of Oklahoma Printing Services, Norman, Oklahoma, is issued by the Oklahoma Geological Survey as authorized by Title 70, Oklahoma Statutes 1971, Section 3310, and Title 74, Oklahoma Statutes 1971, Sections 231-238. 1,800 copies have been prepared for distribution at a cost to the taxpayers of the State of Oklahoma of $2,545.

OBSERVATIONS AND INTERPRETATIONS CONCERNING QUATERNARY GEOMORPHIC HISTORY OF NORTHEASTERN OKLAHOMA

LeRoy A. Hemish[1]

Abstract–Landscape elements observed in northeastern Oklahoma during the course of a project of mapping Pennsylvanian (Desmoinesian) coal deposits have led me to hypothesize a semiarid paleoclimate in that area during late Quaternary time. Buried geomorphic features analogous to landforms typical of semiarid environments were noted during investigations of highwalls in open-pit mines, and again while constructing cross sections from coal-exploration drill logs. These features include high-angle scarps, debris slopes, pediment-like aprons, and deeply incised, partly filled stream valleys.

Introduction

The purpose of this paper is to direct attention to an assemblage of buried landforms revealed by removal of overburden in the coal strip pits of northeastern Oklahoma. Evidence for the past existence of these geomorphic structures came to my attention during an Oklahoma Geological Survey project of mapping Pennsylvanian (Desmoinesian) coal deposits that was conducted in Craig, Nowata, and Rogers Counties (fig. 1) in 1978–79.

The nature of several features observed in the highwalls of various strip mines in the area led me to hypothesize that these features were formed at a time (likely, during the Quaternary Period) when the climate was more arid than it is at present. Admittedly, discussion here is brief and based on rather general impressions. Also, my study is largely qualitative in nature and does not rest on precise quantitative work. A paucity of information exists in the literature, however, concerning the Quaternary geomorphology of Oklahoma, and I hope my hypothesis will evoke some interest in the topic and will perhaps generate further discussion and propagate additional investigations.

Climatic Geomorphology

Changes of climate can produce recognizable forms in the landscape, and it appears that, as the result of climatic changes during the past few millenniums, landform features characteristic of the warm, humid climate that prevails at present in eastern Oklahoma have been superimposed on landforms characteristic of a semiarid climate that prevailed sometime in the past. Coal-mining activities in Craig, Nowata, and Rogers Counties have

[1]Geologist, Oklahoma Geological Survey.

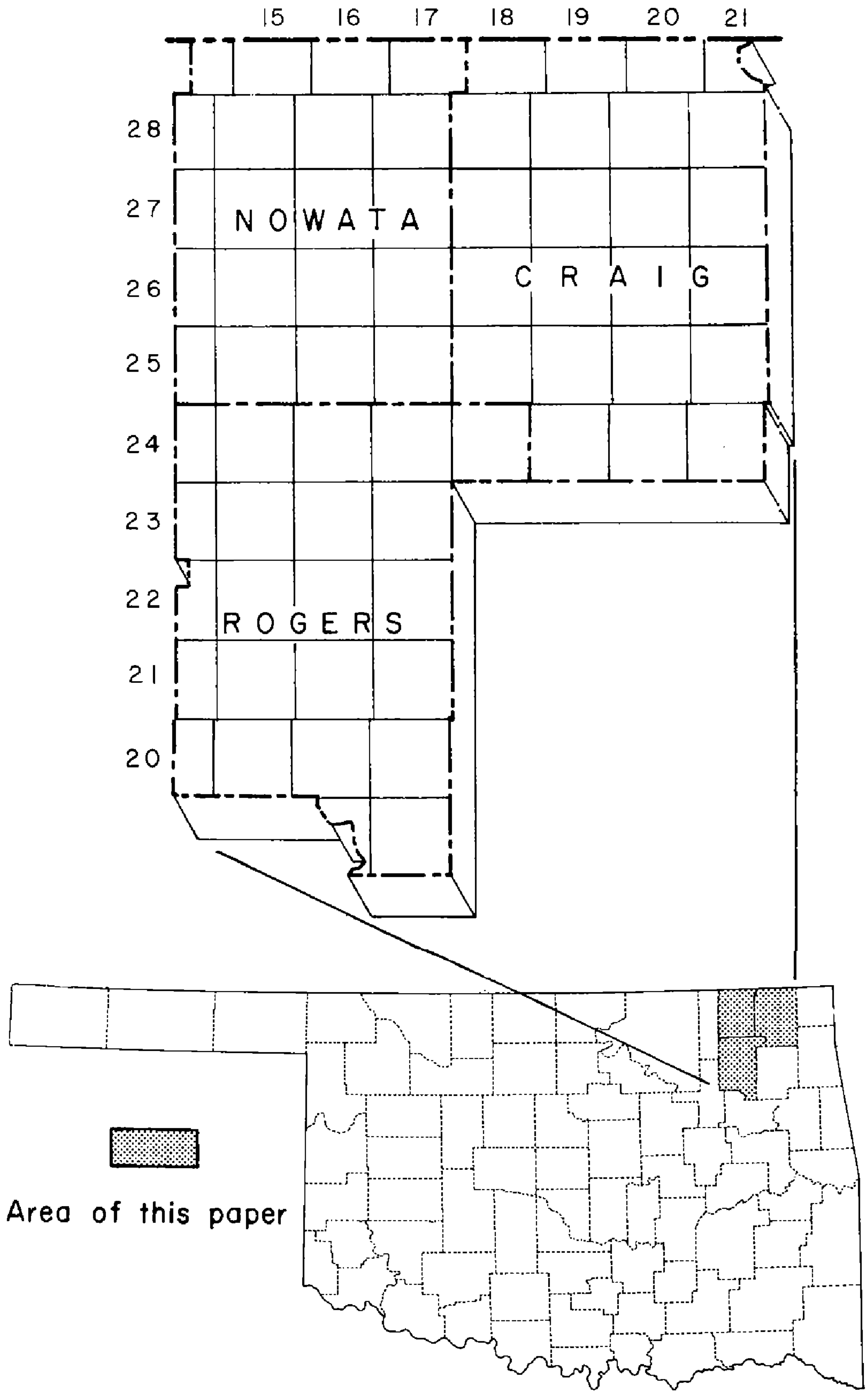


Figure 1. Map of Oklahoma showing location of Craig, Nowata, and Rogers Counties.

revealed evidence of many of these features (see figs. 3–8). Climatic geomorphology deals with the study of such phenomena.

Stoddart (1969, p. 163) stated that climatic geomorphology includes two distinct concepts: climatic geomorphology and climato-genetic geomorphology. The first postulates that different climates, by affecting processes, develop unique assemblages of landforms. The second concept, climato-genetic geomorphology, is based on demonstrable climatic changes, which result in landforms that bear the imprint of climates no longer operative in the area. Systematic climatic geomorphology is the analysis of processes and forms and their relationship to climate; climato-genetic geomorphology is the historical analysis of particular areas. Both concepts are pertinent to my study.

In a discussion of climate and erosion history, Stoddart (1969, p. 202) introduced the principle of succession:

> that a given climate, developing a given assemblage of landforms, will leave an imprint on the landscape which will not immediately be erased by subsequent climates. Landscapes which have undergone . . . climatic changes will, therefore, contain elements of . . . different morphoclimatic landscape assemblages.

This concept is discussed later in connection with morphoclimatic interpretations of specific landscapes illustrated in figures 3–8.

Climatic geomorphology is a complex and controversial topic that goes back to Davis (1899), who recognized that distinctive assemblages of geomorphic processes and landforms occurred in areas of specific climates in different parts of the world. While climatic factors are important in the shaping of a landscape, landform geometry results from an interplay of many variables, including climate, lithology, structure, time, soils, vegetation, precipitation, and runoff (Schumm, 1969; Stoddart, 1969; Wilson, 1969). Indeed, King (1967, p. 158) argued that the concept of climatic control of landforms is a fallacy, and that classifications of landforms based dominantly on "climatic" influences have little value. Further discussion of the pros and cons of the topic are beyond the scope of this paper.

Humid- Versus Arid-Climate Landscapes

As previously stated, I believe the evidence indicates that relicts of elements of a landscape formed under semiarid conditions in northeastern Oklahoma are masked by elements of a landscape formed under present-day humid-temperate conditions in the area. Figure 2 shows the morphologic elements of a hillslope formed under arid or semiarid conditions. Mabbutt (1977, p. 39) stated that climate is the controlling influence in the evolution of hillslope features. In arid climates, the topography is generally characterized by a lack of slopes of intermediate angle. The summit, or crest of the hill, is typically capped by resistant rock and has a low-angle, rounded profile. Wherever this caprock protects a softer layer, a scarp forms (fig. 2), with scarp

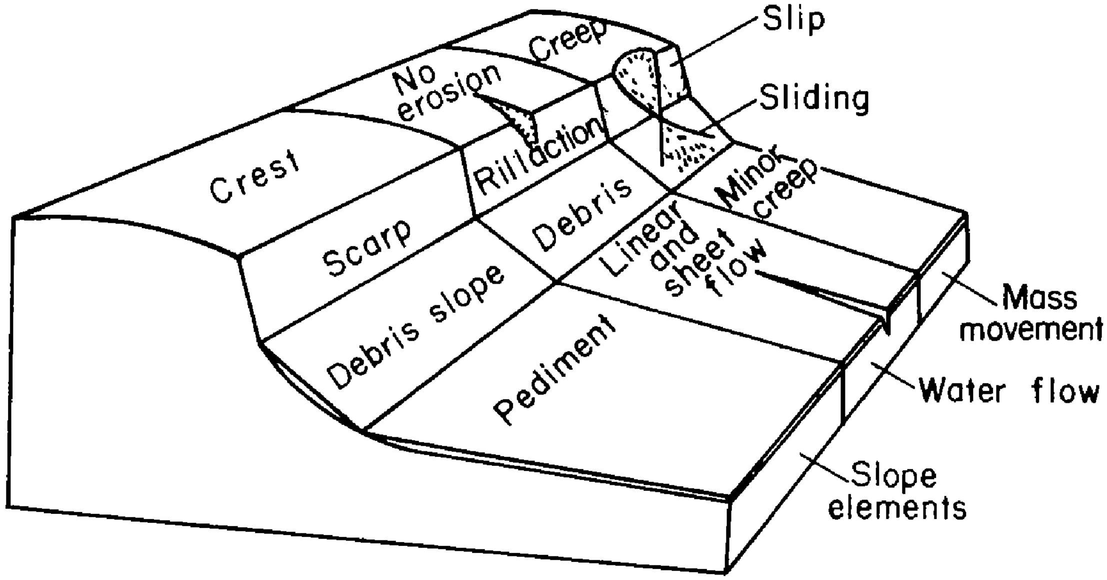


Figure 2. Elements of hillslopes typical of arid and semiarid environments. From King (1957, p. 141).

angles tending to range from 15° to 45°, depending on the lithology of the strata (Mabbutt, 1977, p. 41). In arid or semiarid environments, landscapes evolve by the parallel recession of escarpments, and slope angles are maintained (Penck, 1924).

Land waste produced in the upper part of a steep slope is washed downward onto the lower part. The velocity of the surface wash is checked, and detritus is deposited on the debris slope (fig. 2) as the level of a neighboring stream is approached (King, 1967, p. 140).

As figure 2 shows, the pediment is the flat zone below the debris slope. The term pediment was first used by McGee (1897) to describe piedmont plains in the Sonoran Desert of Arizona. Mabbutt (1977, p. 82) defined a pediment as "a piedmont plane cut in bedrock and separated from the backing hillslope by an abrupt change of gradient." The pediment can be subaerial or covered by a mantle of detritus, in which case it is called a mantled pediment.

Holmes (1955, p. 379) contrasted geomorphic development in humid and arid regions, stating that field facts obviously show "that parallel slope retreat prevails in the more arid regions and that gradual reduction in slope angle is the rule in more humid regions." With an increase in annual precipitation, the density of vegetation increases (Langbein and Schumm, 1958, fig. 7). Schumm (1969, p. 528) said that "changing type and density of vegetation exert a major control on landforms." Antevs (1955, p. 317) stated that "the character of the geologic activity of streams varies with moisture conditions. A dividing line is located between subhumid and semiarid climates." During a subhumid climatic phase, streams erode their valleys because they have large volume and because with ample vegetation the runoff contains relatively little detritus. When the climate turns semiarid, ground cover becomes less dense, erosion increases, and stream flow decreases. The filling of stream channels occurs when the running water becomes unable to transport the increased debris load (see Antevs, 1955, p. 317–318).

Peltier (1962, fig. 10) described a complex relationship between drainage density and climate, stating that stream frequency is greater in semiarid areas (4 drainageways per mile) than in humid-temperate areas (3 drainageways per mile). In humid-temperate areas, the amount of rainfall is higher than it is in semiarid areas, but drainage density is lower because runoff is inhibited by vegetation. Schumm (1969, p. 529) also noted that with a shift to wetter climate, vegetation becomes denser, and the smaller channels are obliterated. Langbein and Schumm (1958, p. 1076) stated that sediment yield is greatest at about 10 to 14 inches of precipitation (semiarid climate), decreasing on both sides of this maximum, because of a deficiency of runoff with lesser amounts and an increase in vegetation with greater amounts of precipitation.

It has been stated previously that gradual reduction in slope angle is the rule in humid regions. Louis (1957, p. 159) called this type of fluvial landscape the *Flachmulden* (gently moulded). Steep slopes are worn down when weathering processes are powerful. Running water carries waste material into natural depressions that fill when the mechanical energy of the water is used up in transporting the mass of sediment. The resultant topography is composed of slopes of varying inclination, with slopes generally convex in their upper parts and concave in their lower parts. The slopes are covered by a layer of detritus and weathered material and are protected by a continuous plant cover (see Birot, 1968, p. 10). An identical situation exists in northeastern Oklahoma at the present time.

Holmes (1955, p. 379–380) summarized the differences between humid and semiarid landscapes:

> In humid regions vegetation impedes both erosion and rate of runoff, resulting in significant contrasts with arid-climate landscapes. (1) Equilibrium wash slopes are under the dual control of vegetation and sediment transport over them, and in consequence are steeper than corresponding vegetation-free slopes; whereas valley sides (the chief gravity slopes) are generally less steep. (2) The more complete drainage network creates a correspondingly greater total length of valley sides, and therefore a more varied and intricate areal pattern in which slope retreat may go on. (3) From the beginning of an erosion cycle, rills and sheet runoff slowly lower the upland surface and round off the upper edges of valley walls, creating the characteristic convex portion of the transverse profile. (4) The strong but partial and inconstant control by vegetation gives rise to slopes of various intermediate degrees of steepness.

Holmes (1955, p. 379) defined wash slopes as graded surfaces of sediment transport (debris slopes and pediments of arid and semiarid regions) and gravity slopes as surfaces that supply the sediment (scarps of arid and semiarid regions).

Wilson (1969) discussed the relationship of climate types, geomorphic processes, and resultant landscape features. Table 1 is an excerpt from Wilson (1969, table 15.2) that shows some of the differences in geomorphic processes and landscape characteristics between the semiarid environment and the humid-temperate environment. It is noteworthy that in semiarid environments, mechanical weathering is dominant and the resultant rock fragments are coarse grained and angular. In humid environments, chemical weathering is dominant and the resultant particulate matter falls largely into the clay-size range.

Wilson (1969, p. 275) stated that maximum fluvial erosion occurs under semiarid conditions, particularly in association with seasonal aridity. Steep slope angles are maintained on scarps, and products of mechanical weathering are periodically moved downward into the debris zone during times of intermittent heavy rainfall.

In contrast, in humid climates the characteristic geomorphic process (creep) is a slow downslope movement of superficial soil or rock debris, which is usually imperceptible except through long-term observation (Douglas, 1977, p. 73). Displacement of soil particles occurs through the effect of intergranular forces that change the strength and stability of the soil or regolith. Such movements are affected by gravity and seepage water and by changes in pore space with depth. Permeability characteristics also vary in the vertical direction, with permeability decreasing at the junction of weathered rock and unweathered rock. This abrupt fall in permeability creates a perched water table, which, after prolonged heavy rain, produces a saturated soil body above the bedrock and gives rise to mass movement of the soil body downslope (Douglas, 1977, p. 57–58).

TABLE 1.—SIMPLE MORPHOGENETIC SYSTEMS

Extracted from Table 15.2 of Wilson (p. 276 in Derbyshire, 1973)

System name	Dominant geomorphic processes	Landscape characteristics
Semiarid	Running water Weathering (especially mechanical) Rapid mass movements	Pediments, fans Angular slopes with coarse debris Badlands
Humid-temperate	Running Water Weathering (especially chemical) Creep (and other mass movements)	Smooth slopes, soil covered Ridges and valleys Stream deposits extensive

The significance of the preceding discussion will become more apparent in the following section, which deals with interpretations of my observations in the study area.

Evidence and Interpretations

Figure 3 shows two diagrammatic profiles of the Plumb Creek valley area in secs. 3 and 4, T. 24 N., R. 17 E., Rogers County, Oklahoma. Logs of coal-test drilling done in the area by Carbonex Coal Co. have made it possible to construct cross sections for interpretation of the subsurface stratigraphy. The Pennsylvanian unit underlying the Quaternary deposits is the Senora Formation of Desmoinesian age. As the accompanying location map (fig. 3) shows, extensive areas are present in the valley where the Croweburg coal has been cut out by erosion. (It should be noted here that my observations during the course of this study were made primarily at sites where the Croweburg coal, or in one instance a combination of the Croweburg, Fleming, and Mineral coals, was being mined. These sites were selected because the topographic expression of the landscape in the area has evolved in response to the lithology of the stratigraphic units and the regional structure. Resistant rocks in the overlying Fort Scott Formation or the upper part of the Senora Formation cap outliers or dip slopes of prominent cuestas that rise above low-lying shale plains. The Croweburg coal generally subcrops in the regolith-mantled hillslopes between the resistant caprock units and the shale plains, or streams eroding into the shale. It is for this reason that stripping operations concentrating on the Croweburg coal are situated in places where evidence of a past semiarid climate such as I have suggested is most likely to be preserved.)

An examination of the profiles of Plumb Creek valley (fig. 3) shows that most of the elements diagrammed by King (1957, p. 141) (see fig. 2) are present beneath a thick cover of weathered, displaced material. I have interpreted the deposits of gravelly detritus found at the base of buried scarps as constituting the debris slope. An alternate interpretation could be that they are terrace remnants associated with the evolution of Plumb Creek valley. Log descriptions of the lithology, observations of bedding characteristics, and present-day surface expression of the land, however, are not suggestive of terraces.

It is clear from studying the diagrams in figure 3 that a pre-existing stream has cut deeply into the bedrock in the area. Since that time, products of mass wasting and running water have filled the old valley to depths of up to 20 feet. I believe this occurred during a time when semiarid climatic conditions prevailed in the area. With the onset of more humid conditions, Plumb Creek and its tributaries once again began cutting into the valley-fill deposits. Through time, the present-day valley profile has evolved.

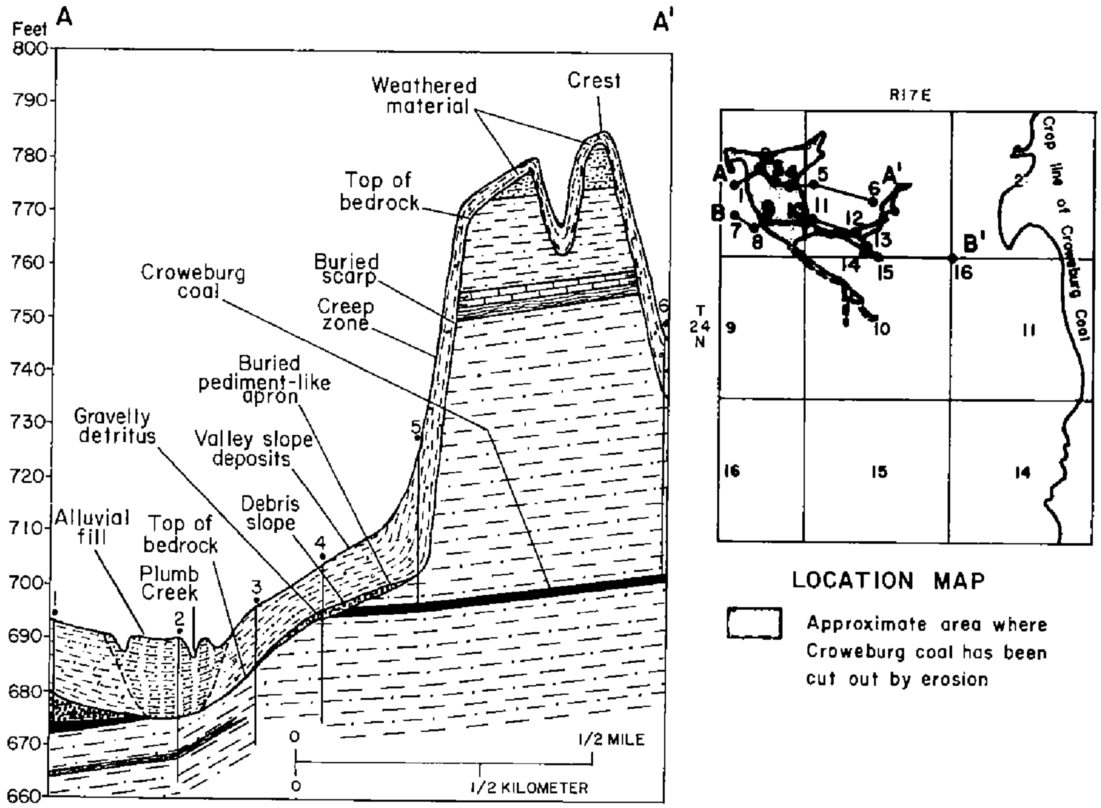


Figure 3. Diagrammatic profiles of Plumb Creek valley, Rogers County, showing sections of Pennsylvanian (Desmoinesian) Senora Formation and overlying Quaternary deposits.

Through application of Stoddart's (1969, p. 163) concept of climatogenetic geomorphology (historical analysis of a particular area), we can readily see that his principle of succession (1969, p. 202), as discussed earlier, is exemplified by the diagrams in figure 3. A former semiarid climate has created landforms that have left an imprint on the present-day landscape. The existing valley profile shows that many elements of the semiarid climate have not been erased by the change to more humid conditions. For example, the angle of the hillslopes has been reduced to some extent but is still quite steep; the configuration of the buried pediment-like features is reflected in the present-day landscape; and knickpoints at the base of buried scarps can still be identified.

Figures 4–8 are diagrammatic sketches made from observations of highwalls in various coal strip mines in the study area. Their purpose is to show geologic features that, I believe, lend support to my interpretations of the area's geomorphic history. It should be noted that contacts between the regolith and the unweathered bedrock surface are not always as sharp as the illustrations portray; the contact is commonly gradational because of many geologic variables that affect weathering processes and mass movements.

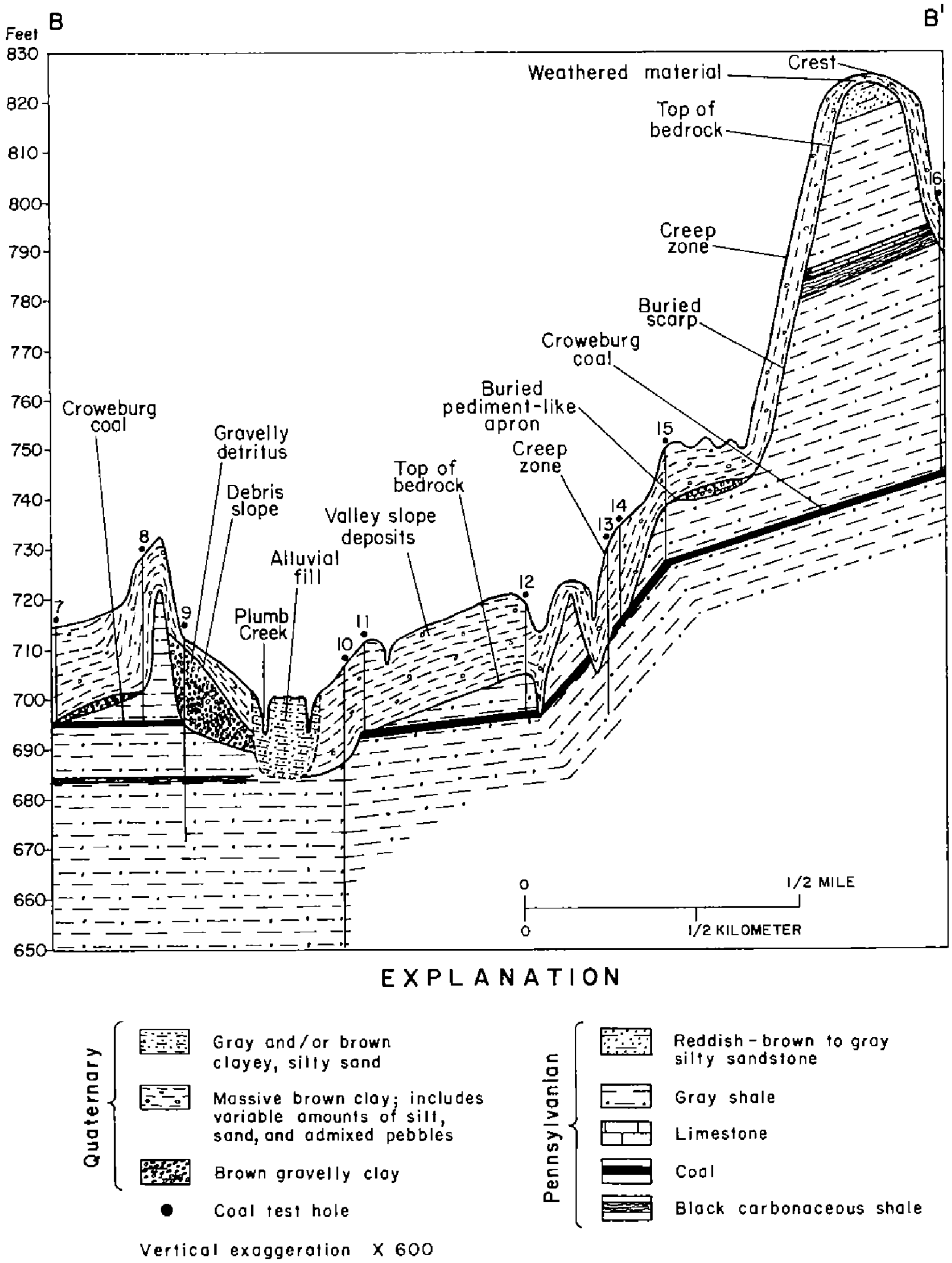


Figure 4 shows the effects of creep on the slopes of a small hill capped by a shaly, weakly indurated sandstone. Note the thin veneer of weathered sandstone at the crest of the hill and the thicker mantle of weathered material and detritus downslope.

Figure 5 shows a 12-foot-thick deposit of massive, clayey, reddish-brown gravel underlying about 5 feet of brown weathered clay and overlying 3 feet of brown weathered shale. The gravel was apparently deposited on a debris slope beneath a rather steep scarp capped by sandstone and limestone. The gravel is highly angular and is composed predominantly of sandstone with a small proportion of limestone. It occurs in a matrix of brown clay. The deposit was built up on a buried topographic bench, which I interpret to be a pediment-like feature associated with semiarid weathering.

Figure 6 shows a buried channel cutting down through the Croweburg coal. Evidence of the channel has been almost totally obliterated by infilling of waste-rock material. Miners are often unaware that situations such as this exist until a costly job of overburden removal has been completed.

Figure 7 shows a channel cutout that has been completely obscured by a mantle of soil and rock debris. The former course of the stream has been shifted laterally several yards, and the change to humid weathering has greatly modified the profile of the landscape.

Figure 8 shows a buried landscape typical of a semiarid weathering environment. Again, we see a small buried channel that has cut out the Fleming coal. The present-day surface expression gives no indication of the presence of the filled channel. Occurrences such as this verify Schumm's (1969, p. 529) statement that "with a shift to wetter climate, vegetation becomes denser and smaller channels are obliterated." Peltier's (1962, fig. 10) claim that drainage density is higher in a semiarid area than in a humid area is also supported. It should be noted, too, that the coal beds do not extend horizontally to intersect the hill surface. This phenomenon is typical throughout the study area, with miners reporting consistently that coal beds

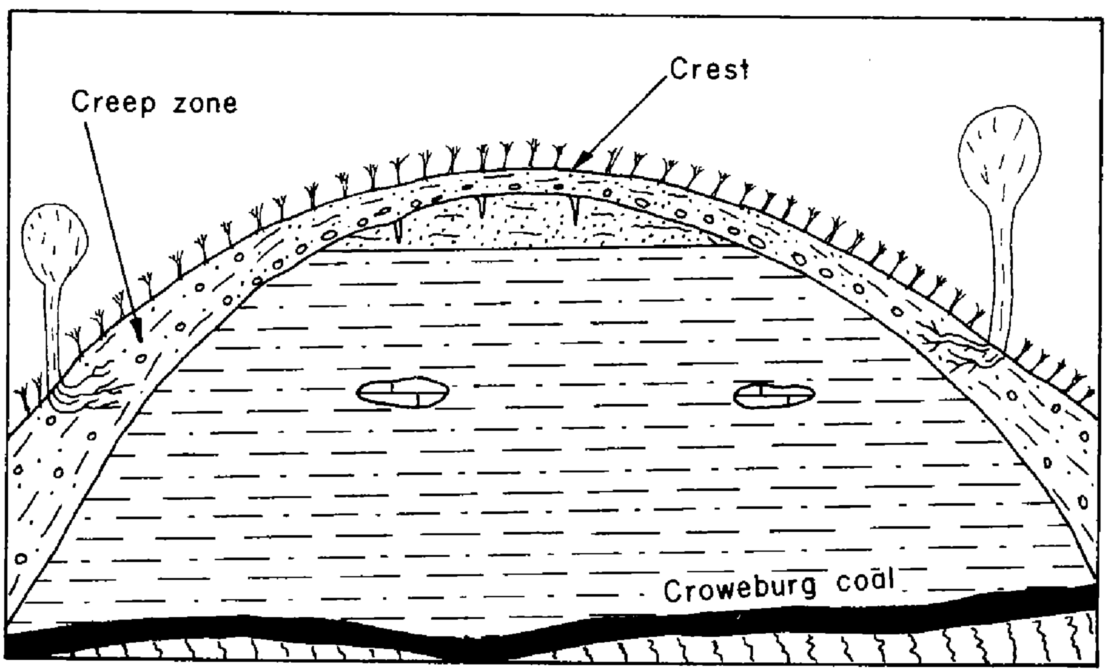


Figure 4. Diagrammatic section showing creeping regolith. NE¼ NW ¼SW¼SE¼ sec. 36, T. 25 N., R. 17 E., Nowata County.

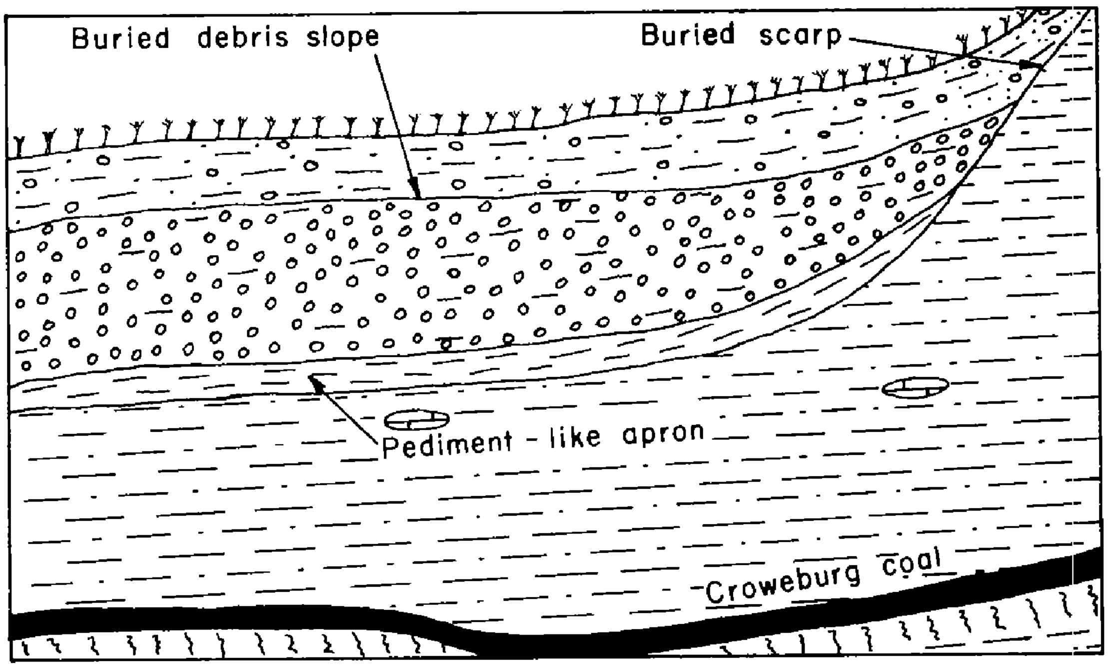


Figure 5. Diagrammatic section showing buried pediment-like bench overlain by gravelly detritus of debris slope. SW¼SE¼SE¼ sec. 19, T. 23 N., R. 17 E., Rogers County.

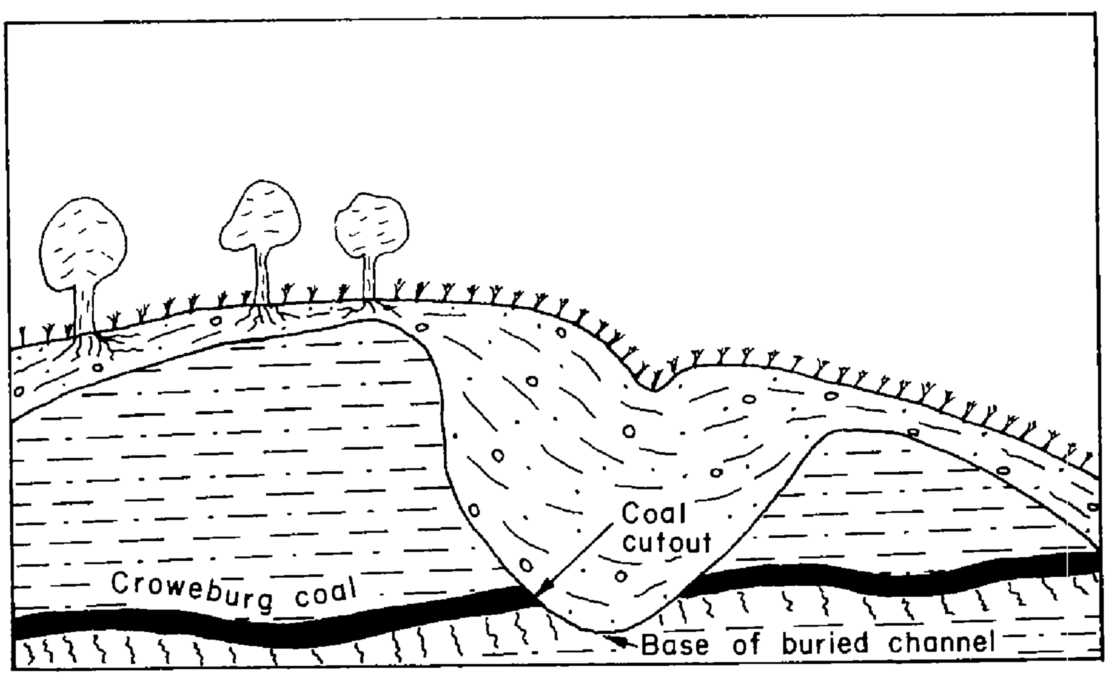


Figure 6. Diagrammatic section showing buried channel cut into bedrock. SE¼SE¼NE¼ sec. 29, T. 27 N., R. 19 E., Craig County.

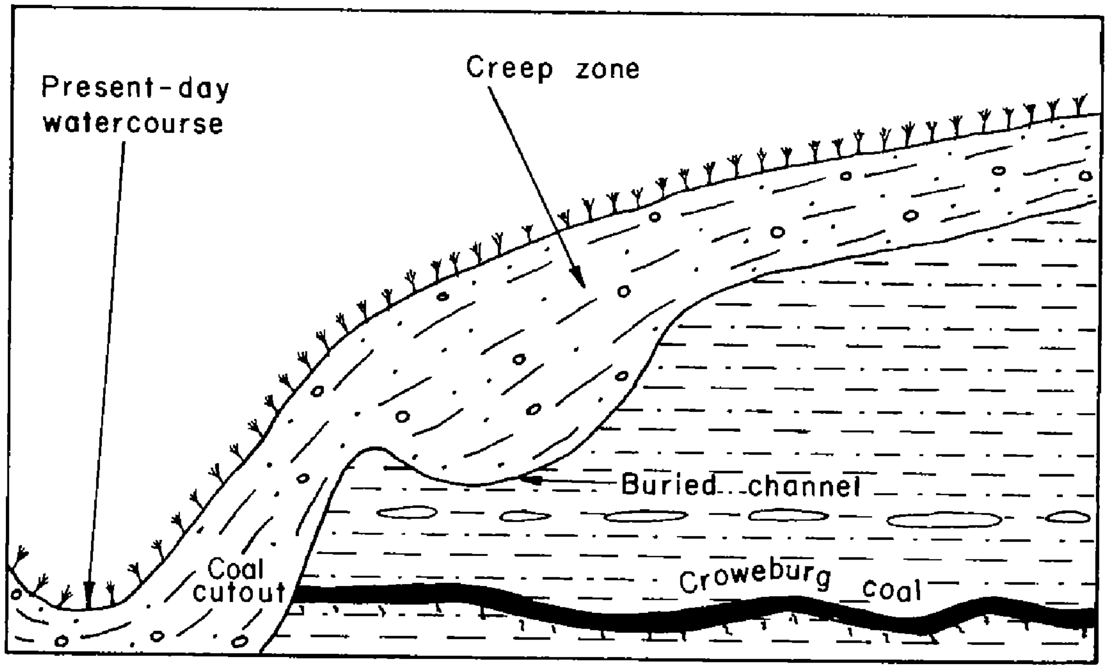


Figure 7. Diagrammatic section showing lateral shift of channel and rounding of present-day topography. SW¼SE¼NE¼ sec. 29, T. 27 N., R. 19 E., Craig County.

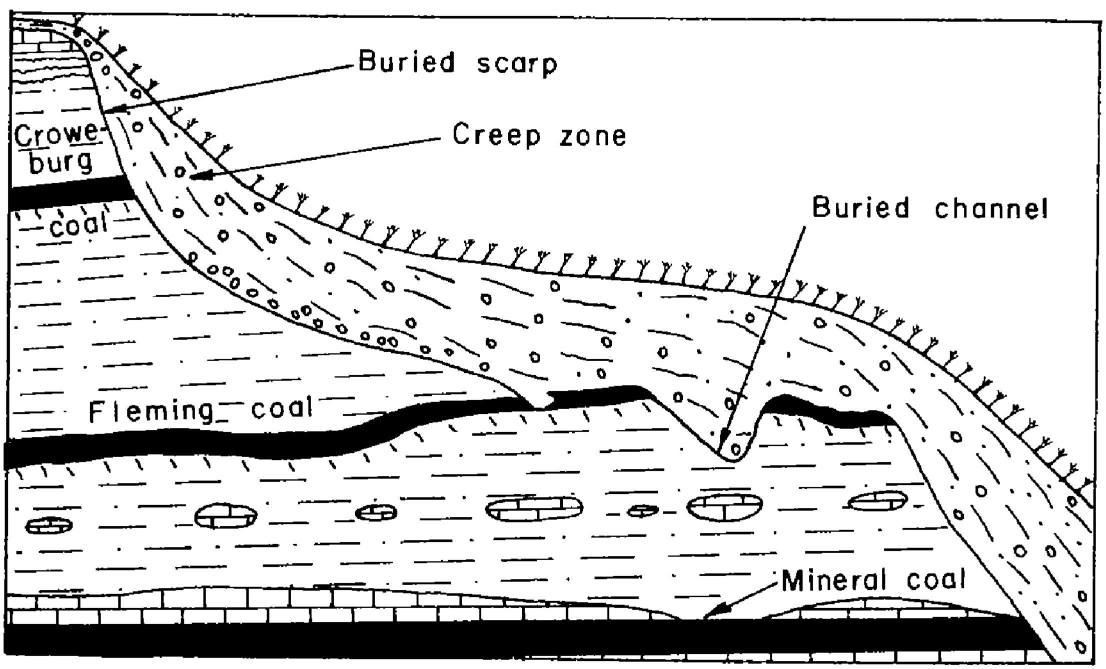


Figure 8. Diagrammatic section showing buried channel, abrupt truncation of coal beds, and rounding of present-day topography. NW¼ sec. 1, T. 28 N., R. 20 E., Craig County.

subcrop on hillslopes at depths of 10–20 feet. In my opinion, the most plausible explanation is that creep has moved a mantle of weathered material down over outcrop surfaces of scarps that existed under dryer conditions.

Geochronology

In the previous discussion it has been suggested that the geomorphic events that shaped the buried landscape in northeastern Oklahoma occurred sometime during the Quaternary Period. Although no datable material was found to verify this hypothesis, a study of the literature seems to substantiate such an interpretation.

Fenneman (1938, p. 661–662) said that following peneplanation during the Tertiary, the Ozark province was again uplifted at the beginning of the Quaternary. He described the uplift as domelike in form, so that resultant downwasting and gorge cutting have roughly restored the outlines of the old structural dome. He stated that cuestas have gradually assumed greater prominence. Results of this uplift are apparent in the study area, which is located on the northwest flank of the Ozarks. Cuestas are conspicuous, and much of the topography has a youthful appearance. Gravel deposits can be found on terrace remnants high above existing stream valleys.

Fenneman believed that glacial ice did not reach into northeastern Oklahoma during the Pleistocene. This, however, seems the most likely time for the valley cutting that has affected the continuity of coal beds in the area (see fig. 3). The lowering of sea level during the Ice Age, uplift in the Ozarks, and effects of abundant rains during pluvial periods probably were all factors in the downcutting. I have suggested that sediment which filled these valleys to depths of 15 to 20 feet (see fig. 3) was deposited during a subsequent time of warm, dry climate.

The existence of such a climatic period is well documented (albeit not specifically in the study area). According to Deevey and Flint (1957, p. 182), following the end of the Ice Age 11,000 years ago, most of the world entered a period when mean annual temperatures exceeded those of the present. The long warm spell that has been dated from approximately 7000 B.C. to approximately 600 B.C. they named the "hypsithermal." Smith (1965, p. 633) listed various other terms that have been used to describe this warm period: "Altithermal," "Xerothermic Interval," "Climatic Optimum," and "Thermal Maximum." In his discussion, he divided the warm period following deglaciation into two parts: (1) a period of humid climate, which he called the Climatic Optimum; and (2) a period of more arid climate, which he called the Xerothermic Interval. Based on paleoecological evidence (primarily adjustment of animal ranges to vegetation changes), he dated the Xerothermic and early post-Xerothermic at 6,000–3,000 years B.P. Smith (1965, p. 634) claimed that he found evidence that the dry climate of the Xerothermic Interval affected animal ranges and fragmented vegetation in the Interior Low Plateaus and the Ozark Plateaus.

Antevs (1955, p. 317) established climatic chronology in the southwestern United States through geologic evidence, pollen analysis, tree-ring dates, and radiocarbon dates. He found evidence for an extended warm, dry climatic period which he called the "Altithermal Long Drought." This period he dated from 5500 to 2000 B.C. Antevs (1955, p. 320) believed that the Long Drought probably also prevailed in Iowa and in central and eastern Texas. Although he did not mention Oklahoma, he said that the dry period was distinguished as far east as Ohio and Connecticut, where it was called the "Xerothermic Maximum."

It seems highly probable from analysis of the preceding evidence that northeastern Oklahoma was affected by a long, warm, dry period extending from approximately 5000 B.C. to 2000 B.C. During this time, stream channels that had been eroded during the preceding wet period were filled. Slopes were partly denuded of their vegetal cover, with a resultant increase in removal of waste material. Slope angles increased on scarps formed below resistant caprocks. A pediment-like bench formed at the base of many of these scarps, and debris-slope deposits were laid down. Mechanical weathering was dominant.

With a return to more humid conditions about 4,000 years ago, the form of the present landscape began to evolve. Chemical weathering prevailed, the thickness of the cover of vegetation increased, erosion by running water was slowed, and streams once again began to cut into valley-fill deposits. With increased rainfall, the regolith was subjected to deeper weathering, and saturation of the weathered zone led to the slow, inexorable downslope movement of the bedrock mantle. In time the steeper slopes took on a rounded, subdued appearance as the landforms of the semiarid topography were masked by products of mass-wasting. Beds (such as coal, or, in some cases, limestone and sandstone) that had previously cropped out at the surface were now concealed by the moving mantle of regolith.

In considering all the above evidence, it becomes apparent why coal miners report that coal beds are often "washed out" in valleys, why channels (now concealed) have been cut through coal beds near the tops of hillslopes, and why 10 to 20 feet (with reports of as much as 40 feet) of regolith now overlies the subcropping coal beds. Stoddart's (1969, p. 163) statement that "climate has demonstrably changed during the Tertiary and Pleistocene, and continues to change" is well-supported by geologic evidence manifested in the topographic expression of the landscape in northeastern Oklahoma.

Conclusions

From the evidence presented, it is apparent that there is a sound basis for my hypothesis that the Quaternary geomorphic history of northeastern Oklahoma includes a period when the area was influenced by a semiarid climate. The most likely time for such a period was during the "Xerothermic Maximum" or "Altithermal Long Drought" recorded in nearby regions from about 5000 B.C. to 2000 B.C.

The present-day landscape bears the imprint of many landscape features characteristic of a semiarid or arid environment. For example, rounded knobs having a relief of 100–200 feet (Lipe Mound, Brushy Mound, Claremore

Mound, Notch Mound) can readily be envisioned as buttes with flat tops and near-vertical sides standing in a semiarid landscape some 5,000 years ago.

Frye and Smith (1942) discussed landforms evolving in western Kansas and western Oklahoma under present-day semiarid climatic conditions. They concluded that pediment-like slopes found in the area resemble typical pediments of more arid regions in origin, in profile, and in their relation to through-flowing streams. It can be seen that a shift of the climate typical of western Oklahoma a few hundred miles to the east would create an analogous set of landscape-forming conditions.

Personal observations I made while mapping coal deposits in western North Dakota served as the basis for forming the hypothesis presented in this paper. The climate in western North Dakota is of the semiarid type, and landscape features are typical of those formed in such an environment. Of particular interest is the fact that coal beds crop out on the hillslopes (except where they have burned and baked the overlying sediment to form scoria). As noted earlier in this paper, coal beds do not crop out on hillslopes in eastern Oklahoma where the climate is humid-temperate. However, if my hypothesis of a semiarid paleoclimate is correct, the coal beds would have cropped out in the past on the hillslopes just as they do in semiarid western North Dakota today. With the change to a wetter climate, deep weathering of surface materials in conjunction with downslope movement of the regolith have buried the former landscape. It might be argued that if climatic conditions in eastern Oklahoma had not changed in recent time, the subsurface truncation of coal beds could be explained in a different way. The process of creep could cause the beds to bend down slope at the juncture of the moving regolith and to thin downslope gradually as they are drawn out until they are eventually obscured by weathering. The field observations I have made up to this time do not indicate the occurrence of such a phenomenon, nor do reports from borings of coal-exploration drillers.

I conclude that the buried features I have observed in coal-mine highwalls and in the cross sections constructed from drill holes add credence to my hypothesis of a semiarid paleoclimate. Satisfactory explanations for *all* geomorphic phenomena observed in the area cannot be achieved through alternate hypotheses.

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Coal Analyses on Open File at OGS

Results of chemical analyses of approximately 325 samples of Oklahoma coals have been placed on open file at the Oklahoma Geological Survey. The samples were collected from active mines by Survey staff over a nine-year period (1971–80). Some of this work was done under a cooperative agreement with the U.S. Geological Survey.

Data presented in the reports include information on proximate and ultimate analyses. Calorific values (Btu), sulfur content, locations, names of coal beds, and thicknesses of beds are also given. Most of the analyses were run in the OGS chemistry laboratory.

The coal-analysis files are available for examination from 8 a.m.–12 m. and 1 p.m.–5 p.m. weekdays at the Survey offices.

OKLAHOMA EARTHQUAKES, 1979

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

Introduction

Oklahoma is part of a geologic region referred to as the Stable Central Province (King, 1951; Hadley and Devine, 1974). This province extends from the western margin of the Appalachian Plateau to the eastern edge of the Rocky Mountain Uplift and from the Gulf Coastal Plain to south-central Canada. Compared to other tectonic provinces, such as the Appalachian Province, the Stable Central Region has displayed little tectonic activity since Late Pennsylvanian time. The historical seismological record has been limited, with a notable exception being the New Madrid, Missouri, area and adjacent regions in Kentucky, Tennessee, and Illinois.

The New Madrid earthquakes of 1811 and 1812 are probably the earliest historical earthquake tremors felt in Oklahoma (then Arkansas Territory) by early residents in southeastern Oklahoma settlements. The earliest documented earthquake in Oklahoma occurred near Cushing in December 1900. This event was followed by two additional earthquakes in the same area in April 1901 (Wells, 1975). The largest known Oklahoma earthquake occurred near El Reno on April 9, 1952. This magnitude-5.5 (mb) earthquake was felt in Austin, Texas, as well as Des Moines, Iowa, and covered a felt area of approximately 362,000 square km (Docekal, 1970; Kalb, 1964; von Hake, 1976). From 1900 through 1978, 182 earthquakes have been located in Oklahoma (Lawson and others, 1979).

Instrumentation

A statewide network of 11 seismograph stations is recording seismological data in Oklahoma (fig. 1). The Oklahoma Geophysical Observatory station, TUL, has been recording earthquake data since December 1961. The Observatory, located near Leonard, Oklahoma, in southern Tulsa County, operates seven seismometers, three long period and four short period, which are installed in a vault detached from the main building. The seismic responses at TUL are recorded on 11 paper-drum recorders; 16 seismograms are recorded on 16-mm film. Seven semipermanent, volunteer-operated seismograph stations and three radio-telemetry stations constitute Oklahoma's regional network. The installation and maintenance of these stations are being supported by the U.S. Nuclear Regulatory Commission (NRC) (Luza, 1978). The regional seismograph network supplements the existing seismological capability at the Oklahoma Geophysical Observatory by providing more accurate location and detection of earthquake activity in Oklahoma.

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[1] Geophysicist, Oklahoma Geophysical Observatory, Leonard.
[2] Geologist, Oklahoma Geological Survey, Norman.

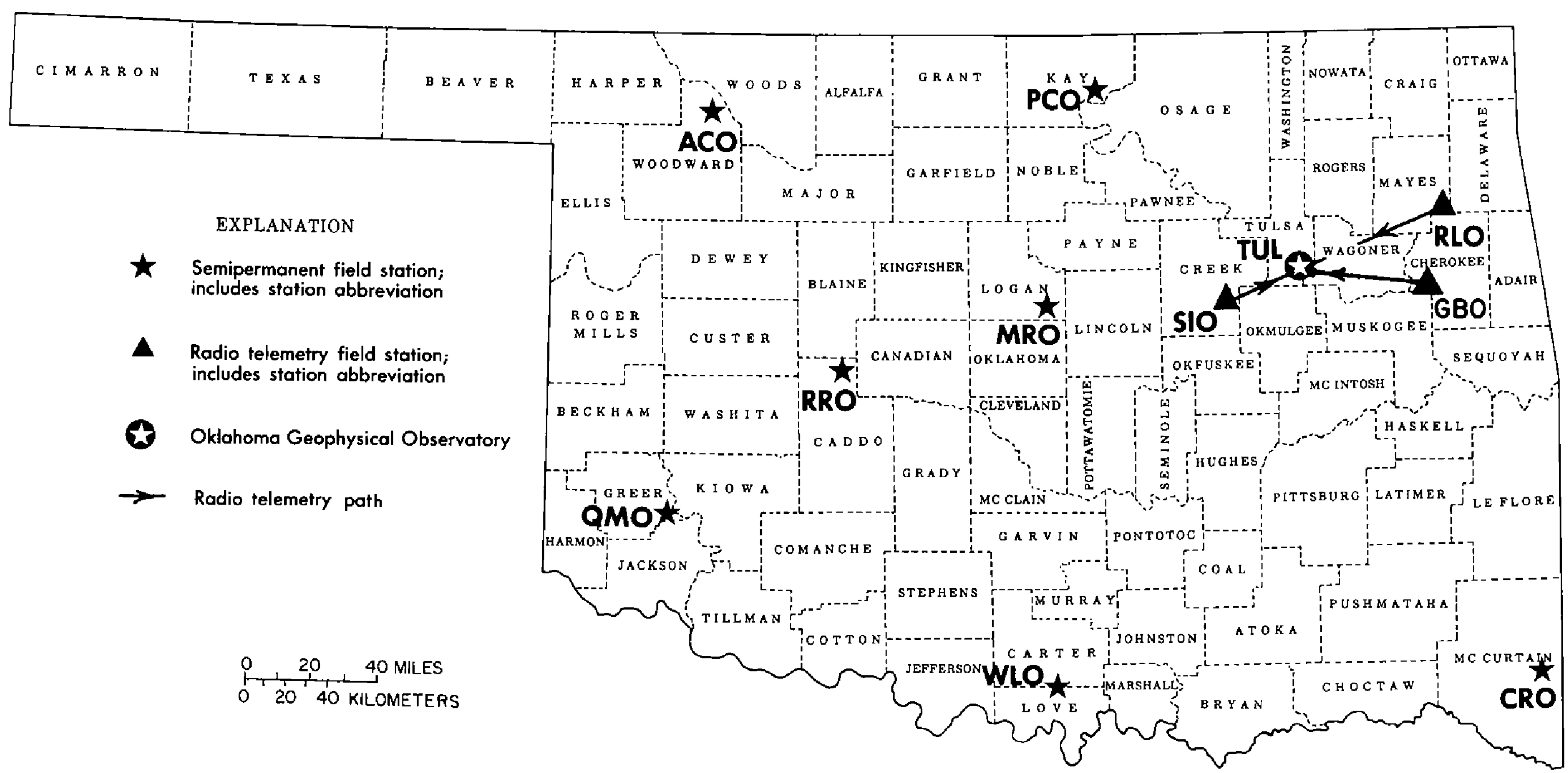

Figure 1. Active seismograph stations in Oklahoma.

Each of the seven volunteer-operated seismograph stations consists of a Geotech S-13, short-period, vertical seismometer; a Sprengnether MEQ-800-B unit, including amplifier, filters, ink-recording unit and a clock; and a Kinemetrics time-signal-radio receiver for high-frequency WWV time signals. Each radio-telemetry system consists of one Geotech S-13 seismometer and one Emheiser Rand and/or Monitron telemetry unit. The telemetry unit amplifies the seismometer output and uses this output to frequency-modulate an audiotone. A 500-milliwatt, crystal-controlled transmitter limits the line-of-sight transmission to 80 km. Seismographs from the radio-telemetry stations are recorded at the Oklahoma Geophysical Observatory.

From January 1, 1979, to December 31, 1979, station coverage was relatively uniform. However, a third radio-telemetry station, named GBO (Fort Gibson), was established July 7, 1979. This site, northeast of Fort Gibson, Cherokee County, has a 55-km line-of-sight path to TUL.

Earthquake Distribution

In 1979, 96 Oklahoma earthquakes were located (fig. 2) by the Oklahoma Geophysical Observatory staff. Magnitude values range from a low of 1.2 (mbLg) in Hughes County to a high of 3.4 (mbLg) in Beckham County. The listing represents only those earthquakes that could be located by using three or more seismograph records. Twelve earthquakes were reported felt by people living in the vicinity of an earthquake epicenter. A summary of these events is listed in table 1.

TABLE 1.—EARTHQUAKES THAT WERE REPORTED FELT IN OKLAHOMA, 1979

Event no.	Date and origin time (UTC)[1]			Nearest city		County	Intensity (MM)[2]
192	Mar	13	232922.56	NE	Union City	Canadian	II
193	Mar	14	031056.83	W	Yukon	Canadian	IV
195	Mar	14	043715.27		Yukon	Canadian	V
215	Mar	18	204419.47	N	Cogar	Canadian	III
221	Mar	18	231901.29		Reck	Carter	III
236	May	22	034923.77	E	Orr	Love	III
239	Jun	7	073935.56	E	Erick	Beckham	III
247	Jul	25	031537.27		Courtney	Love	V
256	Sep	13	004922.97	E	Carter	Beckham	IV
264	Sep	16	155720.84	NW	Minco	Grady	IV
267	Sep	17	204150.53	NW	Minco	Grady	IV
274	Dec	9	231258.66	NW	Pike	Love	III

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

[2] Modified Mercalli (MM) earthquake-intensity scale (see table 2).

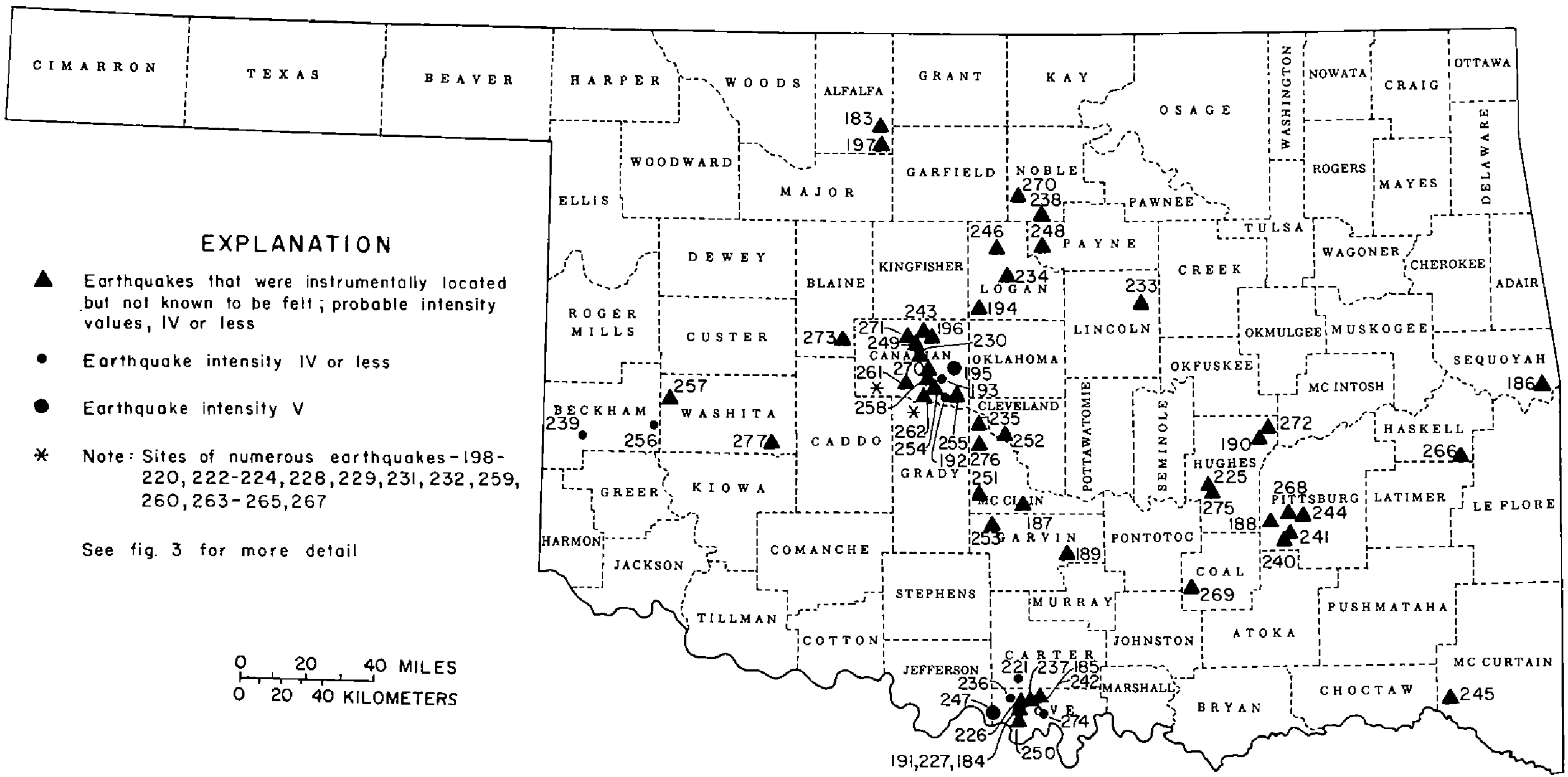

Figure 2. Distribution of Oklahoma earthquakes for 1979. Numbers correspond to event numbers in table 3.

The felt areas for the above earthquakes are probably restricted to a few tens of square kilometers away from the epicentral location. The felt and observed effects of earthquakes are generally given values according to the Modified Mercalli intensity scale, which assigns a Roman numeral to each of 12 levels described by effects on humans, man-made constructions, or natural features (table 2).

Almost one-half of the earthquakes, approximately 42, have epicentral locations in Canadian County (fig. 3). Two earthquake swarms, one north of Cogar and the other northwest of Minco, account for most of the locatable earthquakes in Canadian County. The first earthquake swarm began on March 18 (near Cogar) and lasted until April 1. Thirty earthquakes, with magnitudes ranging from 0.8 (MDUR) to 2.5 (MDUR), had epicentral locations in Canadian, Caddo, and Grady Counties. Only one of these earthquakes, MM III, was reported felt. A second earthquake swarm, northwest of Minco, Grady County, occurred on September 15 and lasted through September 17, 1979. Six earthquakes, with magnitudes ranging from 1.6 (MDUR) to 2.3 (MDUR), had epicentral locations in Grady and Canadian Counties (fig. 3). Of these six, two earthquakes, with MM IV intensities, were reported felt.

The 1979 earthquake epicentral data, when combined with previous earthquake data, produce at least three seismic trends worthy of discussion.

TABLE 2.—MODIFIED MERCALLI (MM) EARTHQUAKE-INTENSITY SCALE (ABRIDGED) (MODIFIED FROM WOOD AND NEUMANN, 1931)

I	Not felt except by a very few under especially favorable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings. Suspended objects may swing.
III	Felt quite noticeably indoors, especially on upper floors of buildings. Automobiles may rock slightly.
IV	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, doors, windows disturbed. Automobiles rocked noticeably.
V	Felt by nearly everyone, many awakened. Some dishes, windows, etc. broken; unstable objects overturned. Pendulum clocks may stop.
VI	Felt by all; many frightened and run outdoors.
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction. Shock noticed by persons driving automobiles.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings; great in poorly built structures. Fall of chimneys, stacks, columns. Persons driving automobiles disturbed.
IX	Damage considerable even in specially designed structures; well-designed frame structures thrown out of plumb. Buildings shifted off foundations. Ground cracked conspicuously.
X	Some well-built wooden structures destroyed; ground badly cracked, rails bent. Landslides and shifting of sand and mud.
XI	Few if any (masonry) structures remain standing. Broad fissures in ground.
XII	Damage total. Waves seen on ground surfaces.

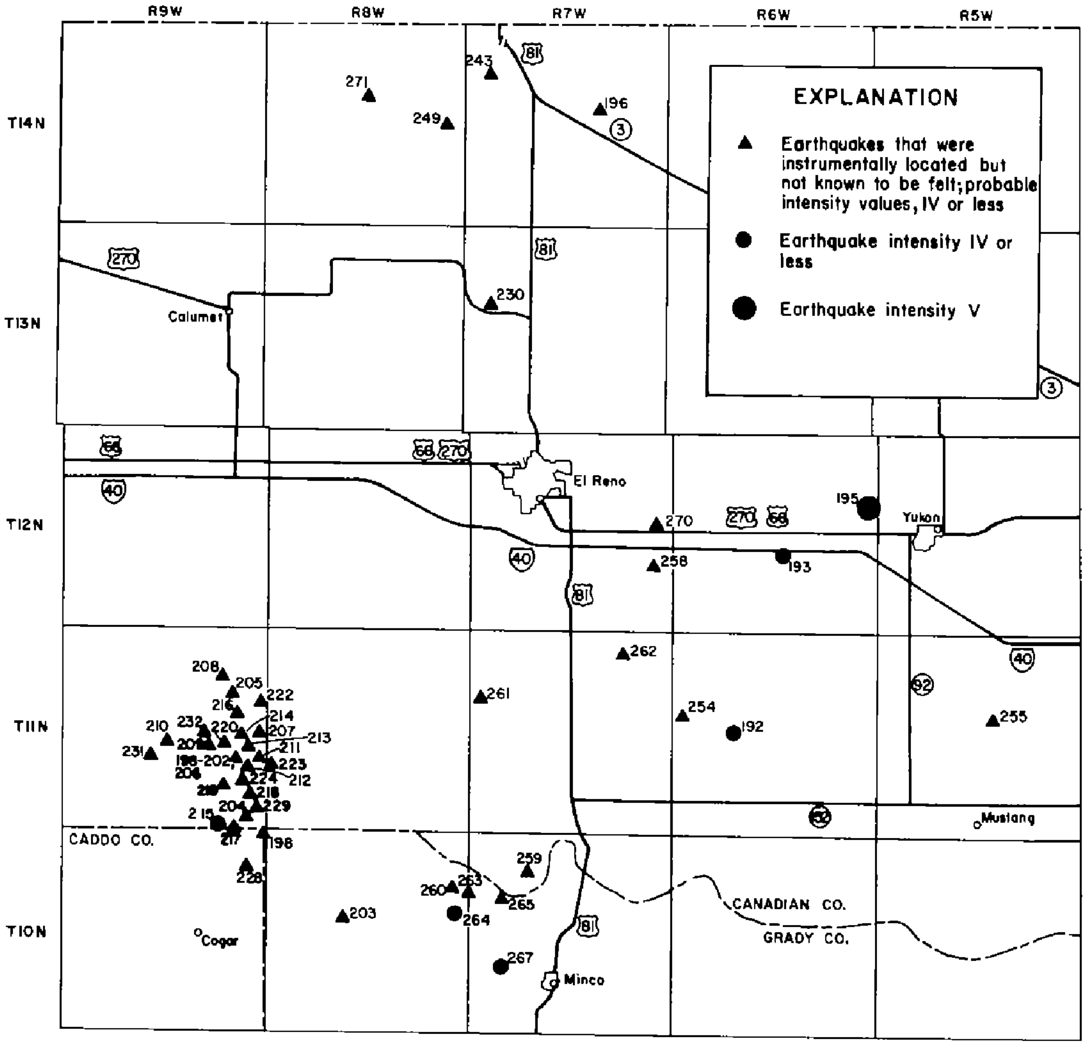

Figure 3. Earthquake epicentral locations in Canadian County and nearby Grady and Caddo Counties.

One trend is located in north-central Oklahoma (fig. 4). The pre-1977 earthquake data (circles) and the 1977–79 earthquake data (triangles) are shown in figure 4. There appears to be a 40-km-wide and 145-km-long earthquake zone that extends northeastward from near El Reno toward Perry (Noble County). Most of the earthquakes within this zone have occurred in the vicinity of the El Reno–Mustang area, which has been the site of numerous earthquakes since 1908. More than half, 56, of the 1979 earthquake locations plot within this zone. Prior to installation of the statewide earthquake-station network, more than one-half of the known Oklahoma earthquakes occurred in the vicinity of El Reno. However, after the El Reno earthquake of 1952, magnitude 5.5 (mb), no earthquakes were reported for this region until 1978.

The correlation of historical and recent earthquake activity to known structural features remains unclear. Some fault features that cut pre-

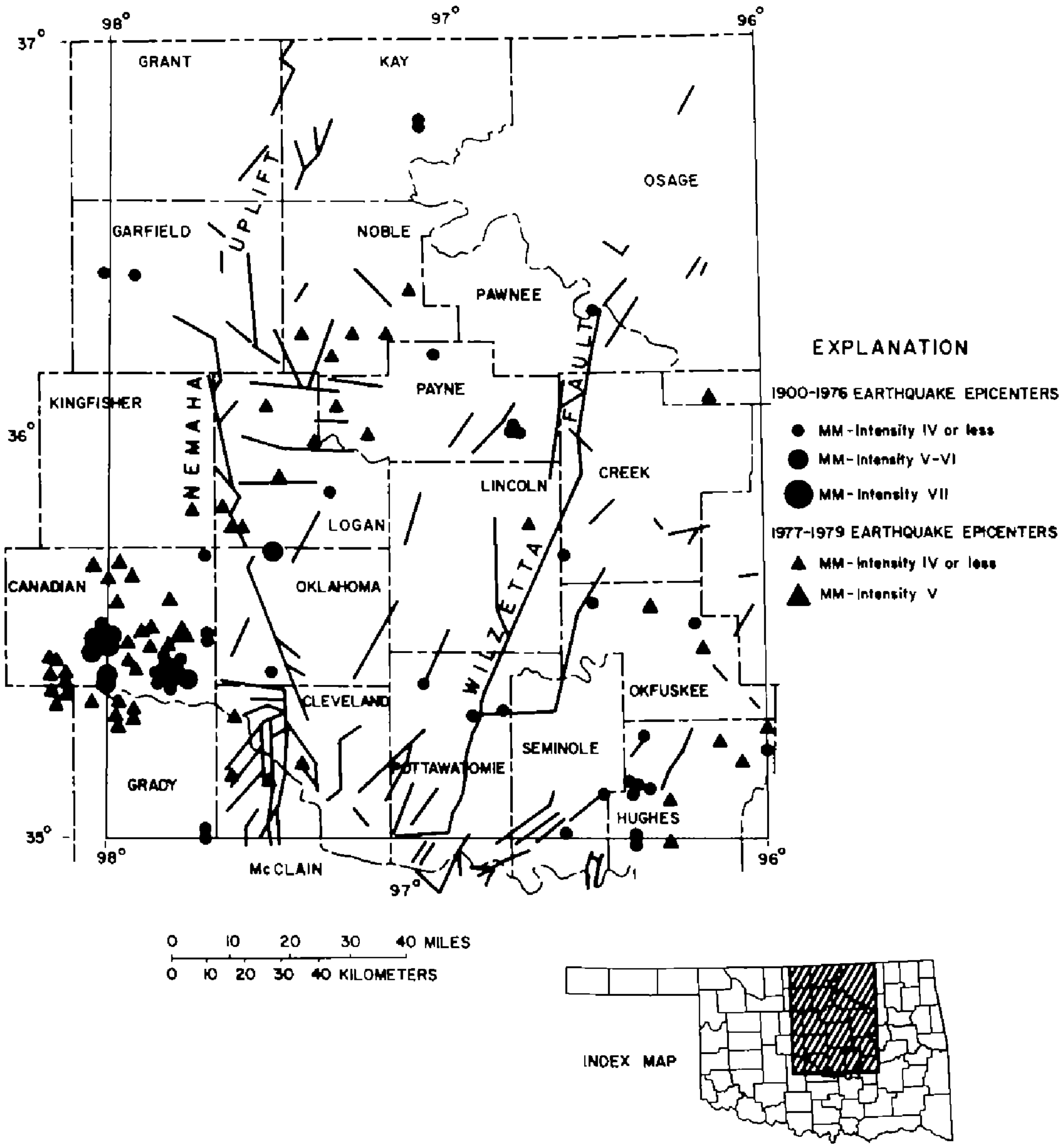

Figure 4. Distribution of faults that cut pre-Pennsylvanian strata and earthquake epicenters for north-central Oklahoma (Wheeler, 1960; Jordan, 1962; unpublished reports).

Pennsylvanian rocks, which are compiled from Jordan (1962), Wheeler (1960), and unpublished reports, are shown in figure 4. The El Reno–Perry trend appears to cut diagonally across the Nemaha Uplift structures at about a 30° angle. The southern end of this trend appears to be more active than the middle and northern parts. The recent as well as the historic earthquake data seem to support this observation. A five- to six-seismograph-station array is planned for the El Reno area this year. It is hoped that additional earthquake data, such as focal-depth determinations, will give us a better understanding of this feature.

In south-central Oklahoma, earthquakes are concentrated in the Wilson area, Carter and Love Counties. Twelve earthquakes, of which four were felt, were located in this region in 1979. In the past, this area has also been the site of numerous small earthquakes. A third general area of earthquake activity is located along and north of the Ouachita front (Arkoma Basin) in southeastern Oklahoma. Twelve earthquakes, with (DUR) magnitudes that range from 1.7 to 2.4, were instrumentally detected in this region.

Catalog

An HP-9825A desk-top computer system is used to calculate local earthquake epicenters. A catalog containing date, origin time, county, intensity, magnitude, location, focal depth, and references is printed in page-size format. Table 3 contains 1979 Oklahoma earthquakes displayed in a modified version of the regional earthquake catalog. Each event is sequentially numbered and arranged according to date and origin time. The numbering system is compatible with the system used for the *Earthquake Map of Oklahoma* (Lawson and others, 1979).

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

Earthquake magnitude is a measurement of energy and is based on data from seismograph records. There are several different scales used to report magnitude. Table 3 has three magnitude scales which are mbLg (Nuttli), m3Hz (Nuttli), and MDUR (Lawson). Each magnitude scale was established to accommodate specific criteria, such as the distance from the epicenter, as well as the availability of certain seismic data.

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

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

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

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

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

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

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

where A is the maximum center-to-peak vertical-ground-motion amplitude

Table 3.—Oklahoma Earthquake Catalog for 1979

Event number	Date and origin time (UTC)		County	Intensity (MM)	Magnitudes 3Hz	bLg	DUR	Latitude (°N.)	Longitude (°W.)	Depth (km)1
183	JAN 8	113542.99	Alfalfa		2.0	2.1	1.9	36.579	98.146	4.7
184	JAN 24	051546.35	Love		1.4		1.5	33.985	97.434	5.0R
185	JAN 24	052532.00	Love		1.8	2.1	1.9	34.022	97.381	5.0R
186	JAN 28	102409.34	Sequoyah		1.4		1.7	35.483	94.568	5.0R
187	JAN 29	192010.40	McClain		2.4	2.6	2.3	34.916	97.383	5.0R
188	FEB 1	123132.28	Pittsburg		1.8	1.7	2.1	34.830	96.062	5.0R
189	FEB 4	165559.96	Garvin		2.6	2.5	2.6	34.672	97.157	5.0R
190	FEB 5	142340.05	Hughes		2.2	1.8	2.2	35.177	96.092	5.0R
191	MAR 1	034218.77	Love		1.9	2.0	1.8	33.969	97.446	5.0R
192	MAR 13	232922.56	Canadian	II	1.7			35.421	97.851	5.0R
193	MAR 14	031056.83	Canadian	IV	2.0	1.9	1.8	35.498	97.826	5.0R
194	MAR 14	040243.05	Logan		1.4,		1.5	35.781	97.650	5.0R
195	MAR 14	043715.27	Canadian	V	2.2	2.2	2.1	35.519	97.781	5.0R
196	MAR 15	103810.48	Canadian		1.6		1.6	35.689	97.923	5.0R
197	MAR 16	123817.42	Alfalfa		2.0	1.9	2.0	36.517	98.123	5.0R
198	MAR 18	172539.66	Canadian		1.6		1.5	35.377	98.100	5.0R
199	MAR 18	173309.23	Canadian				0.8	35.410	98.115	5.0R
200	MAR 18	173516.41	Canadian				1.0	35.410	98.115	5.0R
201	MAR 18	173951.71	Canadian		1.5		1.3	35.410	98.115	5.0R
202	MAR 18	174431.59	Canadian		1.6		1.4	35.410	98.115	5.0R
203	MAR 18	175252.20	Grady		1.8		1.5	35.344	98.053	5.0R
204	MAR 18	175536.84	Canadian		1.6		1.1	35.384	98.110	5.0R
205	MAR 18	180717.57	Canadian		2.1	2.0	1.8	35.439	98.118	5.0R
206	MAR 18	181453.81	Canadian		1.9	1.7	1.5	35.410	98.116	5.0R
207	MAR 18	183036.85	Canadian		2.3	2.3	2.0	35.418	98.108	5.0R
208	MAR 18	184629.65	Canadian		1.9	2.0	1.6	35.443	98.126	5.0R
209	MAR 18	185723.95	Canadian		2.0	2.0	1.8	35.416	98.130	5.0R
210	MAR 18	191350.60	Canadian		2.4	2.4	1.9	35.418	98.155	5.0R
211	MAR 18	193021.23	Canadian		2.2	2.2	1.8	35.418	98.101	5.0R
212	MAR 18	194157.26	Canadian		2.2	2.0	1.8	35.406	98.110	5.0R
213	MAR 18	200530.54	Canadian		2.7	2.5	2.0	35.416	98.110	5.0R
214	MAR 18	202411.90	Canadian		2.3		1.8	35.420	98.110	5.0R
215	MAR 18	204419.47	Canadian	III	2.9	2.9	2.5	35.379	98.124	5.0R
216	MAR 18	210741.09	Canadian		2.0	1.8	1.5	35.429	98.114	5.0R
217	MAR 18	211654.63	Canadian		1.9	1.8	1.3	35.379	98.118	5.0R
218	MAR 18	214210.54	Canadian		2.4	2.5	2.1	35.394	98.108	5.0R
219	MAR 18	220820.53	Canadian		2.1	1.9	1.7	35.396	98.126	5.0R
220	MAR 18	224217.44	Canadian		2.0	1.9	1.5	35.416	98.126	5.0R
221	MAR 18	231901.29	Carter	III	2.5	2.3	2.2	34.100	97.448	5.0R
222	MAR 18	234039.22	Canadian		2.2	2.0	1.7	35.433	98.102	5.0R
223	MAR 19	005432.65	Canadian		2.1	2.0	1.7	35.408	98.102	5.0R
224	MAR 19	034255.14	Canadian		2.5	2.5	2.3	35.400	98.110	5.0R
225	MAR 21	045556.19	Hughes		1.8	1.2	1.7	35.043	96.349	5.0R
226	MAR 23	013148.66	Love				1.3	34.034	97.430	5.0R
227	MAR 23	060139.99	Love				1.8	34.022	97.440	5.0R
228	MAR 23	075737.46	Caddo		1.9	1.8	1.7	35.361	98.108	5.0R
229	MAR 23	084114.13	Canadian		2.0	1.9	1.9	35.387	98.108	5.0R
230	MAR 23	104354.67	Canadian		1.5		0.9	35.605	97.974	5.0R
231	MAR 23	172602.40	Canadian		2.1		1.8	35.411	98.163	5.0R
232	APR 1	122910.76	Canadian		1.8	1.7	1.9	35.420	98.132	5.0R
233	APR 22	092252.46	Lincoln		1.6		1.8	35.789	96.711	5.0R
234	MAY 8	112334.88	Logan		2.1	1.9	2.2	35.923	97.480	5.0R
235	MAY 12	215641.18	McClain		2.1	1.9	2.3	35.301	97.601	5.0R
236	MAY 22	034923.77	Love	III	1.8	1.9	2.0	34.027	97.470	3.7R
237	MAY 23	173008.30	Love			2.2	2.0	34.055	97.405	3.4R
238	JUN 1	110001.61	Noble		1.6	1.4	1.1	36.207	97.330	5.0R
239	JUN 7	073935.56	Beckham	III	3.2	2.9	3.0	35.187	99.812	5.0R
240	JUN 19	044956.95	Pittsburg		1.9	1.4	2.0	34.715	95.965	5.0R
241	JUN 19	045313.53	Pittsburg		1.8		1.9	34.746	95.932	5.0R
242	JUL 1	070016.28	Love		1.9	1.8	2.0	34.028	97.383	5.0R
243	JUL 4	034521.29	Canadian		2.3	2.3	2.2	35.705	97.978	5.0R
244	JUL 7	011533.23	Pittsburg		2.4	1.6	2.1	34.879	95.814	5.0R
245	JUL 13	074813.44	McCurtain		1.3		1.8	34.033	95.087	5.0R
246	JUL 24	022406.27	Logan		2.8	2.5	2.5	36.070	97.506	5.0R

TABLE 3.—*Continued*

Event number	Date and origin time (UTC)		County	Intensity (MM)	Magnitudes 3Hz	bLg	DUR	Latitude (°N.)	Longitude (°W.)	Depth (km)1
247	JUL 25	031537.27	Love	V		2.7	2.3	33.967	97.549	5.0R
248	JUL 31	191105.62	Payne		2.4	2.5	1.9	36.086	97.305	5.0R
249	AUG 3	102911.63	Canadian		2.0	1.9	1.7	35.683	98.005	5.0R
250	AUG 9	000414.86	Love		1.8	2.4	2.0	33.930	97.432	5.0R
251	AUG 16	072712.82	McClain		1.7	1.9	1.7	34.953	97.602	5.0R
252	AUG 19	015807.85	Cleveland		2.4	2.2	2.1	35.203	97.445	5.0R
253	SEP 4	074011.97	Garvin		2.2	2.3	2.1	34.799	97.557	5.0R
254	SEP 5	023848.48	Canadian		1.7	1.9	1.5	35.429	97.871	5.0R
255	SEP 5	040434.49	Canadian		1.8	1.8	1.5	35.427	97.717	5.0R
256	SEP 13	004922.97	Beckham	IV	3.3	3.4	3.1	35.217	99.362	14.5R
257	SEP 13	021951.28	Washita		1.9		2.1	35.380	99.360	14.5R
258	SEP 15	034225.39	Canadian		1.8		1.7	35.493	97.882	5.0R
259	SEP 15	140119.38	Grady		2.0	1.9	1.9	35.369	97.952	5.0R
260	SEP 16	060453.11	Grady		1.7		1.6	35.355	97.997	5.0R
261	SEP 16	062758.42	Canadian		1.7		1.5	35.435	97.981	5.0R
262	SEP 16	104205.85	Canadian		2.0	2.0	1.9	35.455	97.905	5.0R
263	SEP 16	110700.23	Grady		1.9	1.8	1.8	35.355	97.989	5.0R
264	SEP 16	155720.84	Grady	IV	2.5	2.5	2.2	35.343	97.997	5.0R
265	SEP 16	221642.17	Grady		2.1	1.9	1.9	35.355	97.966	5.0R
266	SEP 17	143809.60	Haskell		1.6	1.8	1.7	35.063	94.937	5.0R
267	SEP 17	204150.53	Grady	IV	2.6	2.5	2.3	35.320	97.968	5.0R
268	OCT 6	110851.92	Pittsburg		1.5		1.6	34.887	95.8731	5.0R
269	OCT 21	072907.55	Coal		2.3	2.2	2.4	34.502	96.432	5.0R
270	NOV 7	055409.84	Canadian		2.1		1.9	35.510	97.888	5.0R
271	NOV 11	102657.33	Canadian		2.2	1.9	2.1	35.695	98.050	5.0R
272	NOV 16	055015.60	Hughes				1.3	35.285	95.987	5.0R
273	NOV 27	091036.79	Blaine		3.3	3.3	2.9	35.630	98.408	5.0R
274	DEC 9	231258.66	Love	III	2.9	2.5	2.4	33.988	97.353	5.0R
275	DEC 10	082514.82	Hughes		1.8	1.5	2.0	34.965	96.307	5.0R
276	DEC 14	132009.02	McClain		1.8	1.9	1.8	35.187	97.664	5.0R
277	DEC 16	123737.49	Washita		2.5		2.2	35.158	98.741	5.0R
278	DEC 20	145826.81	Noble		2.1		1.9	36.367	97.379	5.0R

[1] The hypocenter is restrained (R) at an arbitrary depth of 5.0 km, except where indicated, for purposes of computing latitude, longitude, and origin time.

sustained for three or more cycles of Sg waves, near 1 hertz in frequency, measured in nanometers; T is the period of Sg waves measured in seconds; and Δ is the great-circle distance from station to epicenter measured in kilometers.

The MDUR magnitude scale was developed by Lawson (1978) for earthquakes in Oklahoma and adjacent areas. It is defined as

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

where *DUR* is the duration or difference, in seconds, between the Pg-wave arrival time and the time the final coda amplitude decreases to twice the background-noise amplitude. If the Pn wave is the first arrival, the interval between the earthquake-origin time and the decrease of the coda to twice the background-noise amplitude is measured instead.

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

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

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Water-Level Records and PCB Reconnaissance Reports Available from USGS Office

Two recent open-file reports, *Reconnaissance of Polychlorinated Biphenyls in the Arkansas River Between Muskogee and Webbers Falls Lock and Dam, Oklahoma*, by J. D. Stoner, and *Selected Water-Level Records for Oklahoma, 1976–78*, by Robert L. Goemaat and Dannie E. Spiser, are now available in limited quantities from the U.S. Geological Survey.

The PCB analysis reports show that concentrations of suspended and dissolved phases of the chemical in the Arkansas River were less than the detection limit of 0.1 micrograms per liter. The highest concentration in samples of the bottom material was 16 micrograms per kilogram found 5.9 miles below the U.S. Highway 62 bridge in Muskogee.

The water-level records in the Goemaat and Spiser study are published as part of a program begun in 1937 to provide long-term records of water-level fluctuations in representative wells in order to predict water-level trends and provide information for use in research.

Both publications were prepared by the USGS in cooperation with the Oklahoma Water Resources Board and are available from the USGS office at 201 Northwest Third Street, Room 621, Oklahoma City, Oklahoma 73102.

Revised Book on Salt Domes Published

An enlarged and revised edition of Michel T. Halbouty's *Salt Domes: Gulf Region, United States and Mexico* has recently been published by Gulf Publishing Co. of Houston, Texas.

This second edition has been enlarged to include three new chapters, one of which contains a study of salt domes in Mexico and their importance to Mexican oil reserves, geological and geophysical maps, and seismic profiles of many Mexican salt domes. A second new chapter looks at seismic profiling techniques as applied to diapiric structures and basin stratigraphy, while the third describes the application of Landsat (land satellite) images in salt-dome exploration.

The book provides a review of salt dome geology and examines other writers' ideas on the geophysical and economic aspects of salt-dome source beds. A number of salt-dome indexes are listed in the bibliography.

The book is available from Gulf Publishing Co., Book Division, P.O. Box 2608, Houston, Texas 77001. The price is $55.00.

THE CAMERATE CRINOID GENUS *DICHOCRINUS* IN MORROWAN ROCKS OF OKLAHOMA

H. L. Strimple[1]

Representatives of the subclass Camerata are relatively sparse in the late Paleozoic. The family Dichocrinidae is known from Middle and Upper Pennsylvanian rocks of North America, but has never been reported from the Lower Pennsylvanian (see table 1).

In the process of picking washed residues from shale of Morrowan age, a minute radial plate and a basal circlet of *Dichocrinus* sp. were found. The sample from which the specimens were recovered is from a shale in the Brentwood interval, Braggs Member, Sausbee Formation, of the Morrowan Stage that is exposed on the east shore of Grand Lake east of Wagoner, Wagoner County, Oklahoma (SE¼ sec. 22, T. 17 N., R. 19 E.), Locality 16 of Moore and Strimple (1973, p. 79). In the same exposure, *Lampadosocrinus frustulum* Strimple (1979), *Cranocrinus eximius* Strimple (1978), *Allocatillocrinus rotundus* Moore (1940), and *Lasanocrinus nodatus* Moore and Strimple (1973) were found in good preservation; the genera *Cibolocrinus*, *Arkacrinus*, *Diphuicrinus*, and *Parcromyocrinus* were identified from fragmentary remains.

Strimple (1977) reported that 38 crinoid genera were known at that time to have been present in the Bloyd Formation of Arkansas (which includes the Brentwood Limestone Member) and equivalent strata in Oklahoma. Forty-two crinoid genera are now recognized from the zone.

TABLE 1.—DICHOCRINIDS FROM PENNSYLVANIAN ROCKS

	State	Region	Formation	Stage
Dichocrinus sp.	Oklahoma	Northeastern	Sausbee	Morrowan
D. dilatus Strimple and Watkins (1969)	Texas	Llano Uplift	Marble Falls	Atokan (= Lower Desmoinesian)
D. nola Strimple and Moore (1973)	Illinois	Mid-central	Bond	Missourian
Stomiocrinus conlini Strimple and Watkins (1969)	Texas	North-central	Graford	Missourian

[1]Geology Department, The University of Iowa, Iowa City, Iowa 52242.

Dichocrinus sp.

Although the species is represented by fragmentary remains and is probably a juvenile, several conclusions can be drawn concerning its structure. The cup is low because the base is broad, with the two equidimensional basals expanding from the large circular proximal columnar at a low angle. Also, the single radial plate is shorter and relatively wider than those of other Pennsylvanian dichocrinids. There are six unequal plates in the radial circlet of *Dichocrinus*, with the most elongated being the anterior radial and primanal, both of which extend into the adsutural areas of the basal circlet. The other four radials are shorter than that of the anterior but are still relatively narrow in *Dichocrinus dilatus*, *D. nola*, and *Stomiocrinus conlini*. The lateral sides of each radial curve to form a constricted cup summit in *S. conlini*. The radial of *Dichocrinus* sp. expands distalward. The lateral sides of radials in *D. nola* and *D. dilatus* are almost vertical. The radial articular facet of *Dichocrinus* sp. is angustary, horseshoe shaped, and lacks discernible fossae. The outer plate surface is papillose.

The proximal columnal of *Dichocrinus* sp. has faint crenellae about the perimeter. In midsection, there is a small protuberance with a circular outline. There is no lumen present, which indicates that the rest of the stem was uncoupled and a plug formed that sealed off the passageway to the coelomic cavity. If this is so, the crinoid survived without a column, at least long enough to secrete stereom to form the plug. *Dichocrinus* typically and commonly retains its column.

Acknowledgments.—The exposure from which *Dichocrinus* sp. was recovered was first called to my attention by my friend and colleague of many years' standing, Claude Bronaugh of Afton, Oklahoma. The specimens were recovered by my wife, Christina C. Strimple.

Repository.—Specimens of *Dichocrinus* sp. are deposited in the Geology Repository, The University of Iowa, Iowa City, Iowa, catalogue number 47013.

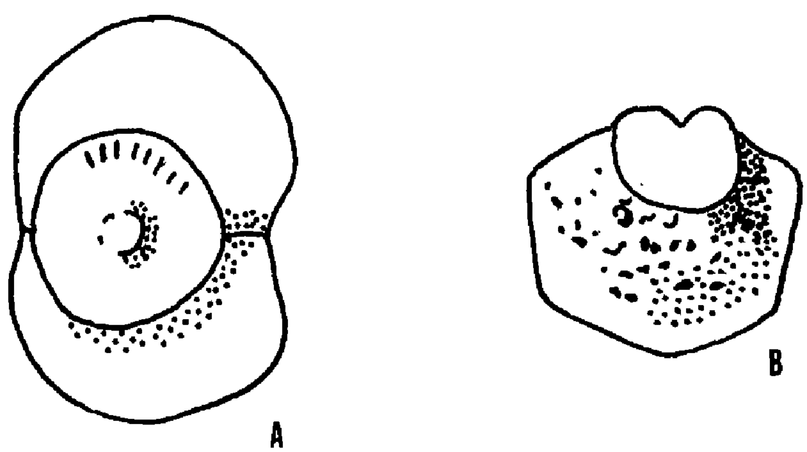

Figure 1. Camera lucida drawings of *Dichocrinus* sp. *A*, basal circlet viewed from below. *B*, radial plate viewed from side. ×50.

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Highway Geology Symposium Scheduled for Texas

The 31st Annual Highway Geology Symposium will be held August 13–15 in Austin, Texas, at the Joe C. Thompson Conference Center. Sponsors for this year's meeting will be the Texas Bureau of Economic Geology and the Texas Department of Highways and Public Transportation. The symposium will emphasize the interdependence of resource development and an adequate transportation network. In addition to technical sessions, the meeting will offer a photo-interpretation workshop and a field trip to the Llano Uplift of central Texas.

For information, contact L. E. Garner, chairman, 31st Highway Geology Symposium, Bureau of Economic Geology, The University of Texas at Austin, University Station, Box X, Austin, Texas 78712. The phone number is (512) 471–1534.

U.S. Board on Geographic Names Decisions

The U.S. Board on Geographic Names recently approved one Oklahoma place name, which was published in the October through December 1979 issue of *Decisions on Geographic Names in the United States* (Decision List 7904).

Denman (not: Denmon) has been adopted to identify a community 5.4 km (3.4 miles) east-southeast of Red Oak; Latimer County; sec. 6, T. 5 N., R. 22 E.; Indian Meridian (34°56′15″ N., 95°01′30″ W.).

Ward Padgett Leaves Department of Mines

On April 30, 1980, Ward Padgett stepped down from his position as chief mine inspector of the Oklahoma Department of Mines. Because of ill health, he resigned at age 69 from the post he had held since 1963, and has moved back to his hometown of McAlester, Oklahoma.

Ward worked many years as a coal miner in Indiana, Kentucky, Illinois, and Oklahoma, and thus gained great insight into the problems of mining companies and their workers. When he first assumed the position of chief mine inspector, it was an elective office. The office was made an appointive position in January of 1979 through a constitutional amendment approved by the voters. He first was appointed to the office by Governor Henry Bellmon in order to fill a vacancy caused by the death of John Malloy. Ward then served under four other governors, including Governors Dewey Bartlett, David Hall, David Boren, and George Nigh.

Ward's mining career began while he was a high school student when he worked in the Indiana coal field during the summer-vacation period. He worked his way up to a supervisory rank with coal companies in Indiana, Kentucky, and Illinois, and eventually came to Oklahoma as an assistant division superintendent of mining for Lone Star Steel Co. at McAlester.

Ward was a major factor in bringing about an effective program of mined-land reclamation in Oklahoma long before it was required by federal legislation. Oklahoma's reclamation requirements, first set forth in 1968 and then updated in 1971, resulted from a concerted effort by Ward and the mining companies of Oklahoma to prevent future abandonment of strip-mined land at the conclusion of mining. Ward also was instrumental in helping to organize the Interstate Mining Compact Commission.

Governor George Nigh has appointed Otis English, of Claremore, to succeed Ward as the State's chief mine inspector. English is currently chairman of the State Mining Board and has had 31 years of experience in the mining industry. The Governor has also appointed Blaney Qualls, of Wister, as deputy chief mine inspector. Qualls is currently chief of reclamation and enforcement in the Oklahoma Department of Mines.

We are all sorry to hear of Ward's retirement from the position he filled so ably, but we look forward to a continuation of effective leadership in the Department of Mines by Otis English and Blaney Qualls.

—Kenneth S. Johnson

Mankin to Chair Board On Mineral and Energy Resources

Charles J. Mankin, director of the Oklahoma Geological Survey and of The University of Oklahoma's Energy Resources Center, was recently appointed to the chairmanship of the Board on Mineral and Energy Resources of the National Research Council. NRC is the research arm of the National Academy of Sciences. The two-year appointment runs from July 1, 1980, through June 30, 1982. Dr. Mankin will also serve as a member of the council's Commission on Natural Resources.

Mankin was first appointed to NRC's Board on Mineral Resources in April 1975 to serve on a newly formed Panel on Gas-Reserve Estimates. In 1977 he was appointed by Interior Secretary Cecil Andrus to serve as chairman of a 12-member Committee on Gas Production Opportunities that was organized by the board to investigate producibility of natural gas in the outer continental shelf in the Gulf of Mexico.

The Board on Mineral Resources was combined with NRC's Board on Energy Studies in 1978 to become the Board on Mineral and Energy Resources. Its purpose is to evaluate the natural resources of the nation, to assess technologies, with projections through the year 2010, and to attempt to resolve related problems of supplying needed resources.

New OCS Oil and Gas Resource Estimates Due Soon

Revised preliminary estimates of "undiscovered recoverable" oil and gas resources of specific provinces of the U.S. Outer Continental Shelf (OCS) (to a water depth of 200 meters) have been compiled by the U.S. Geological Survey. These figures reflect new geologic and geophysical information obtained since the publication in 1975 of USGS Circular 725, *Geological Estimates of Undiscovered Recoverable Oil and Gas Resources in the United States.*

The new estimates for oil and gas resources of the total offshore area, compared to those of 1975, are about the same; however, the distribution between areas, the spread of the ranges, and the relation of gas to oil vary.

The new figures are shown in a number of tables listing specific OCS provinces in the Atlantic, the Gulf of Mexico, the Pacific, and the Alaska regions. These estimates are described as "preliminary" to a more comprehensive reappraisal of both offshore and onshore resources. This project is currently under way, and the findings are expected to be summarized in a report scheduled for publication this summer.

Alumni Day guests enjoy a noontime meal of charcoaled hamburgers at the OU School of Geology and Geophysics.

Rain Doesn't Take Shine Off of 1980 OU Alumni Day

Friday, April 25, was Alumni Day 1980 for The University of Oklahoma School of Geology and Geophysics. Alumni were given the opportunity to see firsthand the involvement and accomplishments of OU students on both individual and group levels.

Alumni Day 1980 was a student effort. The School and the three student organizations (the OU chapter of The American Association of Petroleum Geologists, the Gamma Chapter of Sigma Gamma Epsilon, and the OU chapter of the Society of Exploration Geophysicists) worked together to sponsor a day of student-paper presentations. More than 80 people attended the sessions, which represented individual student work on class projects and thesis research and covered topics from the subsurface to outer space.

A luncheon hamburger cookout, forced indoors by inclement weather, was enjoyed by more than 90 alumni, faculty, and students. The cookout provided an excellent opportunity for the alumni to become better acquainted with the students and their work — an important aspect of Alumni Day 1980.

A social hour and banquet followed the student-paper presentations. Dr. K. F. Wantland, School director, made reference to an earlier announcement of his resignation, and recognized various student groups and their officers. He then presented to William Siard, Alumni Advisory Council past president, an original artwork commemorating his term.

Alumni Day co-chairpersons Evelyn Grossbard and Elizabeth Bartlett, and Joe Hayden, president of the OU chapter of the Society of Exploration Geophysicists, presented to the 130 persons who attended an informative and amusing slide presentation concerning the various activities of the students and student groups.

Karen Bellis, president of the Gamma Chapter of Sigma Gamma Epsilon, presented awards to Elaine Winfrey, outstanding junior; Dale Murphy, outstanding senior; Joe Hayden, outstanding graduate student; and Dr. John Wickham, faculty honor roll.

Alumni Day 1980 co-chairpersons Elizabeth Bartlett and Evelyn Grossbard are to be commended for their hard work and dedication. Under their direction, more than thirty students from five committees made Alumni Day 1980 a successful and memorable event. The large number of student papers and the good attendance by alumni and students are a testament to their efforts. More importantly, Alumni Day 1980 demonstrated the ambitions, involvement, and educational commitment of the students.

—Robert Shoup

Visiting alumni were treated to a day of student presentations that covered a wide range of topics and featured a slide presentation about the activities of students and student organizations.

Conservation Education Association Schedules Convention

"Issues for the '80's" will be the theme of the 1980 Conservation Education Association (CEA) national convention, scheduled for August 10–13, at the East Central University campus in Ada, Oklahoma.

Robert Cutler and other nationally known lecturers will speak on the topics of conservation, education, and human issues for the 1980's. A total of 43 small-group concurrent sessions will then examine these topics in detail.

Field trips are scheduled for visits to museums, ranches, an underground building, a drilling rig, the Arbuckle Mountains, a tar pit, and other points of interest. Also on tap are exhibitions, a business meeting, a watermelon feed, and a variety of other activities.

CEA was organized in 1953 and is one of the oldest conservation education organizations in the world.

For more information, contact Dan Sebert, 105 North Center, P.O. Box 1527, Ada, Oklahoma 74820.

New Theses Added to OU Geology Library

The following M.S. theses have been added to The University of Oklahoma Geology and Geophysics Library:

The Areal Geology and Cretaceous Stratigraphy of Southern Marshall County, Oklahoma, by Kenneth F. Bridges. 126 p., 17 figs., 1 pl., 1 table.

Diagenesis and Pore Evolution of the Reef Plate, Enewetak Atoll, Marshall Islands, by Alan P. Emmendorfer. 136 p., 51 figs., 3 tables.

Lithostratigraphy and Depositional Environments of the Pitkin Limestone and Fayetteville Shale (Chesterian) in Portions of Wagoner, Cherokee and Muskogee Counties, Oklahoma, by April H. Orgren. 144 p., 19 figs., 13 pls., 3 tables.

Aerial Survey Examines Uranium Resources

Portions of Oklahoma are included in the Dalhart Quadrangle of recently released U.S. Department of Energy (DOE) radiometric and magnetic reports. The surveys were flown as part of the DOE Grand Junction office's National Uranium Resource Evaluation (NURE) program to acquire and compile geologic and other information with which to assess the magnitude and distribution of uranium resources and to determine areas favorable for the occurrence of uranium in the United States.

Bound volumes, bound maps, histograms, microfiche data listings for each quadrangle, and other materials, are available in several purchase options. For more information, contact Texas Instruments, Inc., Airborne Geophysical Services, P.O. Box 22561, M.S. 3975, Dallas, Texas 75276.

The reports are also on open file at the Oklahoma Geological Survey.

Roy Davis Receives 25-Year Certificate

The Oklahoma Geological Survey's longest-term employee, cartographer Roy Derrell Davis, was honored May 14 at an awards ceremony sponsored by The University of Oklahoma's Employee Executive Council for his 25 years of faithful service to the Survey and the University. Roy joined the Survey July 6, 1954, and has been employed continuously since that time. Roy was the subject of an interview article in a recent edition of *Our University* magazine, published quarterly at OU. Apart from his meticulous cartographic work, he is best known for his "mud" paintings, faithful reproductions of primitive cave art, that have been prepared with natural earth materials and pigments. Roy has had several other articles about his unique work published by magazines and newspapers.

Keep up the good work, Roy; we'll be checking on you during the next 25 years!

USBM Issues Study of Hartshorne Coal

U.S. Bureau of Mines Report of Investigations 8407, *Methane Content and Geology of the Hartshorne Coalbed in Haskell and Le Flore Counties, Okla.*, by Anthony T. Iannacchione and Donald G. Puglio, has been issued as part of the USBM methane-control program. Data included indicate a methane content of 1.1 to 1.5 trillion cubic feet in the Hartshorne coals.

Single copies of RI8407 can be obtained free of charge from the Section of Publications, Bureau of Mines, U.S. Department of the Interior, 4800 Forbes Avenue, Pittsburgh, Pennsylvania 15213.

Connie Smith Joins OGS as Associate Editor

In April, Connie Gail Smith joined the Oklahoma Geological Survey staff as associate editor, filling a vacancy that had existed since May 1979, when Judy Russell resigned to become an exploration geologist with Mobil Oil Corp. At the Survey, Connie will work closely with editor Bill Rose and associate editor Betty Ham in editing and publishing the various series of reports and maps.

A native Oklahoman from Arkoma (as in "Arkoma Basin"), Connie received her bachelor's degree in journalism here at The University of Oklahoma in 1974. Before joining the Survey, Connie worked for more than 3 years for *World Literature Today* (formerly *Books Abroad*), the prestigious international literary quarterly published at OU and known to scholars all over the world.

In addition to her work for *World Literature Today*, Connie made time to serve OU further as a member of its Board of Publications and as a member of the communications committee of the Employee Executive Council. She will continue to work with these groups.

Earlier, Connie served as publicity director for the Oklahoma Science and Arts Foundation, now the Omniplex, in Oklahoma City.

Connie is married to James C. Davis, also an OU graduate, who is a computer specialist at Tinker Air Force Base in the Oklahoma City area. Connie and James have resided in Norman for the past several years.

Connie's hobbies include photography, art, music, and writing. She is a pianist, and she exhibited an Oriental brush painting in a recent show.

It's a pleasure to have you with us, Connie!

OKLAHOMA ABSTRACTS

GSA Annual Meeting, Rocky Mountain Section
Ogden, Utah, May 16–17, 1980

The following abstract is reprinted from *Abstracts with Programs* of The Geological Society of America, v. 12, no. 6. Page numbers are given in brackets below the abstracts. Permission of the authors and of James R. Clark, publications manager of GSA, to reproduce the abstracts is gratefully acknowledged.

Plate Tectonics of the Ancestral Rocky Mountains

CHARLES F. KLUTH and PETER J. CONEY, Department of Geosciences, University of Arizona, Tucson, Arizona 85721

The Ancestral Rockies and related features developed during Pennsylvanian time from the Ouachita-Marathon regions to Utah-Wyoming. The features are enigmatic because they were fault block uplifts and basins separated by high angle fault zones with complex movement histories; disrupted shelf type sedimentation trends; formed at high angles to, and far from, Pennsylvania plate margins; and were amagmatic. Analysis of age, thickness and facies trends and of faults inferred to have been active at that time, suggest rapid structural differentiation was initiated and concentrated along the Wichita Uplift-Anadarko Basin in early Pennsylvanian. By mid-Pennsylvanian, deformation had spread south-westward into the Marathon region and foreland deformation reached its greatest areal extent and intensity, culminating in the Ancestral Rockies. By late Pennsylvanian, activity waned in the Ouachita region but increased in the Marathon area, and foreland deformation decreased and spread southward into New Mexico and West Texas. Activity in the Marathon region and foreland deformation ended synchronously in early Permian. Interpretation suggests the Ancestral Rockies were part of a complex, intraplate response to collision between North America and South America-Africa. When suturing was taking place south of the Ouachitas, foreland deformation took place in the mid-continent. When suturing was taking place from the Ouachitas to the Marathons, foreland deformation was at a maximum. Later, when suturing was taking place only south of the Marathons, foreland deformation spread south and decreased in extent. These foreland features formed as southwestern North America was

OKLAHOMA ABSTRACTS is intended to present abstracts of recent unpublished papers relating to the geology of Oklahoma and adjacent areas of interest. The editors are therefore interested in obtaining abstracts of formally presented or approved documents, such as dissertations, theses, and papers presented at professional meetings, that have not yet been published.

wrenched during the collision. This tectonic activity is analogous to response of Asia to Cenozoic collision with India. [277]

The University of Oklahoma

The Areal Geology and Cretaceous Stratigraphy of Southern Marshall County, Oklahoma

KENNETH F. BRIDGES, The University of Oklahoma, M.S. thesis, 1979

Southern Marshall County is in the dissected Coastal Plain or Red River Plain, a part of a much larger feature, the Gulf Coastal Plain of southern United States.

Rocks cropping out in the area range in age from Early Cretaceous (Antlers Sandstone) to Late Cretaceous (Woodbine Formation). Younger materials of Pleistocene and Holocene age (Terrace and alluvial deposits respectively) cover much of the Cretaceous terrane along the Red River and other upland areas. Cretaceous rocks exposed in the area under investigation are (in ascending order): the Antlers Sandstone (Trinity Group); Goodland Limestone and Kiamichi Formation (Fredericksburg Group); Caddo Formation, Bokchito Formation, Bennington Limestone and Grayson Marlstone (Washita Group); and the lowermost Woodbine Formation (Dexter Member). Major unconformities separate the Lower Cretaceous rock from the underlying Paleozoic strata and form the overlying units of the Upper Cretaceous.

The gentle southward homoclinal dip of the Cretaceous strata is interrupted in Marshall County by southeast-northwest trending folds which are the Preston Anticline and the Kingston Syncline. These structures, originally formed in Late Paleozoic time, underwent renewed structural movement in Late Cretaceous.

Oil and gas comprise the principal mineral resources in southern Marshall County. Enos and Isom Springs Oil Fields, situated in the area of investigation, represent two of 11 fields in the county. Other natural resources include stone and gravel, as well as an abundant water supply. Recent discoveries of oil and gas in the Ouachita rocks of southern Marshall County have opened a prolific new area of exploration.

The thickness and physical character of the Cretaceous sequence in southern Marshall County suggest that these rocks were deposited in alluvial and shallow-water marine environments on the stable continental shelf of the ancestral Gulf of Mexico. Seas advanced over the eroded surface of the complexly folded Paleozoic rocks in Early Cretaceous time depositing the sandstones, limestones, and clays of the Trinity, Fredericksburg, and Washita Groups. Subsequent withdrawal of seas exposed Lower Cretaceous sediments to erosion until Late Cretaceous time when renewed transgression deposited the sands and clays of the Woodbine Formation. The Tertiary Period represents a time of erosion and peneplanation in southern Marshall County. During the Pleistocene, terrace sands and gravels were deposited by the ancestral Red and Washita Rivers to complete the geologic history.

Lithostratigraphy and Depositional Environments of the Pitkin Limestone and Fayetteville Shale (Chesterian) in Portions of Wagoner, Cherokee and Muskogee Counties, Oklahoma

APRIL H. ORGREN, The University of Oklahoma, M.S. thesis, 1979

The area of study is located in northeastern Oklahoma in T. 15 N. through T. 18 N., R. 19 E., through R. 21 E. Major emphasis in the study was placed on the Pitkin Formation (Chesterian). The underlying Fayetteville Formation (Chesterian) was also included in the study for use in determining the regional relationships. The Chesterian Series in the study area is bounded above and below by unconformities. The lowest Chesterian unit, the Hindsville Formation, which conformably underlies the Fayetteville, is poorly exposed in the study area and was not included in this investigation. The upper unconformity that truncates the Chesterian Series separates the Mississippian System from the Pennsylvanian System in the study area.

Subdivision of the formations into facies was done on the basis of the presumed degree of water turbulence present at the time of deposition. The low energy regime includes the black shale facies, the interbedded shale and carbonate mudstone facies, the spiculite facies, and the nodular wackestone facies. The moderate energy regime includes the bryozoan-crinoidal packstone facies, the mixed skeletal packstone facies, and the oolith-intraclast pelloidal packstone facies. The high energy regime includes the crinoidal-oolitic grainstone facies, and the mixed skeletal grainstone facies.

Higher energy sediments are concentrated in the southern and southwestern portions of the study area, while more moderate energy sediments are concentrated in the northern and northeastern portions. Structural evidence indicates that the shoreline was most likely to the northeast of the study area. The depositional environment then, in the broadest sense, consisted of a seaward wave energy barrier where deposition consisted mainly of sandy sediments. Shoreward of this, and in quieter waters, existed a lagoonal region inhabited by fenestrate type organisms, carbonate mud producers, and a variety of other organisms.

The major transition from the deposition of terrigenous material (Fayetteville) to the production of carbonates (Pitkin) may be explained in either of two ways. It is possible that during a still-stand, the amount of incoming terrigenous materials decreased allowing carbonates to develop on the accumulated terrigenous sediments. An alternative hypothesis may be that all of the facies of the Fayetteville and Pitkin Formations were lateral equivalents and were eventually brought to rest upon each other due to a transgression of the seas. The relationships of the various sediments to each other and to their source areas does not permit an explanation of the depositional history by means of a regression of the seas or a progradation of the carbonate facies.

An unknown sequence of strata was presumably deposited above the rocks that are currently exposed in the study area. An eventual regression of the seas exposed the area to erosion leaving the Pitkin Formation in its present configuration. The regression of the seas is assumed to have been caused by an uplifting of the Ozark Dome causing the Pitkin and Fayetteville Formations in the study area to develop a regional dip of about 0.03° in a southwesterly direction. A beveling of the uplifted edge of the Pitkin caused the truncation of the formation that is evident in the study area.

The limestones of the Pitkin were particularly susceptible to dissolution and developed features typical of karsting. Later subsidence in a southeasterly direction caused a transgression of the Morrowan seas and deposition of quartz-sandy calcarenites and limestone pebble conglomerates over the Pitkin erosional surface.

OKLAHOMA GEOLOGY NOTES

Volume 40 June 1980 Number 3

Page